CHAPTER TWO

2.1 (a) $\dfrac{3\text{ wk}}{}\left|\dfrac{7\text{ d}}{1\text{ wk}}\right|\dfrac{24\text{ h}}{1\text{ d}}\left|\dfrac{3600\text{ s}}{1\text{ h}}\right|\dfrac{1000\text{ ms}}{1\text{ s}} = \underline{1.8144 \times 10^9 \text{ ms}}$

(b) $\dfrac{38.1\text{ ft}/\text{s}}{}\left|\dfrac{0.0006214\text{ mi}}{3.2808\text{ ft}}\right|\dfrac{3600\text{ s}}{1\text{ h}} = 25.98\text{ mi}/\text{h} \Rightarrow \underline{\underline{26.0\text{ mi}/\text{h}}}$

(c) $\dfrac{554\text{ m}^4}{\text{d}\cdot\text{kg}}\left|\dfrac{1\text{ d}}{24\text{ h}}\right|\dfrac{1\text{ h}}{60\text{ min}}\left|\dfrac{1\text{ kg}}{1000\text{ g}}\right|\dfrac{10^8\text{ cm}^4}{1\text{ m}^4} = \underline{\underline{3.85 \times 10^4 \text{ cm}^4/\text{min}\cdot\text{g}}}$

2.2 (a) $\dfrac{760\text{ mi}}{\text{h}}\left|\dfrac{1\text{ m}}{0.0006214\text{ mi}}\right|\dfrac{1\text{ h}}{3600\text{ s}} = \underline{\underline{340\text{ m}/\text{s}}}$

(b) $\dfrac{921\text{ kg}}{\text{m}^3}\left|\dfrac{2.20462\text{ lb}_m}{1\text{ kg}}\right|\dfrac{1\text{ m}^3}{35.3145\text{ ft}^3} = \underline{\underline{57.5\text{ lb}_m/\text{ft}^3}}$

(c) $\dfrac{5.37 \times 10^3\text{ kJ}}{\text{min}}\left|\dfrac{1\text{ min}}{60\text{ s}}\right|\dfrac{1000\text{ J}}{1\text{ kJ}}\left|\dfrac{1.34 \times 10^{-3}\text{ hp}}{1\text{ J}/\text{s}} = 119.93\text{ hp} \Rightarrow \underline{\underline{120\text{ hp}}}$

2.3 Assume that a golf ball occupies the space equivalent to a 2 in $\times$ 2 in $\times$ 2 in cube. For a classroom with dimensions 40 ft $\times$ 40 ft $\times$ 15 ft :

$$n_{\text{balls}} = \dfrac{40 \times 40 \times 15\text{ ft}^3}{}\left|\dfrac{(12)^3\text{ in}^3}{\text{ft}^3}\right|\dfrac{1\text{ ball}}{2^3\text{ in}^3} = 5.18 \times 10^6 \approx \underline{\underline{5\text{ million balls}}}$$

The estimate could vary by an order of magnitude or more, depending on the assumptions made.

2.4 $\dfrac{4.3\text{ light yr}}{}\left|\dfrac{365\text{ d}}{1\text{ yr}}\right|\dfrac{24\text{ h}}{1\text{ d}}\left|\dfrac{3600\text{ s}}{1\text{ h}}\right|\dfrac{1.86 \times 10^5\text{ mi}}{1\text{ s}}\left|\dfrac{3.2808\text{ ft}}{0.0006214\text{ mi}}\right|\dfrac{1\text{ step}}{2\text{ ft}} = \underline{\underline{7 \times 10^{16}\text{ steps}}}$

2.5 Distance from the earth to the moon = 238857 miles

$\dfrac{238857\text{ mi}}{}\left|\dfrac{1\text{ m}}{0.0006214\text{ mi}}\right|\dfrac{1\text{ report}}{0.001\text{ m}} = \underline{\underline{4 \times 10^{11}\text{ reports}}}$

2.6

$\dfrac{19\text{ km}}{1\text{ L}}\left|\dfrac{1000\text{ m}}{1\text{ km}}\right|\dfrac{0.0006214\text{ mi}}{1\text{ m}}\left|\dfrac{1000\text{ L}}{264.17\text{ gal}} = 44.7\text{ mi}/\text{gal}$

Calculate the total cost to travel x miles.

$$\text{Total Cost}_{\text{American}} = \$14{,}500 + \dfrac{\$1.25}{\text{gal}}\left|\dfrac{1\text{ gal}}{28\text{ mi}}\right|x\text{ (mi)} = 14{,}500 + 0.04464x$$

$$\text{Total Cost}_{\text{European}} = \$21{,}700 + \dfrac{\$1.25}{\text{gal}}\left|\dfrac{1\text{ gal}}{44.7\text{ mi}}\right|x\text{ (mi)} = 21{,}700 + 0.02796x$$

Equate the two costs $\Rightarrow x = \underline{\underline{4.3 \times 10^5\text{ miles}}}$

2.7

$$\frac{5320 \text{ imp. gal}}{\text{plane} \cdot \text{h}} \left| \frac{14 \text{ h}}{1 \text{ d}} \right| \frac{365 \text{ d}}{1 \text{ yr}} \left| \frac{10^6 \text{ cm}^3}{220.83 \text{ imp. gal}} \right| \frac{0.965 \text{ g}}{1 \quad \text{cm}^3} \left| \frac{1 \quad \text{kg}}{1000 \text{ g}} \right| \frac{1 \text{ tonne}}{1000 \text{ kg}}$$

$$= 1.188 \times 10^5 \ \frac{\text{tonne kerosene}}{\text{plane} \cdot \text{yr}}$$

$$\frac{4.02 \times 10^9 \text{ tonne crude oil}}{\text{yr}} \left| \frac{1 \text{ tonne kerosene}}{7 \text{ tonne crude oil}} \right| \frac{\text{plane} \cdot \text{yr}}{1.188 \times 10^5 \text{ tonne kerosene}}$$

$$= 4834 \text{ planes} \Rightarrow \underline{\underline{5000 \text{ planes}}}$$

2.8 (a) $\dfrac{25.0 \text{ lb}_m}{} \left| \dfrac{32.1714 \text{ ft} / \text{s}^2}{} \right| \dfrac{1 \qquad \text{lb}_f}{32.1714 \text{ lb}_m \cdot \text{ft} / \text{s}^2} = \underline{\underline{25.0 \text{ lb}_f}}$

(b) $\dfrac{25 \text{ N}}{} \left| \dfrac{1}{9.8066 \text{ m/s}^2} \right| \dfrac{1 \text{ kg} \cdot \text{m/s}^2}{1 \text{ N}} = 2.5493 \text{ kg} \Rightarrow \underline{\underline{2.5 \text{ kg}}}$

(c) $\dfrac{10 \text{ ton}}{} \left| \dfrac{1 \text{ lb}_m}{5 \times 10^{-4} \text{ ton}} \right| \dfrac{1000 \text{ g}}{2.20462 \text{ lb}_m} \left| \dfrac{980.66 \text{ cm} / \text{s}^2}{} \right| \dfrac{1 \text{ dyne}}{1 \text{ g} \cdot \text{cm} / \text{s}^2} = \underline{\underline{9 \times 10^9 \text{ dynes}}}$

2.9 $\dfrac{50 \times 15 \times 2 \text{ m}^3}{} \left| \dfrac{35.3145 \text{ ft}^3}{1 \quad \text{m}^3} \right| \dfrac{85.3 \text{ lb}_m}{1 \quad \text{ft}^3} \left| \dfrac{32.174 \text{ ft}}{1 \quad \text{s}^2} \right| \dfrac{1 \text{ lb}_f}{32.174 \text{ lb}_m / \text{ft} \cdot \text{s}^2} = \underline{\underline{4.5 \times 10^6 \ \text{lb}_f}}$

2.10 $\dfrac{500 \text{ lb}_m}{} \left| \dfrac{1 \quad \text{kg}}{2.20462 \text{ lb}_m} \right| \dfrac{1 \quad \text{m}^3}{11.5 \text{ kg}} \approx 5 \times 10^2 \left(\dfrac{1}{2}\right)\left(\dfrac{1}{10}\right) \approx \underline{\underline{25 \text{ m}^3}}$

2.11 (a)

$$m_{\text{displaced fluid}} = m_{\text{cylinder}} \Rightarrow \rho_f V_f = \rho_c V_c \Rightarrow \rho_f h \pi r^2 = \rho_c H \pi r^2$$

$$\rho_c = \frac{\rho_f h}{H} = \frac{(30 \text{ cm} - 14.1 \text{ cm})(1.00 \text{ g} / \text{cm}^3)}{30 \text{ cm}} = \underline{\underline{0.53 \text{ g} / \text{cm}^3}}$$

(b) $\rho_f = \dfrac{\rho_c H}{h} = \dfrac{(30 \text{ cm})(0.53 \text{ g} / \text{cm}^3)}{(30 \text{ cm} - 20.7 \text{ cm})} = \underline{\underline{1.71 \text{ g} / \text{cm}^3}}$
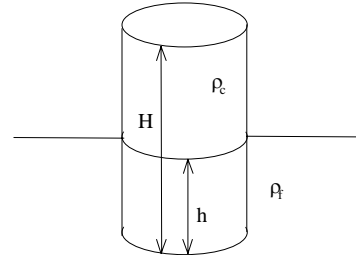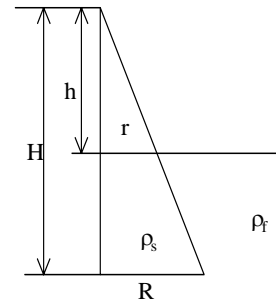

2.12

$$V_s = \frac{\pi R^2 H}{3}; \quad V_f = \frac{\pi R^2 H}{3} - \frac{\pi r^2 h}{3} \ ; \quad \frac{R}{H} = \frac{r}{h} \Rightarrow r = \frac{R}{H} h$$
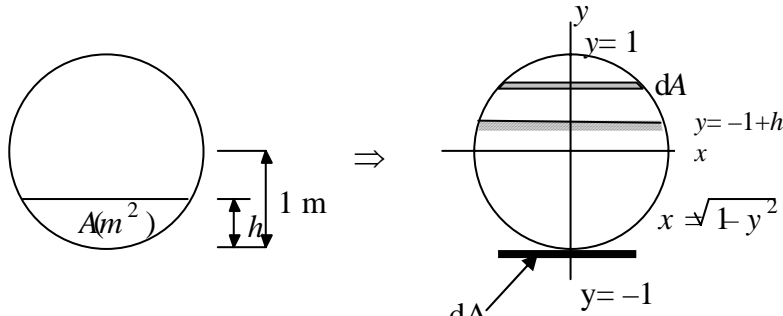
$$\Rightarrow V_f = \frac{\pi R^2 H}{3} - \frac{\pi h}{3}\left(\frac{Rh}{H}\right)^2 = \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right)$$

$$\rho_f V_f = \rho_s V_s \Rightarrow \rho_f \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right) = \rho_s \frac{\pi R^2 H}{3}$$

$$\Rightarrow \rho_f = \rho_s \frac{H}{H - \dfrac{h^3}{H^2}} = \rho_s \frac{H^3}{H^3 - h^3} = \rho_s \frac{1}{\underline{\underline{1 - \left(\dfrac{h}{H}\right)^3}}}$$

2.13 Say $h(m) =$ depth of liquid

$$dA = dy \cdot \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} dx = 2\sqrt{1-y^2}\,dy \Rightarrow A(m^2) = 2\int_{-1}^{-1+h} \sqrt{1-y^2}\,dy$$

⇓ Table of integrals or trigonometric substitution

$$A(m^2) = y\sqrt{1-y^2} + \sin^{-1} y \Big]_{-1}^{h-1} = (h-1)\sqrt{1-(h-1)^2} + \sin^{-1}(h-1) + \frac{\pi}{2}$$

$$W(N) = \frac{4\,m \times A(m^2)}{} \left| \frac{0.879\,g}{cm^3} \right| \frac{10^6\,cm^2}{1\,m^3} \left| \frac{1\,kg}{10^3\,g} \right| \frac{9.81\,N}{\underbrace{kg}_{g/g_0}} = 3.45 \times 10^4\,A$$

⇓ Substitute for A

$$W(N) = 3.45 \times 10^4 \left[(h-1)\sqrt{1-(h-1)^2} + \sin^{-1}(h-1) + \frac{\pi}{2} \right]$$

2.14 $\quad 1\,lb_f = 1\,slug \cdot ft/s^2 = 32.174\,lb_m \cdot ft/s^2 \Rightarrow 1\,slug = 32.174\,lb_m$

$\quad 1\,poundal = 1\,lb_m \cdot ft/s^2 = \dfrac{1}{32.174}\,lb_f$

(a) (i) On the earth:

$$M = \frac{175\,lb_m}{} \left| \frac{1\,slug}{32.174\,lb_m} \right. = \underline{\underline{5.44\,slugs}}$$

$$W = \frac{175\,lb_m}{} \left| \frac{32.174\,ft}{s^2} \right| \frac{1\,poundal}{1\,lb_m \cdot ft/s^2} = \underline{\underline{5.63 \times 10^3\,poundals}}$$

(ii) On the moon

$$M = \frac{175\,lb_m}{} \left| \frac{1\,slug}{32.174\,lb_m} \right. = \underline{\underline{5.44\,slugs}}$$

$$W = \frac{175\,lb_m}{} \left| \frac{32.174\,ft}{6 \quad s^2} \right| \frac{1\,poundal}{1\,lb_m \cdot ft/s^2} = \underline{\underline{938\,poundals}}$$

(b) $F = ma \Rightarrow a = F/m = \dfrac{355\,poundals}{25.0\,slugs} \left| \dfrac{1\,lb_m \cdot ft/s^2}{1\,poundal} \right| \dfrac{1\quad slug}{32.174\,lb_m} \left| \dfrac{1\,m}{3.2808\,ft} \right.$

$\qquad = \underline{\underline{0.135\,m/s^2}}$

2.15 (a) $F = ma \Rightarrow 1 \text{ fern} = (1 \text{ bung})(32.174 \text{ ft} / \text{s}^2)\left(\dfrac{1}{6}\right) = \underline{\underline{5.3623 \text{ bung} \cdot \text{ft} / \text{s}^2}}$

$\Rightarrow \underline{\underline{\dfrac{1 \text{ fern}}{5.3623 \text{ bung} \cdot \text{ft} / \text{s}^2}}}$

(b) On the moon: $W = \dfrac{3 \text{ bung}}{} \left|\dfrac{32.174 \text{ ft}}{6 \quad \text{s}^2}\right| \dfrac{1 \text{ fern}}{5.3623 \text{ bung} \cdot \text{ft} / \text{s}^2} = \underline{\underline{3 \text{ fern}}}$

On the earth: $W = (3)(32.174) / 5.3623 = \underline{\underline{18 \text{ fern}}}$

2.16 (a) $\approx (3)(9) = \underline{\underline{27}}$

$(2.7)(8.632) = \underline{\underline{23}}$

(b) $\approx \dfrac{4.0 \times 10^{-4}}{40} \approx \underline{\underline{1 \times 10^{-5}}}$

$(3.600 \times 10^{-4}) / 45 = \underline{\underline{8.0 \times 10^{-6}}}$

(c) $\approx 2 + 125 = \underline{\underline{127}}$

$2.365 + 125.2 = \underline{\underline{127.5}}$

(d) $\approx 50 \times 10^3 - 1 \times 10^3 \approx 49 \times 10^3 \approx \underline{\underline{5 \times 10^4}}$

$4.753 \times 10^4 - 9 \times 10^2 = \underline{\underline{5 \times 10^4}}$

2.17 $R \approx \dfrac{(7 \times 10^{-1})(3 \times 10^5)(6)(5 \times 10^4)}{(3)(5 \times 10^6)} \approx 42 \times 10^2 \approx \underline{\underline{4 \times 10^3}}$ (Any digit in range 2-6 is acceptable)

$R_{exact} = 3812.5 \Rightarrow \underline{\underline{3810}} \Rightarrow \underline{\underline{3.81 \times 10^3}}$

2.18 (a)

A: $R = 73.1 - 72.4 = \underline{\underline{0.7^\circ \text{C}}}$

$\overline{X} = \dfrac{72.4 + 73.1 + 72.6 + 72.8 + 73.0}{5} = \underline{\underline{72.8^\circ \text{C}}}$

$s = \sqrt{\dfrac{(72.4 - 72.8)^2 + (73.1 - 72.8)^2 + (72.6 - 72.8)^2 + (72.8 - 72.8)^2 + (73.0 - 72.8)^2}{5 - 1}}$

$= \underline{\underline{0.3^\circ \text{C}}}$

B: $R = 103.1 - 97.3 = \underline{\underline{5.8^\circ \text{C}}}$

$\overline{X} = \dfrac{97.3 + 101.4 + 98.7 + 103.1 + 100.4}{5} = \underline{\underline{100.2^\circ \text{C}}}$

$s = \sqrt{\dfrac{(97.3 - 100.2)^2 + (101.4 - 100.2)^2 + (98.7 - 100.2)^2 + (103.1 - 100.2)^2 + (100.4 - 100.2)^2}{5 - 1}}$

$= \underline{\underline{2.3^\circ \text{C}}}$

(b) Thermocouple B exhibits a higher degree of scatter and is also more accurate.

2.19 (a)

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

$$C_{min=} = \overline{X} - 2s = 73.5 - 2(1.2) = \underline{71.1}$$

$$C_{max=} = \overline{X} + 2s = 73.5 + 2(1.2) = \underline{\underline{75.9}}$$

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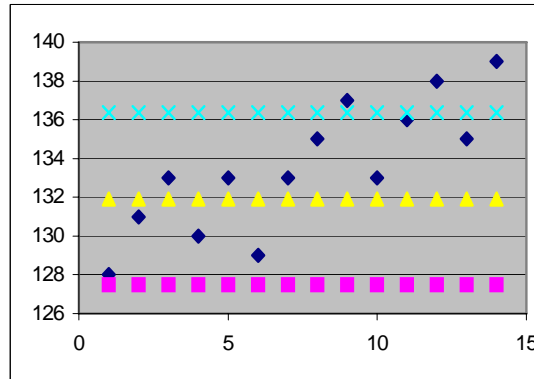
(c) Beginning with Run 11, the process has been near or well over the upper quality assurance limit. An overhaul would have been reasonable after Run 12.

2.21 (a) $Q' = \dfrac{2.36 \times 10^{-4} \ kg \cdot m^2}{h} \left| \dfrac{2.20462 \ lb}{kg} \right| \dfrac{3.2808^2 \ ft^2}{m^2} \left| \dfrac{1 \ h}{3600 \ s} \right.$

(b) $Q'_{approximate} \approx \dfrac{(2 \times 10^{-4})(2)(9)}{3 \times 10^3} \approx 12 \times 10^{(-4-3)} \approx \underline{1.2 \times 10^{-6} \ lb \cdot ft^2 / s}$

$$Q'_{exact} = \underline{\underline{1.56 \times 10^{-6} \ lb \cdot ft^2 / s}} = \underline{\underline{0.00000156 \ lb \cdot ft^2 / s}}$$

2.22 $N_{Pr} = \dfrac{C_p \mu}{k} = \dfrac{0.583 \text{ J} / \text{g} \cdot ^o C}{0.286 \text{ W} / \text{m} \cdot ^o C} \left| \dfrac{1936 \text{ lb}_m}{\text{ft} \cdot \text{h}} \right| \dfrac{1 \text{ h}}{3600 \text{ s}} \left| \dfrac{3.2808 \text{ ft}}{\text{m}} \right| \dfrac{1000 \text{ g}}{2.20462 \text{ lb}_m}$

$N_{Pr} \approx \dfrac{(6 \times 10^{-1})(2 \times 10^3)(3 \times 10^3)}{(3 \times 10^{-1})(4 \times 10^3)(2)} \approx \dfrac{3 \times 10^3}{2} \approx \underline{\underline{1.5 \times 10^3}}$. The calculator solution is $\underline{\underline{1.63 \times 10^3}}$

2.23

$Re = \dfrac{Du\rho}{\mu} = \dfrac{0.48 \text{ ft}}{\text{s}} \left| \dfrac{1 \text{ m}}{3.2808 \text{ ft}} \right| \dfrac{2.067 \text{ in}}{0.43 \times 10^{-3} \text{ kg} / \text{m} \cdot \text{s}} \left| \dfrac{1 \text{ m}}{39.37 \text{ in}} \right| \dfrac{0.805 \text{ g}}{\text{cm}^3} \left| \dfrac{1 \text{ kg}}{1000 \text{ g}} \right| \dfrac{10^6 \text{ cm}^3}{1 \quad \text{m}^3}$

$Re \approx \dfrac{(5 \times 10^{-1})(2)(8 \times 10^{-1})(10^6)}{(3)(4 \times 10)(10^3)(4 \times 10^{-4})} \approx \dfrac{5 \times 10^{1-(-3)}}{3} \approx 2 \times 10^4 \Rightarrow \underline{\text{the flow is turbulent}}$

2.24 (a) $\dfrac{k_g d_p y}{D} = 2.00 + 0.600 \left(\dfrac{\mu}{\rho D} \right)^{1/3} \left(\dfrac{d_p u \rho}{\mu} \right)^{1/2}$

$= 2.00 + 0.600 \left[\dfrac{1.00 \times 10^{-5} \text{ N} \cdot \text{s/m}^2}{(1.00 \text{ kg/m}^3)(1.00 \times 10^{-5} \text{ m}^2 / \text{s})} \right]^{1/3} \left[\dfrac{(0.00500 \text{ m})(10.0 \text{ m/s})(1.00 \text{ kg/m}^3)}{(1.00 \times 10^{-5} \text{ N} \cdot \text{s/m}^2)} \right]^{1/2}$

$= 44.426 \Rightarrow \dfrac{k_g (0.00500 \text{ m})(0.100)}{1.00 \times 10^{-5} \text{ m}^2 / \text{s}} = 44.426 \Rightarrow k_g = \underline{\underline{0.888 \text{ m} / \text{s}}}$

(b) The diameter of the particles is not uniform, the conditions of the system used to model the equation may differ significantly from the conditions in the reactor (out of the range of empirical data), all of the other variables are subject to measurement or estimation error.

(c)

d_p (m)	y	D (m^2/s)	μ (N-s/m^2)	ρ (kg/m^3)	u (m/s)	k_g
0.005	0.1	1.00E-05	1.00E-05	1	10	0.889
0.010	0.1	1.00E-05	1.00E-05	1	10	0.620
0.005	0.1	2.00E-05	1.00E-05	1	10	1.427
0.005	0.1	1.00E-05	2.00E-05	1	10	0.796
0.005	0.1	1.00E-05	1.00E-05	1	20	1.240

2.25 (a) $\underline{\underline{200 \text{ crystals} / \text{min} \cdot \text{mm}}}$; $\underline{\underline{10 \text{ crystals} / \text{min} \cdot \text{mm}^2}}$

(b) $r = \dfrac{200 \text{ crystals}}{\text{min} \cdot \text{mm}} \left| \dfrac{0.050 \text{ in}}{} \right| \dfrac{25.4 \text{ mm}}{\text{in}} - \dfrac{10 \text{ crystals}}{\text{min} \cdot \text{mm}^2} \left| \dfrac{0.050^2 \text{ in}^2}{} \right| \dfrac{(25.4)^2 \text{ mm}^2}{\text{in}^2}$

$= 238 \text{ crystals} / \text{min} \Rightarrow \dfrac{238 \text{ crystals}}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} \right. = \underline{\underline{4.0 \text{ crystals} / \text{s}}}$

(c) $D(\text{mm}) = \dfrac{D'(\text{in})}{} \left| \dfrac{25.4 \text{ mm}}{1 \text{ in}} \right. = 25.4 D'$; $r \left(\dfrac{\text{crystals}}{\text{min}} \right) = r' \dfrac{\text{crystals}}{\text{s}} \left| \dfrac{60 \text{ s}}{1 \text{ min}} \right. = 60 r'$

$\Rightarrow 60 r' = 200(25.4 D') - 10(25.4 D')^2 \Rightarrow \underline{\underline{r' = 84.7 D' - 108(D')^2}}$

2.26 (a) $70.5 \ lb_m / ft^3$; $\quad 8.27 \times 10^{-7} \ in^2 / lb_f$

(b) $\rho = (70.5 \ lb_m / ft^3) \exp\left[\dfrac{8.27 \times 10^{-7} \ in^2}{lb_f} \left| \dfrac{9 \times 10^6 \ N}{m^2} \right| \dfrac{14.696 \ lb_f / in^2}{1.01325 \times 10^5 \ N/m^2}\right]$

$\quad = \dfrac{70.57 \ lb_m}{ft^3} \left| \dfrac{35.3145 \ ft^3}{m^3} \right| \dfrac{1 \quad m^3}{10^6 \ cm^3} \left| \dfrac{1000 \ g}{2.20462 \ lb_m} \right. = 1.13 \ g/cm^3$

(c) $\rho\left(\dfrac{lb_m}{ft^3}\right) = \rho' \dfrac{g}{cm^3} \left| \dfrac{1 \ lb_m}{453.593 \ g} \right| \dfrac{28,317 \ cm^3}{1 \ ft^3} = 62.43\rho'$

$\quad P\left(\dfrac{lb_f}{in^2}\right) = P' \dfrac{N}{m^2} \left| \dfrac{0.2248 \ lb_f}{1 \ N} \right| \dfrac{1^2 \quad m^2}{39.37^2 \ in^2} = 1.45 \times 10^{-4} \ P'$

$\quad \Rightarrow 62.43\rho' = 70.5 \exp\left[\left(8.27 \times 10^{-7}\right)\left(1.45 \times 10^{-4} \ P'\right)\right] \Rightarrow \rho' = 1.13 \exp\left(1.20 \times 10^{-10} \ P'\right)$

$\quad P' = 9.00 \times 10^6 \ N / m^2 \Rightarrow \rho' = 1.13 \exp[(1.20 \times 10^{-10})(9.00 \times 10^6)] = 1.13 \ g / cm^3$

2.27 (a) $V\left(cm^3\right) = \dfrac{V'\left(in^3\right)}{} \left| \dfrac{28,317 \ cm^3}{1728 \ in^3} \right. = 16.39V'$; $\quad t(s) = 3600 t'(hr)$

$\quad \Rightarrow 16.39V' = \exp(3600 t') \Rightarrow V' = 0.06102 \exp(3600 t')$

(b) The t in the exponent has a coefficient of s^{-1}.

2.28 (a) $3.00 \ mol / L$, $\quad 2.00 \ min^{-1}$

(b) $t = 0 \Rightarrow C = 3.00 \exp[(-2.00)(0)] = 3.00 \ mol / L$

$\quad t = 1 \Rightarrow C = 3.00 \exp[(-2.00)(1)] = 0.406 \ mol / L$

$\quad$ For t=0.6 min: $\qquad C_{int} = \dfrac{0.406 - 3.00}{1 - 0}(0.6 - 0) + 3.00 = 1.4 \ mol / L$

$\qquad\qquad\qquad\qquad\quad C_{exact} = 3.00 \exp[(-2.00)(0.6)] = 0.9 \ mol / L$

$\quad$ For C=0.10 mol/L: $\quad t_{int} = \dfrac{1 - 0}{0.406 - 3}(0.10 - 3.00) + 0 = 1.12 \ min$

$\qquad\qquad\qquad\qquad\quad t_{exact} = -\dfrac{1}{2.00} \ln \dfrac{C}{3.00} = -\dfrac{1}{2} \ln \dfrac{0.10}{3.00} = 1.70 \ min$

(c)
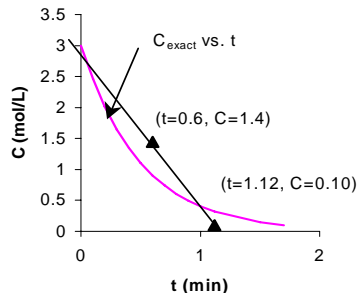
2.29 (a) $p^* = \dfrac{60-20}{199.8-166.2}(185-166.2)+20 = \underline{\underline{42 \text{ mm Hg}}}$

(b)

```
c     MAIN PROGRAM FOR PROBLEM 2.29
      IMPLICIT REAL*4(A–H, 0–Z)
      DIMENSION TD(6), PD(6)
      DO 1 I = 1, 6
          READ (5, *) TD(I), PD(I)
1     CONTINUE
      WRITE (5, 902)
902   FORMAT ('0', 5X, 'TEMPERATURE    VAPOR PRESSURE'/6X,
   *         '            (C)            (MM HG)'/)
      DO 2 I = 0, 115, 5
      T = 100 + I
      CALL VAP (T, P, TD, PD)
      WRITE (6, 903)  T, P
903   FORMAT (10X, F5.1, 10X, F5.1)
2     CONTINUE
      END
      SUBROUTINE VAP (T, P, TD, PD)
      DIMENSION TD(6), PD(6)
      I = 1
1     IF (TD(I).LE.T.AND.T.LT.TD(I + 1)) GO TO 2
      I = I + 1
      IF (I.EQ.6) STOP
      GO TO 1
2     P = PD(I) + (T – TD(I))/(TD(I + 1) – TD(I)) * (PD(I + 1) – PD(I))
      RETURN
      END
```

DATA		OUTPUT	
98.5	1.0	TEMPERATURE	VAPOR PRESSURE
131.8	5.0	(C)	(MM HG)
⋮	⋮	100.0	1.2
215.5	100.0	105.0	1.8
		⋮	⋮
		215.0	98.7

2.30 (b) $\ln y = \ln a + bx \Rightarrow y = ae^{bx}$

   $b = (\ln y_2 - \ln y_1) / (x_2 - x_1) = (\ln 2 - \ln 1) / (1 - 2) = -0.693$

   $\ln a = \ln y - bx = \ln 2 + 0.63(1) \Rightarrow a = 4.00 \Rightarrow \underline{\underline{y = 4.00e^{-0.693x}}}$

(c) $\ln y = \ln a + b \ln x \Rightarrow y = ax^b$

   $b = (\ln y_2 - \ln y_1) / (\ln x_2 - \ln x_1) = (\ln 2 - \ln 1) / (\ln 1 - \ln 2) = -1$

   $\ln a = \ln y - b \ln x = \ln 2 - (-1)\ln(1) \Rightarrow a = 2 \Rightarrow \underline{\underline{y = 2 / x}}$

(d) $\ln(xy) = \ln a + b(y/x) \Rightarrow xy = ae^{by/x} \Rightarrow y = (a/x)e^{by/x}$ [can't get $y = f(x)$]

   $b = [\ln(xy)_2 - \ln(xy)_1]/[(y/x)_2 - (y/x)_1] = (\ln 807.0 - \ln 40.2)/(2.0 - 1.0) = 3$

   $\ln a = \ln(xy) - b(y/x) = \ln 807.0 - 3\ln(2.0) \Rightarrow a = 2 \Rightarrow \underline{\underline{xy = 2e^{3y/x}}}$

   [can't solve explicitly for $y(x)$]

2.30 (cont'd)

(e) $\ln(y^2/x) = \ln a + b\ln(x-2) \Rightarrow y^2/x = a(x-2)^b \Rightarrow y = [ax(x-2)^b]^{1/2}$

$$b = [\ln(y^2/x)_2 - \ln(y^2/x)_1]/[\ln(x-2)_2 - \ln(x-2)_1]$$

$$= (\ln 807.0 - \ln 40.2)/(\ln 2.0 - \ln 1.0) = 4.33$$

$$\ln a = \ln(y^2/x) - b(x-2) = \ln 807.0 - 4.33\ln(2.0) \Rightarrow a = 40.2$$

$$\Rightarrow y^2/x = 40.2(x-2)^{4.33} \Rightarrow \underline{\underline{y = 6.34x^{1/2}(x-2)^{2.165}}}$$

2.31 (b) Plot y^2 vs. x^3 on rectangular axes. Slope $= m$, Intcpt $= -n$

(c) $\dfrac{1}{\ln(y-3)} = \dfrac{1}{b} + \dfrac{a}{b}\sqrt{x} \Rightarrow$ Plot $\dfrac{1}{\ln(y-3)}$ vs. $\sqrt{x}$ [rect. axes], slope $= \dfrac{a}{b}$, intercept $= \dfrac{1}{b}$

(d)

$\dfrac{1}{(y+1)^2} = a(x-3)^3 \Rightarrow$ Plot $\dfrac{1}{(y+1)^2}$ vs. $(x-3)^3$ [rect. axes], slope $= a$, intercept $= 0$

OR

$2\ln(y+1) = -\ln a - 3\ln(x-3)$

Plot $\ln(y+1)$ vs. $\ln(x-3)$ [rect.] or $(y+1)$ vs. $(x-3)$ [log]

$\Rightarrow$ slope $= -\dfrac{3}{2}$, intercept $= -\dfrac{\ln a}{2}$

(e) $\ln y = a\sqrt{x} + b$

Plot $\ln y$ vs. $\sqrt{x}$ [rect.] or y vs. $\sqrt{x}$ [semilog], slope $=$ a, intercept $=$ b

(f) $\log_{10}(xy) = a(x^2 + y^2) + b$

Plot $\log_{10}(xy)$ vs. $(x^2 + y^2)$ [rect.] $\Rightarrow$ slope $=$ a, intercept $=$ b

(g) $\dfrac{1}{y} = ax + \dfrac{b}{x} \Rightarrow \dfrac{x}{y} = ax^2 + b \Rightarrow$ Plot $\dfrac{x}{y}$ vs. x^2 [rect.], slope $= a$, intercept $= b$

OR $\dfrac{1}{y} = ax + \dfrac{b}{x} \Rightarrow \dfrac{1}{xy} = a + \dfrac{b}{x^2} \Rightarrow$ Plot $\dfrac{1}{xy}$ vs. $\dfrac{1}{x^2}$ [rect.], slope $= b$, intercept $=$ a

2.32 **(a)** A plot of y vs. R is a line through ($R = 5$, $y = 0.011$) and ($R = 80$, $y = 0.169$).
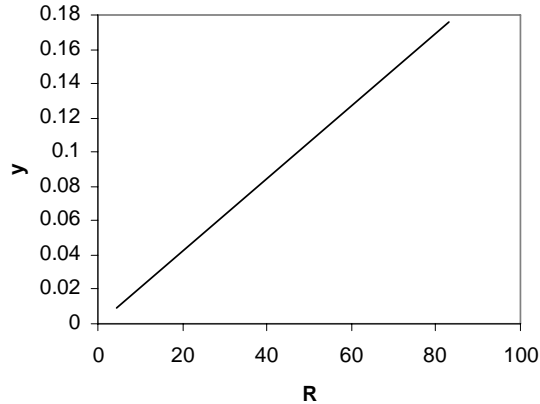
$$y = a R + b \qquad a = \frac{0.169 - 0.011}{80 - 5} = 2.11 \times 10^{-3}$$
$$b = 0.011 - \left(2.11 \times 10^{-3}\right)(5) = 4.50 \times 10^{-4}$$
$$\Rightarrow y = 2.11 \times 10^{-3} R + 4.50 \times 10^{-4}$$

(b) $R = 43 \Rightarrow y = \left(2.11 \times 10^{-3}\right)(43) + 4.50 \times 10^{-4} = 0.092$ kg H_2O/kg

$$\left(1200 \ \text{kg/h}\right)\left(0.092 \ \text{kg} \ H_2O/\text{kg}\right) = 110 \ \text{kg} \ H_2O/\text{h}$$

2.33 (a) $\ln T = \ln a + b \ln \phi \Rightarrow T = a\phi^b$

$b = (\ln T_2 - \ln T_1) / (\ln \phi_2 - \ln \phi_1) = (\ln 120 - \ln 210) / (\ln 40 - \ln 25) = -1.19$

$\ln a = \ln T - b \ln \phi = \ln 210 - (-1.19)\ln(25) \Rightarrow a = 9677.6 \Rightarrow T = 9677.6\phi^{-1.19}$

(b) $T = 9677.6\phi^{-1.19} \Rightarrow \phi = \left(9677.6 / T\right)^{0.8403}$

$T = 85^\circ C \Rightarrow \phi = \left(9677.6 / 85\right)^{0.8403} = 53.5 \ \text{L} / \text{s}$

$T = 175^\circ C \Rightarrow \phi = \left(9677.6 / 175\right)^{0.8403} = 29.1 \ \text{L} / \text{s}$

$T = 290^\circ C \Rightarrow \phi = \left(9677.6 / 290\right)^{0.8403} = 19.0 \ \text{L} / \text{s}$

(c) The estimate for T=175°C is probably closest to the real value, because the value of temperature is in the range of the data originally taken to fit the line. The value of T=290°C is probably the least likely to be correct, because it is farthest away from the date range.

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.
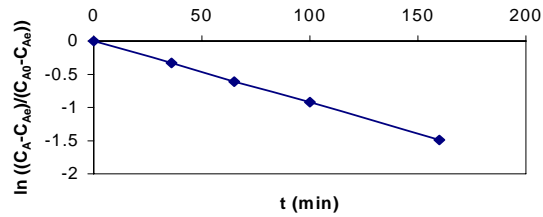
$$\text{Slope} = -0.0093 \Rightarrow \underline{\underline{k = 9.3 \times 10^{-3} \ \text{min}^{-1}}}$$

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

$C_A = (0.1823 - 0.0495)e^{-(9.3\times10^{-3})(120)} + 0.0495 = 9.300 \times 10^{-2} \ \text{g/L}$

$$C = m/V \Rightarrow m = CV = \frac{9.300 \times 10^{-2} \ \text{g}}{\text{L}} \left| \frac{30.5 \ \text{gal}}{} \right| \frac{28.317 \ \text{L}}{7.4805 \ \text{gal}} = \underline{\underline{10.7 \ \text{g}}}$$

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

(b) $\ln(V)$ vs. t^2 in rectangular coordinates, slope=2 and intercept= $\ln(3.53 \times 10^{-2})$; or

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

(c) $\underline{\underline{V(\text{m}^3) = 1.00 \times 10^{-3} \exp(1.5 \times 10^{-7} t^2)}}$

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

$\ln P = -1.573(\ln V) + 12.736$
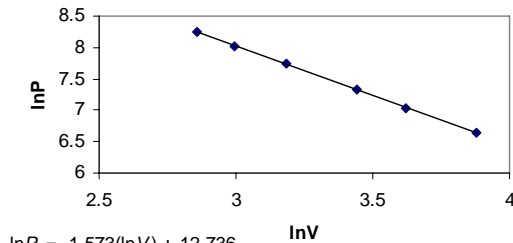
$k = -\text{slope} = -(-1.573) = \underline{1.573}$ (dimensionless)

$\text{Intercept} = \ln C = 12.736 \Rightarrow C = e^{12.736} = \underline{\underline{3.40 \times 10^5}} \ \text{mm Hg} \cdot \text{cm}^{4.719}$

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

$\ln(G_0-G)/(G-G_L) = 2.4835 \ln C - 10.045$
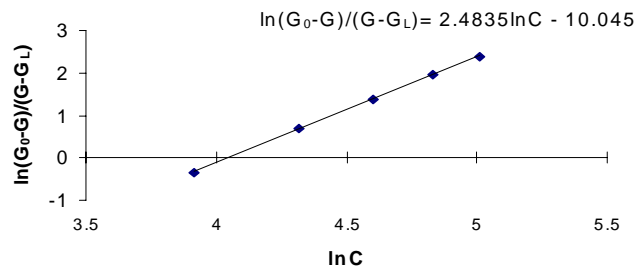
2.37 (cont'd)

$m = \text{slope} = \underline{\underline{2.483}}$ (dimensionless)

$\text{Intercept} = \ln K_L = -10.045 \Rightarrow K_L = \underline{\underline{4.340 \times 10^{-5}}} \text{ ppm}^{-2.483}$

(b) $C = 475 \Rightarrow \dfrac{G - 1.80 \times 10^{-3}}{3.00 \times 10^{-3} - G} = 4.340 \times 10^{-5}(475)^{2.483} \Rightarrow G = \underline{\underline{1.806 \times 10^{-3}}}$

$C=475$ ppm is well beyond the range of the data.

2.38 (a) For runs 2, 3 and 4:

$Z = a\dot{V}^b p^c \Rightarrow \ln Z = \ln a + b \ln \dot{V} + c \ln p$

$\left.\begin{array}{l}\ln(3.5) = \ln a + b\ln(1.02) + c\ln(9.1)\\[4pt]\ln(2.58) = \ln a + b\ln(1.02) + c\ln(11.2)\\[4pt]\ln(3.72) = \ln a + b\ln(1.75) + c\ln(11.2)\end{array}\right\}$ $\Rightarrow$ $\begin{array}{l}b = \underline{\underline{0.68}}\\[4pt]c = \underline{\underline{-1.46}}\\[4pt]a = \underline{\underline{86.7 \text{ volts}\cdot\text{kPa}^{1.46}/(\text{L}/\text{s})^{0.678}}}\end{array}$

(b) When P is constant (runs 1 to 4), plot $\ln Z$ vs. $\ln\dot{V}$. Slope=b, Intercept=$\ln a + c\ln p$

InZ = 0.5199lnV + 1.0035
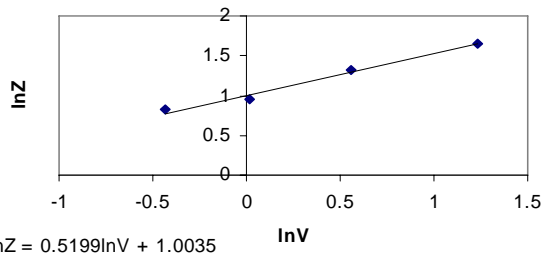
$b = \text{slope} = \underline{\underline{0.52}}$

$\text{Intercept} = \ln a + c\ln P = 1.0035$

When $\dot{V}$ is constant (runs 5 to 7), plot ln$Z$ vs. ln$P$. Slope=c, Intercept=$\ln a + c\ln\dot{V}$

InZ = -0.9972lnP + 3.4551
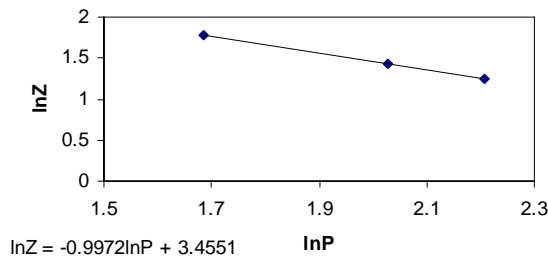
$c = \text{slope} = -0.997 \Rightarrow \underline{\underline{1.0}}$

$\text{Intercept} = \ln a + b\ln\dot{V} = 3.4551$

Plot Z vs $\dot{V}^b P^c$. Slope=a (no intercept)

Z = 31.096V^bP^c
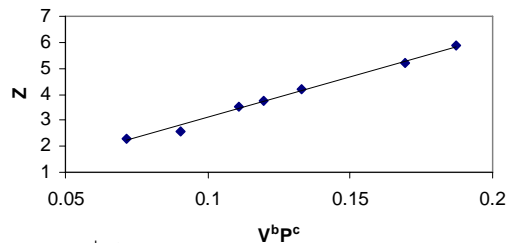
$a = \text{slope} = \underline{\underline{31.1 \text{ volt}\cdot\text{kPa}/(\text{L}/\text{s})^{.52}}}$

The results in part (b) are more reliable, because more data were used to obtain them.

2.39 (a)

$$s_{xy} = \frac{1}{n}\sum_{i=1}^{n} x_i y_i = [(0.4)(0.3) + (2.1)(1.9) + (3.1)(3.2)]/3 = 4.677$$

$$s_{xx} = \frac{1}{n}\sum_{i=1}^{n} x_i^2 = (0.3^2 + 1.9^2 + 3.2^2)/3 = 4.647$$

$$s_x = \frac{1}{n}\sum_{i=1}^{n} x_i = (0.3 + 1.9 + 3.2)/3 = 1.8; \quad s_y = \frac{1}{n}\sum_{i=1}^{n} y_i = (0.4 + 2.1 + 3.1)/3 = 1.867$$

$$a = \frac{s_{xy} - s_x s_y}{s_{xx} - (s_x)^2} = \frac{4.677 - (1.8)(1.867)}{4.647 - (1.8)^2} = 0.936$$

$$b = \frac{s_{xx} s_y - s_{xy} s_x}{s_{xx} - (s_x)^2} = \frac{(4.647)(1.867) - (4.677)(1.8)}{4.647 - (1.8)^2} = 0.182$$

$$\underline{\underline{y = 0.936x + 0.182}}$$

(b) $a = \dfrac{s_{xy}}{s_{xx}} = \dfrac{4.677}{4.647} = 1.0065 \Rightarrow \underline{\underline{y = 1.0065x}}$

y = 0.936x + 0.182

y = 1.0065x
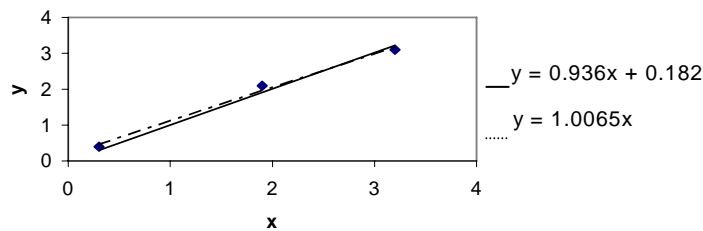
2.40 (a) 1/C vs. t. Slope= b, intercept=a

(b) $b = \text{slope} = \underline{\underline{0.477\ \text{L}/\text{g}\cdot\text{h}}}; \qquad a = \text{Intercept} = \underline{\underline{0.082\ \text{L}/\text{g}}}$

1/C = 0.4771t + 0.0823

—■— C   —▲— C-fitted
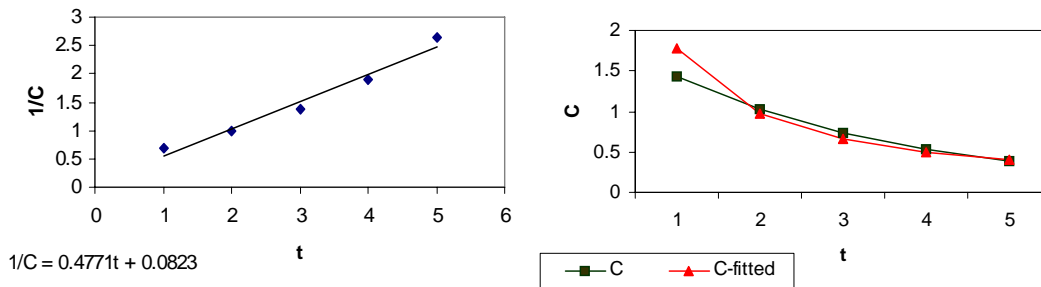
(c) $C = 1/(a+bt) \Rightarrow 1/[0.082 + 0.477(0)] = \underline{\underline{12.2\ \text{g}/\text{L}}}$

$$t = (1/C - a)/b = (1/0.01 - 0.082)/0.477 = \underline{209.5\ \text{h}}$$

(d) t=0 and C=0.01 are out of the range of the experimental data.

(e) The concentration of the hazardous substance could be enough to cause damage to the biotic resources in the river; the treatment requires an extremely large period of time; some of the hazardous substances might remain in the tank instead of being converted; the decomposition products might not be harmless.

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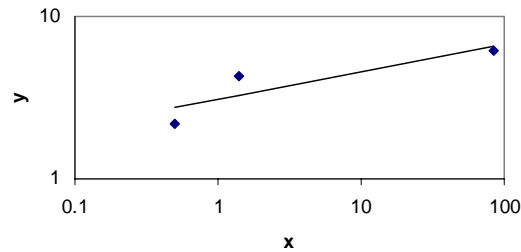
(b) $y = ax^b \Rightarrow \ln y = \ln a + b \ln x$; Slope = b, Intercept = $\ln a$

$\ln y = 0.1684\ln x + 1.1258$
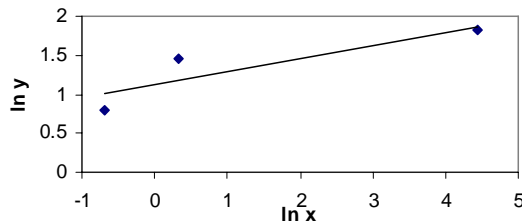
$b = \text{slope} = \underline{\underline{0.168}}$

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

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

(b)

$\ln(1\text{-}Cp/Cao) = -0.0062t$ — **Lab 1**

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

$\ln(1\text{-}Cp/Cao) = -0.0111t$ — **Lab 2**

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

$\ln(1\text{-}Cp/Cao) = -0.0063t$ — **Lab 3**
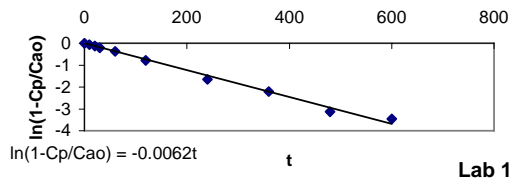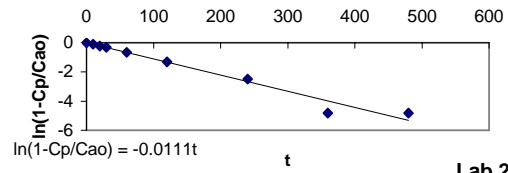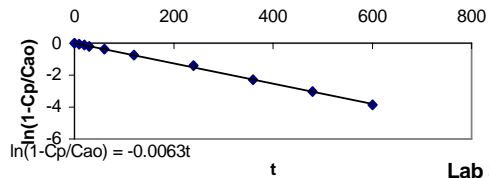
$k = \underline{\underline{0.0063 \ s^{-1}}}$
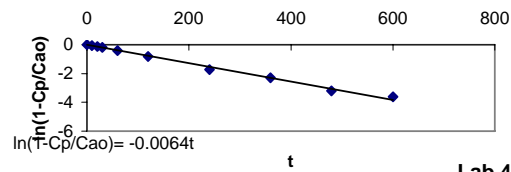
$\ln(1\text{-}Cp/Cao) = -0.0064t$ — **Lab 4**

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

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

(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.

2.43 $y_i = ax_i \Rightarrow \phi(a) = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} (y_i - ax_i)^2 \Rightarrow \dfrac{d\phi}{da} = 0 = \sum_{i=1}^{n} 2(y_i - ax_i)x_i \Rightarrow \sum_{i=1}^{n} y_i x_i - a\sum_{i=1}^{n} x_i^2 = 0$

$$\Rightarrow \underline{\underline{a = \sum_{i=1}^{n} y_i x_i / \sum_{i=1}^{n} x_i^2}}$$

2.44

```
        DIMENSION X(100), Y(100)
        READ (5, 1) N
C    N = NUMBER OF DATA POINTS
       1FORMAT (I10)
        READ (5, 2) (X(J), Y(J), J = 1, N
       2FORMAT (8F 10.2)
        SX = 0.0
        SY = 0.0
        SXX = 0.0
        SXY = 0.0
        DO 100J = 1, N
        SX = SX + X(J)
        SY = SY + Y(J)
        SXX = SXX + X(J) ** 2
    100SXY = SXY + X(J) * Y(J)
        AN = N
        SX = SX/AN
        SY = SY/AN
        SXX = SXX/AN
        SXY = SXY/AN
        CALCULATE SLOPE AND INTERCEPT
        A = (SXY - SX * SY)/(SXX - SX ** 2)
        B = SY - A * SX
        WRITE (6, 3)
       3FORMAT (1H1, 20X 'PROBLEM 2-39'/)
        WRITE (6, 4) A, B
       4FORMAT (1H0, 'SLOPEb -- bAb =', F6.3, 3X 'INTERCEPTb -- b8b =', F7.3/)
C     CALCULATE FITTED VALUES OF Y, AND SUM OF SQUARES OF
             RESIDUALS
        SSQ = 0.0
        DO 200J = 1, N
        YC = A * X(J) + B
        RES = Y(J) - YC
        WRITE (6, 5) X(J), Y(J), YC, RES
       5FORMAT (3X 'Xb =', F5.2, 5X /Yb =', F7.2, 5X 'Y(FITTED)b =', F7.2, 5X
      *    'RESIDUALb =', F6.3)
    200SSQ = SSQ + RES ** 2
        WRITE (6, 6) SSQ
       6FORMAT (IH0, 'SUM OF SQUARES OF RESIDUALSb =', E10.3)
        STOP
        END
      $DATA
          5
      1.0   2.35   1.5    5.53   2.0    8.92   2.5   12.15
      3.0   15.38
```

SOLUTION: $\underline{\underline{a = 6.536, b = -4.206}}$

2.45 (a) E(cal/mol), D_0 (cm^2/s)

(b) ln D vs. 1/T, Slope=$-E/R$, intercept=ln D_0.

(c) Intercept = ln D_0 = -3.0151 $\Rightarrow D_0 = \underline{0.05 \text{ cm}^2/\text{s}}$.

Slope $= -E/R$ = -3666 K $\Rightarrow E$ = (3666 K)(1.987 cal/mol·K) = $\underline{7284 \text{ cal/mol}}$

ln D = -3666(1/T) - 3.0151   **1/T**
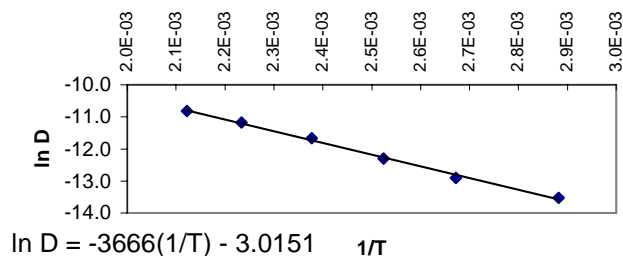
(d) Spreadsheet

T	D	1/T	lnD	(1/T)*(lnD)	(1/T)**2
347	1.34E-06	2.88E-03	-13.5	-0.03897	8.31E-06
374.2	2.50E-06	2.67E-03	-12.9	-0.03447	7.14E-06
396.2	4.55E-06	2.52E-03	-12.3	-0.03105	6.37E-06
420.7	8.52E-06	2.38E-03	-11.7	-0.02775	5.65E-06
447.7	1.41E-05	2.23E-03	-11.2	-0.02495	4.99E-06
471.2	2.00E-05	2.12E-03	-10.8	-0.02296	4.50E-06

Sx	2.47E-03
Sy	-12.1
Syx	-3.00E-02
Sxx	6.16E-06
-E/R	-3666
ln D_0	-3.0151
D_0	7284
E	0.05

CHAPTER THREE

3.1 **(a)** $m = \dfrac{16 \times 6 \times 2 \text{ m}^3}{} \Bigg| \dfrac{1000 \text{ kg}}{\text{m}^3} \approx (2 \times 10)(5)(2)(10^3) \approx \underline{\underline{2 \times 10^5 \text{ kg}}}$

(b) $\dot{m} = \dfrac{8 \text{ oz}}{2 \text{ s}} \Bigg| \dfrac{1 \text{ qt}}{32 \text{ oz}} \Bigg| \dfrac{10^6 \text{ cm}^3}{1056.68 \text{ qt}} \Bigg| \dfrac{1 \text{ g}}{\text{cm}^3} \approx \dfrac{4 \times 10^6}{(3 \times 10)(10^3)} \approx \underline{\underline{1 \times 10^2 \text{ g/s}}}$

(c) Weight of a boxer $\approx 220 \text{ lb}_m$

$W_{max} \geq \dfrac{12 \times 220 \text{ lb}_m}{} \Bigg| \dfrac{1 \text{ stone}}{14 \text{ lb}_m} \approx \underline{\underline{220 \text{ stones}}}$

(d)   dictionary

$V = \dfrac{\pi D^2 L}{4} = \dfrac{3.14}{4} \Bigg| \dfrac{4.5^2 \text{ ft}^2}{} \Bigg| \dfrac{800 \text{ miles}}{} \Bigg| \dfrac{5880 \text{ ft}}{1 \text{ mile}} \Bigg| \dfrac{7.4805 \text{ gal}}{1 \text{ ft}^3} \Bigg| \dfrac{1 \text{ barrel}}{42 \text{ gal}}$

$\approx \dfrac{3 \times 4 \times 5 \times (8 \times 10^2) \times (5 \times 10^3) \times 7}{4 \times 4 \times 10} \approx \underline{\underline{1 \times 10^7 \text{ barrels}}}$

(e) $(i) \; V \approx \dfrac{6 \text{ ft} \times 1 \text{ ft} \times 0.5 \text{ ft}}{} \Bigg| \dfrac{28,317 \text{ cm}^3}{1 \text{ ft}^3} \approx 3 \times 3 \times 10^4 \approx \underline{\underline{1 \times 10^5 \text{ cm}^3}}$

$(ii) \; V \approx \dfrac{150 \text{ lb}_m}{} \Bigg| \dfrac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \Bigg| \dfrac{28,317 \text{ cm}^3}{1 \text{ ft}^3} \approx \dfrac{150 \times 3 \times 10^4}{60} \approx \underline{\underline{1 \times 10^5 \text{ cm}^3}}$

(f) $\underline{\underline{SG \approx 1.05}}$

3.2 **(a)** (i) $\dfrac{995 \text{ kg}}{\text{m}^3} \Bigg| \dfrac{1 \text{ lb}_m}{0.45359 \text{ kg}} \Bigg| \dfrac{0.028317 \text{ m}^3}{1 \text{ ft}^3} = \underline{\underline{62.12 \text{ lb}_m / \text{ft}^3}}$

(ii) $\dfrac{995 \text{ kg} / \text{m}^3}{} \Bigg| \dfrac{62.43 \text{ lb}_m / \text{ft}^3}{1000 \text{ kg} / \text{m}^3} = \underline{\underline{62.12 \text{ lb}_m / \text{ft}^3}}$

(b) $\rho = \rho_{H_2O} \times SG = 62.43 \text{ lb}_m / \text{ft}^3 \times 5.7 = \underline{\underline{360 \text{ lb}_m / \text{ft}^3}}$

3.3 **(a)** $\dfrac{50 \text{ L}}{} \Bigg| \dfrac{0.70 \times 10^3 \text{ kg}}{\text{m}^3} \Bigg| \dfrac{1 \text{ m}^3}{10^3 \text{ L}} = \underline{\underline{35 \text{ kg}}}$

(b) $\dfrac{1150 \text{ kg}}{\text{min}} \Bigg| \dfrac{\text{m}^3}{0.7 \times 1000 \text{ kg}} \Bigg| \dfrac{1000 \text{ L}}{1 \text{ m}^3} \Bigg| \dfrac{1 \text{ min}}{60 \text{ s}} = \underline{\underline{27 \text{ L/s}}}$

(c) $\dfrac{10 \text{ gal}}{2 \text{ min}} \Bigg| \dfrac{1 \text{ ft}^3}{7.481 \text{ gal}} \Bigg| \dfrac{0.70 \times 62.43 \text{ lb}_m}{1 \text{ ft}^3} \cong \underline{\underline{29 \text{ lb}_m / \text{min}}}$

3.3 (cont'd)

(d) Assuming that 1 cm^3 kerosene was mixed with V_g (cm^3) gasoline

$$V_g \left(\text{cm}^3 \text{gasoline}\right) \Rightarrow 0.70 V_g \left(\text{g gasoline}\right)$$

$$1 \left(\text{cm}^3 \text{ kerosene}\right) \Rightarrow 0.82 \left(\text{g kerosene}\right)$$

$$SG = \frac{\left(0.70 V_g + 0.82\right)\left(\text{g blend}\right)}{V_g + 1 \left(\text{cm}^3 \text{ blend}\right)} = 0.78 \;\Rightarrow\; V_g = \frac{0.82 - 0.78}{0.78 - 0.70} = 0.50 \text{ cm}^3$$

$$\underline{\text{Volumetric ratio}} = \frac{V_{\text{gasoline}}}{V_{\text{kerosene}}} = \frac{0.50 \text{ cm}^3}{1 \text{ cm}^3} = \underline{\underline{0.50 \text{ cm}^3 \text{ gasoline} / \text{cm}^3 \text{ kerosene}}}$$

3.4   In France: $\dfrac{50.0 \text{ kg}}{}\left|\dfrac{\text{L}}{0.7 \times 1.0 \text{ kg}}\right|\dfrac{5 \text{ Fr}}{1\text{L}}\left|\dfrac{\$1}{5.22 \text{ Fr}}\right. = \underline{\underline{\$68.42}}$

In U.S.: $\dfrac{50.0 \text{ kg}}{}\left|\dfrac{\text{L}}{0.70 \times 1.0 \text{ kg}}\right|\dfrac{1 \text{ gal}}{3.7854 \text{ L}}\left|\dfrac{\$1.20}{1 \text{ gal}}\right. = \underline{\underline{\$22.64}}$

3.5

$\dot{V}_B \,(\text{ft}^3 / \text{h}), \; \dot{m}_B \,(\text{lb}_m / \text{h})$

$\dot{V}_H \,(\text{ft}^3 / \text{h}), \; \dot{m}_H \,(\text{lb}_m / \text{h})$

$\dot{V}(\text{ft}^3 / \text{h}), \; SG = 0.850$

$700 \text{ lb}_m / \text{h}$

(a) $\dot{V} = \dfrac{700 \text{ lb}_m}{\text{h}}\left|\dfrac{\text{ft}^3}{0.850 \times 62.43 \text{ lb}_m}\right. = 13.19 \text{ ft}^3 / \text{h}$

$\dot{m}_B = \dfrac{\dot{V}_B \left(\text{ft}^3\right)}{(\text{h})}\left|\dfrac{0.879 \times 62.43 \text{ lb}_m}{\text{ft}^3}\right. = 54.88 \dot{V}_B \,\left(\text{kg} / \text{h}\right)$

$\dot{m}_H = \left(\dot{V}_H\right)\left(0.659 \times 62.43\right) = 41.14 \dot{V}_H \,\left(\text{kg} / \text{h}\right)$

$\dot{V}_B + \dot{V}_H = 13.19 \text{ ft}^3 / \text{h}$

$\dot{m}_B + \dot{m}_H = 54.88 \dot{V}_B + 41.14 \dot{V}_H = 700 \text{ lb}_m$

$\Rightarrow \quad \dot{V}_B = \underline{11.4 \text{ ft}^3 / \text{h}} \;\Rightarrow\; \dot{m}_B = \underline{\underline{628 \text{ lb}_m / \text{h benzene}}}$

$\dot{V}_H = \underline{1.74 \text{ ft}^3 / \text{h}} \;\Rightarrow\; \dot{m}_H = \underline{\underline{71.6 \text{ lb}_m / \text{h hexane}}}$

(b) – No buildup of mass in unit.

 – ρ_B and ρ_H at inlet stream conditions are equal to their tabulated values (which are strictly valid at 20°C and 1 atm.)

 – Volumes of benzene and hexane are additive.

 – Densitometer gives correct reading.

3.6 **(a)** $V = \dfrac{195.5 \text{ kg } H_2SO_4}{} \bigg| \dfrac{1 \text{ kg solution}}{0.35 \text{kg } H_2SO_4} \bigg| \dfrac{L}{1.2563 \times 1.000 \text{ kg}} = \underline{\underline{445 \text{ L}}}$

(b)

$V_{ideal} = \dfrac{195.5 \text{ kg } H_2SO_4}{} \bigg| \dfrac{L}{1.8255 \times 1.00 \text{ kg}}$

$\quad + \dfrac{195.5 \text{ kg } H_2SO_4}{} \bigg| \dfrac{0.65 \text{ kg } H_2O}{0.35 \text{ kg } H_2SO_4} \bigg| \dfrac{L}{1.000 \text{ kg}} = 470 \text{ L}$

$\underline{\% \text{ error}} = \dfrac{470 - 445}{445} \times 100\% = \underline{5.6\%}$

3.7 Buoyant force $(\text{up}) \underset{\Downarrow}{=} \text{Weight of block (down)}$

Mass of oil displaced $+$ Mass of water displaced $=$ Mass of block

$\rho_{oil}\,(0.542)V + \rho_{H_2O}\,(1 - 0.542)V = \rho_c\,V$

From Table B.1: $\rho_c = 2.26 \text{ g / cm}^3$, $\rho_w = 1.00 \text{ g / cm}^3 \Rightarrow \rho_{oil} = 3.325 \text{ g / cm}^3$

$m_{oil} = \rho_{oil} \times V = 3.325 \text{ g / cm}^3 \times 35.3 \text{ cm}^3 = 117.4 \text{ g}$

$m_{oil + flask} = 117.4 \text{ g} + 124.8 \text{ g} = \underline{\underline{242 \text{ g}}}$

3.8 Buoyant force $(\text{up}) = \text{Weight of block (down)}$

$\Rightarrow W_{\text{displaced liquid}} = W_{\text{block}} \Rightarrow (\rho V g)_{\text{disp. Liq}} = (\rho V g)_{\text{block}}$

$\underline{\text{Expt. 1}}$: $\rho_w(1.5A)g = \rho_B(2A)g \Rightarrow \rho_B = \rho_w \times \dfrac{1.5}{2}$

$\xrightarrow{\rho_w = 1.00 \text{ g/cm}^3} \rho_B = 0.75 \text{ g / cm}^3 \Rightarrow \underline{\underline{(SG)_B = 0.75}}$

$\underline{\text{Expt. 2}}$: $\rho_{soln}(A)g = \rho_B(2A)g \Rightarrow \rho_{soln} = 2\rho_B = 1.5 \text{ g / cm}^3 \Rightarrow \underline{\underline{(SG)_{soln} = 1.5}}$

3.9

Let $\rho_w =$ density of water. $\underline{\text{Note: } \rho_A > \rho_w}$ (object sinks)
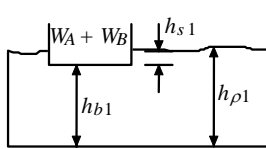
Before object is jettisoned

$\underline{\text{Volume displaced}}$: $V_{d1} = A_b h_{si} = A_b\left(h_{p1} - h_{b1}\right)$ (1)

$\underline{\text{Archimedes}} \Rightarrow \qquad \underbrace{\rho_w V_{d1} g}_{\text{weight of displaced water}} = W_A + W_B$

Subst. (1) for V_{d1}, solve for $\left(h_{p1} - h_{b1}\right)$

$h_{p1} - h_{b1} = \dfrac{W_A + W_B}{p_w g A_b}$ (2)

$\underline{\text{Volume of pond water}}$: $V_w = A_p h_{p1} - V_{d1} \overset{(i)}{\Rightarrow} V_w = A_p h_{p1} - A_b\left(h_{p1} - h_{b1}\right)$

$\xrightarrow[\text{for } b_{p1} - h_{b1}]{\text{subst. (2)}} V_w = A_p h_{p1} - \dfrac{W_A + W_B}{p_w g} \Rightarrow h_{p1} = \dfrac{V_w}{A_p} + \dfrac{W_A + W_B}{p_w g A_p}$ (3)

$\xrightarrow[\text{(2), solve for } h_{b1}]{\text{subst. (3) for } h_{p1} \text{ in}} h_{b1} = \dfrac{V_w}{A_p} + \dfrac{(W_A + W_B)}{p_w g}\left[\dfrac{1}{A_p} - \dfrac{1}{A_b}\right]$ (4)

3.9 (cont'd)

After object is jettisoned
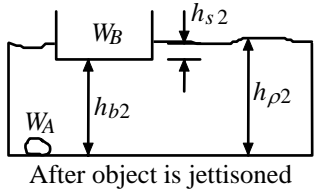
Let V_A = volume of jettisoned object = $\dfrac{W_A}{\rho_A g}$ (5)

Volume displaced by boat: $V_{d2} = A_b\left(h_{p2} - h_{b2}\right)$ (6)

Archimedes $\Rightarrow \rho_W V_{d2} g \underset{\Downarrow}{=} W_B$

Subst. for V_{d2}, solve for $\left(h_{p2} - h_{b2}\right)$

$$h_{p2} - h_{b2} = \frac{W_B}{\rho_w g A_b} \tag{7}$$

Volume of pond water: $V_w = A_p h_{p2} - V_{d2} - V_A \xrightarrow{\text{(5), (6) \& (7)}} V_w = A_p h_{p2} - \dfrac{W_B}{\rho_w g} - \dfrac{W_A}{\rho_A g}$

$$\underset{h_{p2}}{\overset{\text{solve for}}{\Rightarrow}} \quad h_{p2} = \frac{V_w}{A_p} + \frac{W_B}{\rho_w g A_p} + \frac{W_A}{\rho_A g A_p} \tag{8}$$

$$\underset{\text{for } h_{p2} \text{ in (7), solve for } h_{b2}}{\overset{\text{subst. (8)}}{\Rightarrow}} \quad h_{b2} = \frac{V_w}{A_p} + \frac{W_B}{\rho_w g A_p} + \frac{W_A}{\rho_A g A_p} - \frac{W_B}{\rho_w g A_b} \tag{9}$$

(a) Change in pond level

$$h_{p2} - h_{p1} \overset{(8)-(3)}{=} \frac{W_A}{A_p g}\left[\frac{1}{\rho_A} - \frac{1}{\rho_W}\right] = \frac{W_A\left(\rho_W - \rho_A\right)}{\rho_A \rho_W g A_p} \xrightarrow{\rho_W < \rho_A} < 0$$

$\Rightarrow$ the pond level falls

(b) Change in boat level

$$h_{p2} - h_{p1} \overset{(9)-(4)}{=} \frac{W_A}{A_p g}\left[\frac{1}{\rho_A A_p} - \frac{1}{\rho_W A_p} + \frac{1}{\rho_W A_b}\right] \overset{(5)}{=} \overbrace{\left(\frac{V_A}{A_p}\right)}^{>0}\left[1 + \overbrace{\left(\frac{\rho_A}{\rho_W}\left(\frac{A_p}{A_b} - 1\right)\right)}^{>0}\right] > 0$$

$\Rightarrow$ the boat rises

3.10 (a) $\rho_{\text{bulk}} = \dfrac{2.93 \text{ kg CaCO}_3}{\text{L CaCO}_3}\left|\dfrac{0.70 \text{ L CaCO}_3}{\text{L total}}\right. = \underline{\underline{2.05 \text{ kg / L}}}$

(b) $W_{bag} = \rho_{bulk} V g = \dfrac{2.05 \text{ kg}}{\text{L}}\left|\dfrac{50 \text{ L}}{}\right|\dfrac{9.807 \text{ m / s}^2}{}\left|\dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m / s}^2}\right. = \underline{\underline{1.00 \times 10^3 \text{ N}}}$

Neglected the weight of the bag itself and of the air in the filled bag.

(c) The limestone would fall short of filling three bags, because
– the powder would pack tighter than the original particles.
– you could never recover 100% of what you fed to the mill.

3.11 **(a)** $W_b = m_b g = \dfrac{122.5 \text{ kg}}{} \left| \dfrac{9.807 \text{ m}/\text{s}^2}{} \right| \dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m}/\text{s}^2} = \underline{\underline{1202 \text{ N}}}$

$V_b = \dfrac{W_b - W_I}{\rho_w g} = \dfrac{(1202 \text{ N} - 44.0 \text{ N})}{0.996 \text{ kg}/\text{L} \times 9.807 \text{ m}/\text{s}^2} \left| \dfrac{1 \text{ kg} \cdot \text{m}/\text{s}^2}{1 \text{ N}} \right. = \underline{\underline{119 \text{ L}}}$

$\rho_b = \dfrac{m_b}{V_b} = \dfrac{122.5 \text{ kg}}{119 \text{ L}} = \underline{\underline{1.03 \text{ kg}/\text{L}}}$

(b)

$$m_f + m_{nf} = m_b \qquad\qquad (1)$$

$$x_f = \dfrac{m_f}{m_b} \Rightarrow m_f = m_b x_f \qquad\qquad (2)$$

$$(1),(2) \Rightarrow m_{nf} = m_b\left(1 - x_f\right) \qquad\qquad (3)$$

$$V_f + V_{nf} = V_b \Rightarrow \dfrac{m_f}{\rho_f} + \dfrac{m_{nf}}{\rho_{nf}} = \dfrac{m_b}{\rho_b}$$

$$\overset{(2),(3)}{\Rightarrow} m_b\left(\dfrac{x_f}{\rho_f} + \dfrac{1 - x_f}{\rho_{nf}}\right) = \dfrac{m_b}{\rho_b} \Rightarrow x_f\left(\dfrac{1}{\rho_f} - \dfrac{1}{\rho_{nf}}\right) = \dfrac{1}{\rho_b} - \dfrac{1}{\rho_{nf}} \Rightarrow \underline{\underline{x_f = \dfrac{1/\rho_b - 1/\rho_{nf}}{1/\rho_f - 1/\rho_{nf}}}}$$

(c) $x_f = \dfrac{1/\rho_b - 1/\rho_{nf}}{1/\rho_f - 1/\rho_{nf}} = \dfrac{1/1.03 - 1/1.1}{1/0.9 - 1/1.1} = \underline{\underline{0.31}}$

(d) $V_f + V_{nf} + V_{lungs} + V_{other} = V_b$

$$\dfrac{m_f}{\rho_f} + \dfrac{m_{nf}}{\rho_{nf}} + V_{lungs} + V_{other} = \dfrac{m_b}{\rho_b}$$

$$\xrightarrow[m_{nf} = m_b(1-x_f)]{m_f = m_b x_f} m_b\left(\dfrac{x_f}{\rho_f} - \dfrac{1 - x_f}{\rho_{nf}}\right) + (V_{lungs} + V_{other}) = m_b\left(\dfrac{1}{\rho_b} - \dfrac{1}{\rho_{nf}}\right)$$

$$\Rightarrow x_f\left(\dfrac{1}{\rho_f} - \dfrac{1}{\rho_{nf}}\right) = \dfrac{1}{\rho_b} - \dfrac{1}{\rho_{nf}} - \dfrac{V_{lungs} + V_{other}}{m_b}$$

$$\Rightarrow x_f = \dfrac{\left(\dfrac{1}{\rho_b} - \dfrac{1}{\rho_{nf}}\right) - \left(\dfrac{V_{lungs} + V_{other}}{m_b}\right)}{\left(\dfrac{1}{\rho_f} - \dfrac{1}{\rho_{nf}}\right)} = \dfrac{\left(\dfrac{1}{1.03} - \dfrac{1}{1.1}\right) - \left(\dfrac{1.2 + 0.1}{122.5}\right)}{\left(\dfrac{1}{0.9} - \dfrac{1}{1.1}\right)} = \underline{\underline{0.25}}$$

3.12 (a)
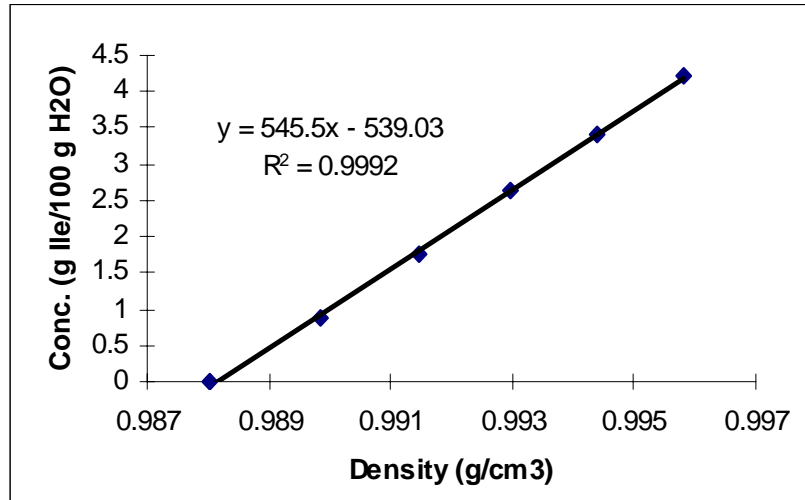
From the plot above, $r = 545.5\rho - 539.03$

(b) For $\rho = 0.9940 \ g/cm^3$, $\quad r = 3.197 \ g \ Ile / 100g \ H_2O$

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

(c) The measured solution density is $0.9940 \ g \ ILE/cm^3$ 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 $0.9940 \ g \ ILE/cm^3$. The ILE mass flow rate calculated in Part (b) is therefore <u>too low.</u>

3.13 (a)
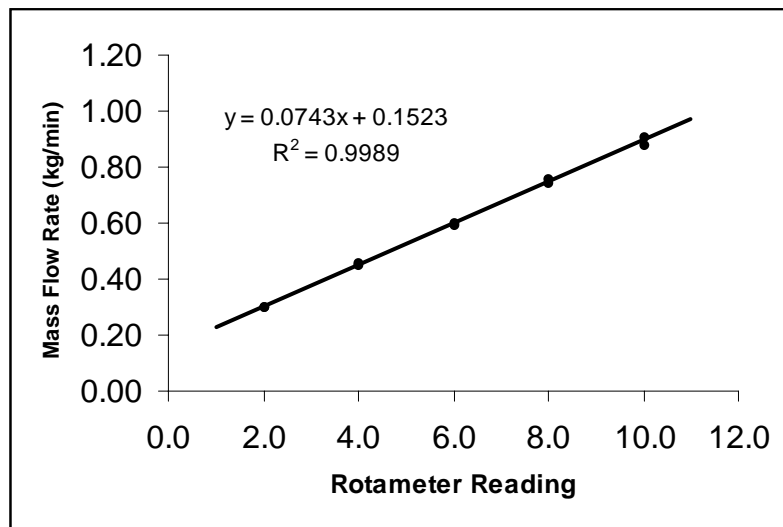
3.13 (cont'd)

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		
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	0.0104
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	

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

<u>95% confidence limits</u>: $(0.610 \pm 1.74\overline{D_i}) \text{ kg / min} = \underline{\underline{0.610 \pm 0.018 \text{ kg / min}}}$

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) $\dfrac{15.0 \text{ kmol C}_6\text{H}_6}{} \bigg| \dfrac{78.114 \text{ kg C}_6\text{H}_6}{\text{kmol C}_6\text{H}_6} = \underline{\underline{1.17 \times 10^3 \text{ kg C}_6\text{H}_6}}$

(b) $\dfrac{15.0 \text{ kmol C}_6\text{H}_6}{} \bigg| \dfrac{1000 \text{ mol}}{\text{kmol}} = \underline{\underline{1.5 \times 10^4 \text{ mol C}_6\text{H}_6}}$

(c) $\dfrac{15,000 \text{ mol C}_6\text{H}_6}{} \bigg| \dfrac{\text{lb - mole}}{453.6 \text{ mol}} = \underline{\underline{33.07 \text{ lb - mole C}_6\text{H}_6}}$

(d) $\dfrac{15,000 \text{ mol C}_6\text{H}_6}{} \bigg| \dfrac{6 \text{ mol C}}{1 \text{ mol C}_6\text{H}_6} = \underline{\underline{90,000 \text{ mol C}}}$

(e) $\dfrac{15,000 \text{ mol C}_6\text{H}_6}{} \bigg| \dfrac{6 \text{ mol H}}{1 \text{ mol C}_6\text{H}_6} = \underline{\underline{90,000 \text{ mol H}}}$

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

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

(h) $\dfrac{15,000 \text{ mol C}_6\text{H}_6}{} \bigg| \dfrac{6.022 \times 10^{23}}{\text{mol}} = \underline{\underline{9.03 \times 10^{27} \text{ molecules of C}_6\text{H}_6}}$

3.15 **(a)** $\dot{m} = \dfrac{175\ \text{m}^3}{\text{h}} \left| \dfrac{1000\ \text{L}}{\text{m}^3} \right| \dfrac{0.866\ \text{kg}}{\text{L}} \left| \dfrac{1\ \text{h}}{60\ \text{min}} \right. = \underline{\underline{2526\ \text{kg/min}}}$

(b) $\dot{n} = \dfrac{2526\ \text{kg}}{\text{min}} \left| \dfrac{1000\ \text{mol}}{92.13\ \text{kg}} \right| \dfrac{1\ \text{min}}{60\ \text{s}} = \underline{\underline{457\ \text{mol/s}}}$

(c) Assumed density (SG) at T, P of stream is the same as the density at 20°C and 1 atm

3.16 **(a)** $\dfrac{200.0\ \text{kg mix}}{} \left| \dfrac{0.150\ \text{kg CH}_3\text{OH}}{\text{kg mix}} \right| \dfrac{\text{kmol CH}_3\text{OH}}{32.04\ \text{kg CH}_3\text{OH}} \left| \dfrac{1000\ \text{mol}}{1\ \text{kmol}} \right. = \underline{\underline{936\ \text{mol CH}_3\text{OH}}}$

(b) $\dot{m}_{mix} = \dfrac{100.0\ \text{lb - mole MA}}{\text{h}} \left| \dfrac{74.08\ \text{lb}_\text{m}\ \text{MA}}{1\ \text{lb - mole MA}} \right| \dfrac{1\ \text{lb}_\text{m}\ \text{mix}}{0.850\ \text{lb}_\text{m}\ \text{MA}} = \underline{\underline{8715\ \text{lb}_\text{m}\text{/h}}}$

3.17 $\overline{M} = \dfrac{0.25\ \text{mol N}_2}{} \left| \dfrac{28.02\ \text{g N}_2}{\text{mol N}_2} \right. + \dfrac{0.75\ \text{mol H}_2}{} \left| \dfrac{2.02\ \text{g H}_2}{\text{mol H}_2} \right. = 8.52\ \text{g/mol}$

$\dot{m}_{N_2} = \dfrac{3000\ \text{kg}}{\text{h}} \left| \dfrac{\text{kmol}}{8.52\ \text{kg}} \right| \dfrac{0.25\ \text{kmol N}_2}{\text{kmol feed}} \left| \dfrac{28.02\ \text{kg N}_2}{\text{kmol N}_2} \right. = \underline{\underline{2470\ \text{kg N}_2\text{/h}}}$

3.18 $M_{\text{suspension}} = 565\ \text{g} - 65\ \text{g} = 500\ \text{g}$, $M_{\text{CaCO}_3} = 215\ \text{g} - 65\ \text{g} = 150\ \text{g}$

(a) $\dot{V} = \underline{\underline{455\ \text{mL/min}}}$, $\dot{m} = \underline{\underline{500\ \text{g/min}}}$

(b) $\rho = \dot{m}/\dot{V} = 500\ \text{g}/455\ \text{mL} = \underline{\underline{1.10\ \text{g/mL}}}$

(c) $150\ \text{g CaCO}_3 / 500\ \text{g suspension} = \underline{\underline{0.300\ \text{g CaCO}_3/\text{g suspension}}}$

3.19 Assume 100 mol mix.

$m_{\text{C}_2\text{H}_5\text{OH}} = \dfrac{10.0\ \text{mol C}_2\text{H}_5\text{OH}}{} \left| \dfrac{46.07\ \text{g C}_2\text{H}_5\text{OH}}{\text{mol C}_2\text{H}_5\text{OH}} \right. = 461\ \text{g C}_2\text{H}_5\text{OH}$

$m_{\text{C}_4\text{H}_8\text{O}_2} = \dfrac{75.0\ \text{mol C}_4\text{H}_8\text{O}_2}{} \left| \dfrac{88.1\ \text{g C}_4\text{H}_8\text{O}_2}{\text{mol C}_4\text{H}_8\text{O}_2} \right. = 6608\ \text{g C}_4\text{H}_8\text{O}_2$

$m_{\text{CH}_3\text{COOH}} = \dfrac{15.0\ \text{mol CH}_3\text{COOH}}{} \left| \dfrac{60.05\ \text{g CH}_3\text{COOH}}{\text{mol CH}_3\text{COOH}} \right. = 901\ \text{g CH}_3\text{COOH}$

$x_{\text{C}_2\text{H}_5\text{OH}} = \dfrac{461\ \text{g}}{461\ \text{g} + 6608\ \text{g} + 901\ \text{g}} = \underline{\underline{0.0578\ \text{g C}_2\text{H}_5\text{OH / g mix}}}$

$x_{\text{C}_4\text{H}_8\text{O}_2} = \dfrac{6608\ \text{g}}{461\ \text{g} + 6608\ \text{g} + 901\ \text{g}} = \underline{\underline{0.8291\ \text{g C}_4\text{H}_8\text{O}_2 / g mix}}$

$x_{\text{CH}_3\text{COOH}} = \dfrac{901\ \text{g}}{461\ \text{g} + 6608\ \text{g} + 901\ \text{g}} = \underline{\underline{0.113\ \text{g CH}_3\text{COOH / g mix}}}$

$\overline{MW} = \dfrac{461\ \text{g} + 6608\ \text{g} + 901\ \text{g}}{100\ \text{mol}} = \underline{\underline{79.7\ \text{g / mol}}}$

$m = \dfrac{25\ \text{kmol EA}}{} \left| \dfrac{100\ \text{kmol mix}}{75\ \text{kmol EA}} \right| \dfrac{79.7\ \text{kg mix}}{1\ \text{kmol mix}} = \underline{\underline{2660\ \text{kg mix}}}$

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) $m_{gypsum} = \dfrac{1 \text{ L slurry}}{} \left| \dfrac{0.35 \text{ kg } CaSO_4 \cdot 2H_2O}{\text{L slurry}} = \underline{\underline{0.35 \text{ kg } CaSO_4 \cdot 2H_2O}}\right.$

$V_{gypsum} = \dfrac{0.35 \text{ kg } CaSO_4 \cdot 2H_2O}{} \left| \dfrac{\text{L } CaSO_4 \cdot 2H_2O}{2.32 \text{ kg } CaSO_4 \cdot 2H_2O} = \underline{\underline{0.151 \text{ L } CaSO_4 \cdot 2H_2O}}\right.$

$CaSO_4$ in gypsum: $m = \dfrac{0.35 \text{ kg } gypsum}{} \left| \dfrac{136.15 \text{ kg } CaSO_4}{172.18 \text{ kg } gypsum} = \underline{\underline{0.277 \text{ kg } CaSO_4}}\right.$

$CaSO_4$ in soln.: $m = \dfrac{(1-0.151) \text{ L sol}}{} \left| \dfrac{1.05 \text{ kg}}{\text{L}} \right| \dfrac{0.209 \text{ kg } CaSO_4}{100.209 \text{ kg sol}} = \underline{\underline{0.00186 \text{ kg } CaSO_4}}$

(c) $m = \dfrac{0.35 \text{ kg gypsum}}{} \left| \dfrac{0.05 \text{ kg sol}}{0.95 \text{ kg gypsum}} \right| \dfrac{0.209 \text{ g } CaSO_4}{100.209 \text{ g sol}} = 3.84 \times 10^{-5} \text{ kg } CaSO_4$

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

3.21

$\underline{\text{CSA:}} \quad \dfrac{45.8 \text{ L}}{\text{min}} \left| \dfrac{0.90 \text{ kg}}{\text{L}} \right| \dfrac{\text{kmol}}{75 \text{ kg}} = 0.5496 \dfrac{\text{kmol}}{\text{min}}$

$\underline{\text{FB:}} \quad \dfrac{55.2 \text{ L}}{\text{min}} \left| \dfrac{0.75 \text{ kg}}{\text{L}} \right| \dfrac{\text{kmol}}{90 \text{ kg}} = 0.4600 \dfrac{\text{kmol}}{\text{min}}$

$\Rightarrow \dfrac{0.5496}{0.4600} = 1.2 \dfrac{\text{mol CSA}}{\text{mol FB}}$

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

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

$\dfrac{6910 \text{ g EtOH}}{} \left| \dfrac{0.600 \text{ g } H_2O}{0.400 \text{ g EtOH}} = 10365 \text{ g } H_2O\right.$

$V = \dfrac{6910 \text{ g EtOH}}{} \left| \dfrac{\text{L}}{789 \text{ g EtOH}} \right. + \dfrac{10365 \text{ g } H_2O}{} \left| \dfrac{\text{L}}{1000 \text{ g } H_2O} \right. = 19.123 \text{ L} \Rightarrow \underline{\underline{19.1 \text{ L}}}$

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

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

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

3.23

$$\overline{M} = \frac{0.09 \text{ mol CH}_4}{} \left| \frac{16.04 \text{ g}}{\text{mol}} \right. + \frac{0.91 \text{ mol Air}}{} \left| \frac{29.0 \text{ g Air}}{\text{mol}} \right. = 27.83 \text{ g/mol}$$

$$\frac{700 \text{ kg}}{\text{h}} \left| \frac{\text{kmol}}{27.83 \text{ kg}} \right| \frac{0.090 \text{ kmol CH}_4}{1.00 \text{ kmol mix}} = 2.264 \text{ kmol CH}_4/\text{h}$$

$$\frac{2.264 \text{ kmol CH}_4}{\text{h}} \left| \frac{0.91 \text{ kmol air}}{0.09 \text{ kmol CH}_4} \right. = 22.89 \text{ kmol air/h}$$

$$\underline{5\% \text{ CH}_4} \Rightarrow \frac{2.264 \text{ kmol CH}_4}{\text{h}} \left| \frac{0.95 \text{ kmol air}}{0.05 \text{ kmol CH}_4} \right. = 43.01 \text{ kmol air/h}$$

$$\underline{\text{Dilution air required:}} \frac{(43.01 - 22.89) \text{ kmol air}}{\text{h}} \left| \frac{1000 \text{ mol}}{1 \text{ kmol}} \right. = \underline{\underline{20200 \text{ mol air/h}}}$$

$$\underline{\text{Product gas:}} \frac{700 \text{ kg}}{\text{h}} + \frac{20.20 \text{ kmol Air}}{\text{h}} \left| \frac{29 \text{ kg Air}}{\text{kmol Air}} \right. = \underline{\underline{1286 \text{ kg/h}}}$$

$$\frac{43.01 \text{ kmol Air}}{\text{h}} \left| \frac{0.21 \text{ kmol O}_2}{1.00 \text{ kmol Air}} \right| \frac{32.00 \text{ kg O}_2}{1 \text{ kmol O}_2} \left| \frac{\text{h}}{1286 \text{ kg total}} \right. = \underline{\underline{0.225 \frac{\text{kg O}_2}{\text{kg}}}}$$

3.24

$$x_i = \frac{m_i}{M} \ , \ \rho_i = \frac{m_i}{V_i} \ , \ \overline{\rho} = \frac{M}{V}$$

$$A: \ \sum x_i \rho_i = \sum \frac{m_i}{M} \frac{m_i}{V_i} = \frac{1}{M} \sum \frac{m_i^2}{V_i} \ \neq \overline{\rho} \qquad \text{Not helpful.}$$

$$B: \ \sum \frac{x_i}{\rho_i} = \sum \frac{m_i}{M} \frac{V_i}{m_i} = \frac{1}{M} \sum V_i = \frac{V}{M} = \frac{1}{\overline{\rho}} \qquad \text{Correct.}$$

$$\frac{1}{\overline{\rho}} = \sum \frac{x_i}{\rho_i} = \frac{0.60}{0.791} + \frac{0.25}{1.049} + \frac{0.15}{1.595} = 1.091 \ \Rightarrow \ \overline{\rho} = \underline{\underline{0.917 \text{ g/cm}^3}}$$

3.25 (a) Basis: 100 mol $N_2 \Rightarrow$ 20 mol $CH_4 \Rightarrow$
$$\begin{cases} 20 \times \dfrac{80}{25} = 64 \text{ mol CO}_2 \\ 20 \times \dfrac{40}{25} = 32 \text{ mol CO} \end{cases}$$

$$N_{total} = 100 + 20 + 64 + 32 = 216 \text{ mol}$$

$$x_{CO} = \frac{32}{216} = \underline{\underline{0.15 \text{ mol CO/mol}}} \ , \ x_{CO_2} = \frac{64}{216} = \underline{\underline{0.30 \text{ mol CO}_2 / \text{mol}}}$$

$$x_{CH_4} = \frac{20}{216} = \underline{\underline{0.09 \text{ mol CH}_4 / \text{mol}}} \ , \ x_{N_2} = \frac{100}{216} = \underline{\underline{0.46 \text{ mol N}_2 / \text{mol}}}$$

(b) $\overline{M} = \sum y_i M_i = 0.15 \times 28 + 0.30 \times 44 + 0.09 \times 16 + 0.46 \times 28 = \underline{\underline{32 \text{ g/mol}}}$

3.26 (a)

Samples	Species	MW	k	Peak Area	Mole Fraction	Mass Fraction	moles	mass
1	CH4	16.04	0.150	3.6	0.156	0.062	0.540	8.662
	C2H6	30.07	0.287	2.8	0.233	0.173	0.804	24.164
	C3H8	44.09	0.467	2.4	0.324	0.353	1.121	49.416
	C4H10	58.12	0.583	1.7	0.287	0.412	0.991	57.603
2	CH4	16.04	0.150	7.8	0.249	0.111	1.170	18.767
	C2H6	30.07	0.287	2.4	0.146	0.123	0.689	20.712
	C3H8	44.09	0.467	5.6	0.556	0.685	2.615	115.304
	C4H10	58.12	0.583	0.4	0.050	0.081	0.233	13.554
3	CH4	16.04	0.150	3.4	0.146	0.064	0.510	8.180
	C2H6	30.07	0.287	4.5	0.371	0.304	1.292	38.835
	C3H8	44.09	0.467	2.6	0.349	0.419	1.214	53.534
	C4H10	58.12	0.583	0.8	0.134	0.212	0.466	27.107
4	CH4	16.04	0.150	4.8	0.333	0.173	0.720	11.549
	C2H6	30.07	0.287	2.5	0.332	0.324	0.718	21.575
	C3H8	44.09	0.467	1.3	0.281	0.401	0.607	26.767
	C4H10	58.12	0.583	0.2	0.054	0.102	0.117	6.777
5	CH4	16.04	0.150	6.4	0.141	0.059	0.960	15.398
	C2H6	30.07	0.287	7.9	0.333	0.262	2.267	68.178
	C3H8	44.09	0.467	4.8	0.329	0.380	2.242	98.832
	C4H10	58.12	0.583	2.3	0.197	0.299	1.341	77.933

(b)
```
REAL A(10), MW(10), K(10), MOL(10), MASS(10), MOLT, MASST
INTEGER N, ND, ID, J
READ (5, *) N
CN-NUMBER OF SPECIES
READ (5, *) (MW(J), K(J), J = 1, N)
READ (5, *) ND
DO 20 ID = 1, ND
    READ (5, *)(A(J), J = 1, N)
    MOLT = 0.0
    MASST = 0.0
    DO 10 J = 1, N
      MOL(J) =
      MASS(J) = MOL(J) * MW(J)
      MOLT = MOLT + MOL(J)
      MASST = MASST + MASS(J)
10        CONTINUE
    DO 15 J = 1, N
      MOL(J) = MOL(J)/MOLT
      MASS(J) = MASS(J)/MASST
15        CONTINUE
    WRITE (6, 1) ID, (J, MOL(J), MASS (J), J = 1, N)
20  CONTINUE
1   FORMAT (' SAMPLE:  `, I3, /,
    * ' SPECIES MOLE FR. MASS FR.', /,
```

3.26 (cont'd)

```
* 10(3X, I3, 2(5X, F5.3), /), /)
END
$DATA
*
   4
16.04   0.150
30.07   0.287
44.09   0.467
58.12   0.583
   5
3.6   2.8   2.4   1.7
7.8   2.4   5.6   0.4
3.4   4.5   2.6   0.8
4.8   2.5   1.3   0.2
6.4   7.9   4.8   2.3
[OUTPUT]
SAMPLE:      1
```

SPECIES	MOLE FR	MASS FR
1	0.156	0.062
2	0.233	0.173
3	0.324	0.353
4	0.287	0.412

SAMPLE: 2
(ETC.)

3.27 (a)

$$\frac{(8.7 \times 10^6 \times 0.40)\text{ kg C}}{} \left| \frac{44\text{ kg CO}_2}{12\text{ kg C}} \right. = 1.28 \times 10^7 \text{ kg CO}_2 \Rightarrow 2.9 \times 10^5 \text{ kmol CO}_2$$

$$\frac{(1.1 \times 10^6 \times 0.26)\text{ kg C}}{} \left| \frac{28\text{ kg CO}}{12\text{ kg C}} \right. = 6.67 \times 10^5 \text{ kg CO} \Rightarrow 2.38 \times 10^4 \text{ kmol CO}$$

$$\frac{(3.8 \times 10^5 \times 0.10)\text{ kg C}}{} \left| \frac{16\text{ kg CH}_4}{12\text{ kg C}} \right. = 5.07 \times 10^4 \text{ kg CH}_4 \Rightarrow 3.17 \times 10^3 \text{ kmol CH}_4$$

$$m = \frac{(1.28 \times 10^7 + 6.67 \times 10^5 + 5.07 \times 10^4)\text{ kg}}{} \left| \frac{1\text{ metric ton}}{1000\text{ kg}} \right. = 13,500 \; \frac{\text{metric tons}}{\text{yr}}$$

$$\overline{M} = \sum y_i M_i = 0.915 \times 44 + 0.075 \times 28 + 0.01 \times 16 = \underline{\underline{42.5 \text{ g / mol}}}$$

3.28 (a) <u>Basis</u>: 1 liter of solution

$$\frac{1000\text{ mL}}{} \left| \frac{1.03\text{ g}}{\text{mL}} \right| \frac{5\text{ g H}_2\text{SO}_4}{100\text{ g}} \left| \frac{\text{mol H}_2\text{SO}_4}{98.08\text{ g H}_2\text{SO}_4} \right. = 0.525 \text{ mol / L} \Rightarrow \underline{\underline{0.525 \text{ molar solution}}}$$

3.28 (cont'd)

(b) $t = \dfrac{V}{\dot{V}} = \dfrac{55 \text{ gal}}{} \left| \dfrac{3.7854 \text{ L}}{\text{gal}} \right| \dfrac{\text{min}}{87 \text{ L}} \left| \dfrac{60 \text{ s}}{\text{min}} \right. = \underline{\underline{144 \text{ s}}}$

$\dfrac{55 \text{ gal}}{} \left| \dfrac{3.7854 \text{ L}}{\text{gal}} \right| \dfrac{10^3 \text{ mL}}{1 \text{ L}} \left| \dfrac{1.03 \text{ g}}{\text{mL}} \right| \dfrac{0.0500 \text{ g H}_2\text{SO}_4}{\text{g}} \left| \dfrac{1 \text{ lbm}}{453.59 \text{ g}} \right. = \underline{\underline{23.6 \text{ lb}_m \text{ H}_2\text{SO}_4}}$

(c) $u = \dfrac{\dot{V}}{A} = \dfrac{87 \text{ L}}{\text{min}} \left| \dfrac{\text{m}^3}{1000 \text{ L}} \right| \dfrac{1 \text{ min}}{60 \text{ s}} \left| \dfrac{}{(\pi \times 0.06^2 / 4) \text{ m}^2} \right. = 0.513 \text{ m / s}$

$t = \dfrac{L}{u} = \dfrac{45 \text{ m}}{0.513 \text{ m / s}} = \underline{\underline{88 \text{ s}}}$

3.29 (a)

$\dot{n}_1$ (mol/min)
0.180 mol C_6H_{14}/mol
0.820 mol N_2/mol

$\dot{n}_2$ (mol/min)
0.050 mol C_6H_{14}/mol
0.950 mol N_2/mol

1.50 L $C_6H_{14}(l)$/min
$\dot{n}_3$ (mol $C_6H_{14}(l)$/min)
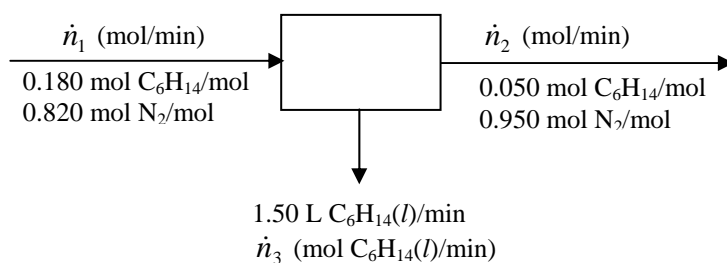
$\dot{n}_3 = \dfrac{1.50 \text{ L}}{\text{min}} \left| \dfrac{0.659 \text{ kg}}{\text{L}} \right| \dfrac{1000 \text{ mol}}{86.17 \text{ kg}} = 11.47 \text{ mol / min}$

$\underline{\text{Hexane balance: } 0.180\dot{n}_1 = 0.050\dot{n}_2 + 11.47 \text{ (mol } C_6H_{14} \text{ / min)}}$
$\underline{\text{Nitrogen balance: } 0.820\dot{n}_1 = 0.950\dot{n}_2 \text{ (mol } N_2 \text{ / min)}}$ $\left.\begin{array}{c}\\\\\end{array}\right\}$ solve $\Rightarrow$ $\left\{\begin{array}{l} \dot{n}_1 = 83.8 \text{ mol / min} \\ \dot{n}_2 = 72.3 \text{ mol / min} \end{array}\right.$

(b) $\underline{\text{Hexane recovery}} = \dfrac{\dot{n}_3}{\dot{n}_1} \times 100\% = \dfrac{11.47}{0.180(83.8)} \times 100\% = \underline{\underline{76\%}}$

3.30 $\dfrac{30 \text{ mL}}{} \left| \dfrac{1 \text{ L}}{10^3 \text{ mL}} \right| \dfrac{0.030 \text{ mol}}{1 \text{ L}} \left| \dfrac{172 \text{ g}}{1 \text{ mol}} \right. = \underline{\underline{0.155 \text{ g Nauseum}}}$

3.31 (a) kt is dimensionless $\Rightarrow k$ (min^{-1})

(b) A semilog plot of C_A vs. t is a straight line $\Rightarrow$ $\ln C_A = \ln C_{AO} - kt$
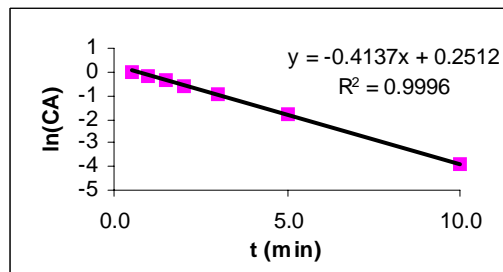
$$\underline{\underline{k = 0.414 \text{ min}^{-1}}}$$

$$\ln C_{AO} = 0.2512 \Rightarrow \underline{\underline{C_{AO} = 1.286 \text{ lb-moles}/\text{ft}^3}}$$

(c) $C_A \left(\dfrac{\text{lb-moles}}{\text{ft}^3} \right) = C_A' \dfrac{\text{mol}}{\text{liter}} \left| \dfrac{28.317 \text{ liter}}{1 \text{ ft}^3} \right| \dfrac{2.26462 \text{ lb-moles}}{1000 \text{ mol}} = 0.06243 C_A'$

$t(\text{min}) = \dfrac{t'(s)}{} \left| \dfrac{1 \text{ min}}{60 \text{ s}} = t'/60 \right.$

$\Downarrow$ $C_A = C_{A0} \exp(-kt)$

$0.06243 C_A' = 1.334 \exp(-0.419 t'/60) \overset{\text{drop primes}}{\Rightarrow} \underline{\underline{C_A (\text{mol}/L) = 21.4 \exp(-0.00693 t)}}$

$t = 200 \text{ s} \Rightarrow C_A = \underline{\underline{5.30 \text{ mol}/L}}$

3.32 (a) $\dfrac{2600 \text{ mm Hg}}{} \left| \dfrac{14.696 \text{ psi}}{760 \text{ mm Hg}} = \underline{\underline{50.3 \text{ psi}}} \right.$

(b) $\dfrac{275 \text{ ft H}_2\text{O}}{} \left| \dfrac{101.325 \text{ kPa}}{33.9 \text{ ft H}_2\text{O}} = \underline{\underline{822.0 \text{ kPa}}} \right.$

(c) $\dfrac{3.00 \text{ atm}}{} \left| \dfrac{1.01325 \times 10^5 \text{ N}/\text{m}^2}{1 \text{ atm}} \right| \dfrac{1^2 \text{ m}^2}{100^2 \text{ cm}^2} = \underline{\underline{30.4 \text{ N}/\text{cm}^2}}$

(d) $\dfrac{280 \text{ cm Hg}}{} \left| \dfrac{10 \text{ mm}}{1 \text{ cm}} \right| \dfrac{1.01325 \times 10^6 \text{ dynes}/\text{cm}^2}{760 \text{ mm Hg}} \left| \dfrac{100^2 \text{ cm}^2}{1^2 \text{ m}^2} = \underline{\underline{3.733 \times 10^{10} \dfrac{\text{dynes}}{\text{m}^2}}} \right.$

(e) $1 \text{ atm} - \dfrac{20 \text{ cm Hg}}{} \left| \dfrac{10 \text{ mm}}{1 \text{ cm}} \right| \dfrac{1 \text{ atm}}{760 \text{ mm Hg}} = \underline{\underline{0.737 \text{ atm}}}$

3-14

3.32 (cont'd)

(f) $\dfrac{25.0 \text{ psig}}{} \dfrac{760 \text{ mm Hg (gauge)}}{14.696 \text{ psig}} = \underline{\underline{1293 \text{ mm Hg (gauge)}}}$

(g) $\dfrac{(25.0 + 14.696)\text{psi}}{} \dfrac{760 \text{ mm Hg}}{14.696 \text{ psi}} = \underline{\underline{2053 \text{ mm Hg (abs)}}}$

(h) $325 \text{ mm Hg} - 760 \text{ mm Hg} = \underline{\underline{-435 \text{ mm Hg (gauge)}}}$

(i) Eq. (3.4-2) $\Rightarrow h = \dfrac{P}{\rho g} = \dfrac{35.0 \text{ lb}_f}{\text{in}^2} \left| \dfrac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \dfrac{\text{ft}^3}{1.595 \text{x} 62.43 \text{ lb}_m} \left| \dfrac{\text{s}^2}{32.174 \text{ ft}} \right| \dfrac{32.174 \text{ lb}_m \cdot \text{ft}}{\text{s}^2 \cdot \text{lb}_f} \left| \dfrac{100 \text{ cm}}{3.2808 \text{ ft}} \right.$

$= \underline{\underline{1540 \text{ cm CCl}_4}}$

3.33 (a) $P_g = \rho g h = \dfrac{0.92 \times 1000 \text{ kg}}{\text{m}^3} \left| \dfrac{9.81 \text{ m}/\text{s}^2}{} \right| \dfrac{h \text{ (m)}}{} \left| \dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m}/\text{s}^2} \right| \dfrac{1 \text{ kPa}}{10^3 \text{ N}/\text{m}^2}$

$\Rightarrow h \text{ (m)} = 0.111 P_g \text{ (kPa)}$
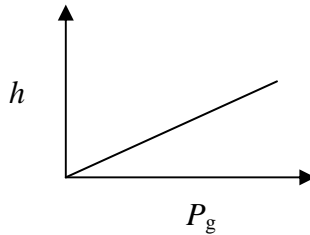
$P_g = 68 \text{ kPa} \Rightarrow h = 0.111 \times 68 = \underline{7.55 \text{ m}}$

$m_{oil} = \rho V = \left(0.92 \times 1000 \ \dfrac{\text{kg}}{\text{m}^3} \right) \times \left(7.55 \times \pi \times \dfrac{16^2}{4} \text{ m}^3 \right) = \underline{\underline{1.4 \times 10^6 \text{ kg}}}$

(b) $P_g + P_{atm} = P_{top} + \rho g h$

$\Downarrow$

$68 + 101 = 115 + \left[(0.92 \times 1000) \times (9.81)/10^3 \right] h \Rightarrow h = \underline{\underline{5.98 \text{ m}}}$

3.34 (a) Weight of block $=$ Sum of weights of displaced liquids

$(h_1 + h_2) A \rho_b g = h_1 A \rho_1 g + h_2 A \rho_2 g \Rightarrow \rho_b = \dfrac{\rho_1 h_1 + \rho_2 h_2}{h_1 + h_2}$

(b)

$P_{top} = P_{atm} + \rho_1 g h_0 , \quad P_{bottom} = P_{atm} + \rho_1 g (h_0 + h_1) + \rho_2 g h_2 , \quad W_b = \rho_b (h_1 + h_2) A$

$\Rightarrow F_{down} = (P_{atm} + \rho_1 g h_0) A + \rho_b (h_1 + h_2) A, \quad F_{up} = [P_{atm} + \rho_1 g (h_0 + h_1) + \rho_2 g h_2] A$

$F_{down} = F_{up} \Rightarrow \rho_b (h_1 + h_2) A = \rho_1 g h_1 A + \rho_2 g h_2 A \Rightarrow W_{block} = W_{liquid \ displaced}$

3.35 $\Delta P = \left(P_{atm} + \rho gh\right) - P_{inside}$

$$= 1 \text{ atm} - 1 \text{ atm} + \frac{(1.05)1000 \text{ kg}}{\text{m}^3} \left| \frac{9.8066 \text{ m}}{\text{s}^2} \right| \frac{150 \text{ m}}{} \left| \frac{1^2 \text{ m}^2}{100^2 \text{ cm}^2} \right| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m}/\text{s}^2}$$

$$F = \frac{154 \text{ N}}{\text{cm}^2} \left| \frac{65 \text{ cm}^2}{} = \underline{\underline{1.00 \times 10^4 \text{ N}}} \times \left(\frac{0.22481 \text{ lb}_f}{1 \text{ N}} \right) = \underline{\underline{2250 \text{ lb}_f}}$$

3.36 $m = \rho V = \dfrac{1.4 \times 62.43 \text{ lb}_m}{\text{ft}^3} \left| \dfrac{1 \text{ ft}^3}{7.481 \text{ gal}} \right| \dfrac{2.3 \times 10^6 \text{ gal}}{} = \underline{\underline{2.69 \times 10^7 \text{ lb}_m}}$

$P = P_0 + \rho gh$

$$= 14.7 \frac{\text{lb}_f}{\text{in}^2} + \frac{1.4 \times 62.43 \text{ lb}_m}{\text{ft}^3} \left| \frac{32.174 \text{ ft}}{\text{s}^2} \right| \frac{30 \text{ ft}}{} \left| \frac{1 \text{ lb}_f}{32.174 \text{ lb}_m \cdot \text{ft}/\text{s}^2} \right| \frac{1^2 \text{ ft}^2}{12^2 \text{ in}^2}$$

$$= \underline{\underline{32.9 \text{ psi}}}$$

— Structural flaw in the tank.
— Tank strength inadequate for that much force.
— Molasses corroded tank wall

3.37 (a) $m_{head} = \dfrac{\pi \times 24^2 \times 3 \text{ in}^3}{4} \left| \dfrac{1 \text{ ft}^3}{12^3 \text{ in}^3} \right| \dfrac{8.0 \times 62.43 \text{ lb}_m}{\text{ft}^3} = 392 \text{ lb}_m$

$$W = m_{head} g = \frac{392 \text{ lb}_m}{} \left| \frac{32.174 \text{ ft}/\text{s}^2}{} \right| \frac{1 \text{ lb}_f}{32.174 \text{ lb}_m \cdot \text{ft}/\text{s}^2} = 392 \text{ lb}_f$$

$$F_{net} = F_{gas} - F_{atm} - W = \frac{\left[(30 + 14.7)\right] \text{lb}_f}{\text{in}^2} \left| \frac{\pi \times 20^2 \text{ in}^2}{4} \right.$$

$$- \frac{14.7 \text{ lb}_f}{\text{in}^2} \left| \frac{\pi \times 24^2 \text{ in}^2}{4} \right. - 392 \text{ lb}_f = \underline{\underline{7.00 \times 10^3 \text{ lb}_f}}$$

The head would blow off.

<u>Initial acceleration:</u> $a = \dfrac{F_{net}}{m_{head}} = \dfrac{7.000 \times 10^3 \text{ lb}_f}{392 \text{ lb}_m} \left| \dfrac{32.174 \text{ lb}_m \cdot \text{ft}/\text{s}^2}{1 \text{ lb}_f} \right. = \underline{\underline{576 \text{ ft}/\text{s}^2}}$

(b) <u>Vent the reactor through a valve to the outside or a hood before removing the head.</u>

3.38 (a)
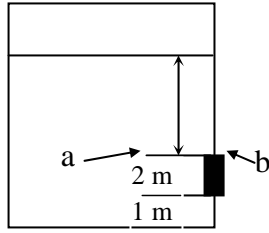
$$P_a = \rho g h + P_{atm} \quad , \quad P_b = P_{atm}$$

If the inside pressure on the door equaled P_a, the force on the door would be $F = A_{door}(P_a - P_b) = \rho g h A_{door}$

Since the pressure at every point on the door is greater than P_a, Since the pressure at every point on the door is greater than P_a, $F > \rho g h A_{door}$

a → 2 m ← b
1 m

(b) Assume an average bathtub 5 ft long, 2.5 ft wide, and 2 ft high takes about 10 min to fill.

$$\dot{V}_{tub} = \frac{V}{t} \approx \frac{5 \times 2.5 \times 2 \text{ ft}^3}{10 \text{ min}} = 2.5 \text{ ft}^3 / \text{min} \Rightarrow \dot{V} = 5 \times 2.5 = 12.5 \text{ ft}^3 / \text{min}$$

(i) For a full room, $h = 7$ m

$$\Rightarrow F > \frac{1000 \text{ kg}}{\text{m}^3} \left| \frac{9.81 \text{ m}}{\text{s}^2} \right| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \left| \frac{7 \text{ m}}{} \right| \frac{2 \text{ m}^2}{} \Rightarrow \underline{\underline{F > 1.4 \times 10^5 \text{ N}}}$$

The door will break before the room fills

(ii) If the door holds, it will take

$$t_{fill} = \frac{V_{room}}{\dot{V}} = \frac{(5 \times 15 \times 10) \text{ m}^3}{} \left| \frac{}{12.5 \text{ ft}^3 / \text{min}} \right| \frac{35.3145 \text{ ft}^3}{1 \text{ m}^3} \left| \frac{1 \text{ h}}{60 \text{ min}} \right| = \underline{\underline{31 \text{ h}}}$$

He will not have enough time.

3.39 (a) $\left(P_g\right)_{tap} = \dfrac{25 \text{ m H}_2\text{O}}{} \left| \dfrac{101.3 \text{ kPa}}{10.33 \text{ m H}_2\text{O}} = \underline{\underline{245 \text{ kPa}}}\right.$

$\left(P_g\right)_{junction} = \dfrac{(25+5) \text{ m H}_2\text{O}}{} \left| \dfrac{101.3 \text{ kPa}}{10.33 \text{ m H}_2\text{O}} = \underline{\underline{294 \text{ kPa}}}\right.$

(b) <u>Air in the line. (lowers average density of the water.)</u>

(c) <u>The line could be clogged, or there could be a leak between the junction and the tap.</u>

3.40 $P_{abs} = \underline{\underline{800 \text{ mm Hg}}}$

$P_{gauge} = \underline{\underline{25 \text{ mm Hg}}}$

$P_{atm} = 800 - 25 = \underline{\underline{775 \text{ mm Hg}}}$

3.41 (a) $P_1 + \rho_A g(h_1 + h_2) = P_2 + \rho_B g h_1 + \rho_C g h_2$

$$\Rightarrow \underline{\underline{P_1 - P_2 = (\rho_B - \rho_A)g h_1 + (\rho_C - \rho_A)g h_2}}$$

(b) $P_1 = 121 \text{ kPa} + \left[\dfrac{(1.0 - 0.792)\text{ g}}{\text{cm}^3} \left| \dfrac{981 \text{ cm}}{\text{s}^2} \right| 30.0 \text{ cm} + \dfrac{(1.37 - 0.792)\text{ g}}{\text{cm}^3} \left| \dfrac{981 \text{ cm}}{\text{s}^2} \right| 24.0 \text{ cm} \right]$

$$\times \left(\dfrac{1 \text{ dyne}}{1 \text{ g} \cdot \text{cm}/\text{s}^2} \right) \left(\dfrac{101.325 \text{ kPa}}{1.01325 \times 10^6 \text{ dynes}/\text{cm}^2} \right) = \underline{\underline{123.0 \text{ kPa}}}$$

3.42 **(a)** Say ρ_t (g/cm³) = density of toluene, ρ_m (g/cm³) = density of manometer fluid

$$\rho_t g(500 - h + R) = \rho_m g R \Rightarrow R = \dfrac{500 - h}{\dfrac{\rho_m}{\rho_t} - 1}$$

(i) Hg: $\rho_t = 0.866$, $\rho_m = 13.6$, $h = 150$ cm $\Rightarrow R = \underline{\underline{23.8 \text{ cm}}}$

(ii) H₂O: $\rho_t = 0.866$, $\rho_m = 1.00$, $h = 150$ cm $\Rightarrow R = \underline{\underline{2260 \text{ cm}}}$

Use mercury, because the water manometer would have to be too tall.

(b) If the manometer were simply filled with toluene, the level in the glass tube would be at the level in the tank.
Advantages of using mercury: smaller manometer; less evaporation.

(c) The nitrogen blanket is used to avoid contact between toluene and atmospheric oxygen, minimizing the risk of combustion.

3.43 $P_{atm} = \rho_f g(7.23 \text{ m}) \Rightarrow \rho_f = \dfrac{P_{atm}}{7.23 \text{ g}}$

$$P_a - P_b = (\rho_f - \rho_w) g(26 \text{ cm}) = \left(\dfrac{P_{atm}}{7.23 \text{ m}} - \rho_w g \right)(26 \text{ cm})$$

$$= \left(\dfrac{756 \text{ mmHg}}{7.23 \text{ m}} \left| \dfrac{1 \text{ m}}{100 \text{ cm}} - \dfrac{1000 \text{ kg}}{\text{m}^3} \right| \dfrac{9.81 \text{ m/s}^2}{} \left| \dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \dfrac{760 \text{ mmHg}}{1.01325 \times 10^5 \text{ N/m}^2} \left| \dfrac{1 \text{ m}}{100 \text{ cm}} \right. \right) (26 \text{ cm})$$

$$\Rightarrow \underline{\underline{P_a - P_b = 8.1 \text{ mm Hg}}}$$

3.44 (a) $\Delta h = 900 - h_1 = \dfrac{7.5 \text{ psi}}{} \left| \dfrac{760 \text{ mm Hg}}{14.696 \text{ psi}} = 388 \text{ mm Hg} \Rightarrow h_1 = 900 - 388 = \underline{\underline{512 \text{ mm}}}$

(b) $\Delta h = 388 - 25 \times 2 = 338 \text{ mm} \Rightarrow P_g = \dfrac{338 \text{ mm Hg}}{} \left| \dfrac{14.696 \text{ psi}}{760 \text{ mm Hg}} = \underline{\underline{6.54 \text{ psig}}}$

3.45 (a) $h = L \sin\theta$

(b) $h = (8.7 \text{ cm})\sin(15°) = 2.3 \text{ cm H}_2\text{O} = \underline{\underline{23 \text{ mm H}_2\text{O}}}$

3.46 (a) $P = P_{atm} - P_{oil} - P_{Hg}$

$$= 765 - 365 - \frac{920 \text{ kg}}{\text{m}^3} \left| \frac{9.81 \text{ m/s}^2}{} \right| \frac{0.10 \text{ m}}{} \left| \frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2} \right| \frac{760 \text{ mm Hg}}{1.01325\times 10^5 \text{ N/m}^2}$$

$= \underline{\underline{393 \text{ mm Hg}}}$

(b) — Nonreactive with the vapor in the apparatus.
— Lighter than and immiscible with mercury.
— Low rate of evaporation (low volatility).

3.47 (a) Let ρ_f = manometer fluid density (1.10 g/cm^3), ρ_{ac} = acetone density (0.791 g/cm^3)

Differential manometer formula: $\Delta P = (\rho_f - \rho_{ac})gh$

$$\Delta P (\text{mm Hg}) = \frac{(1.10 - 0.791)\text{g}}{\text{cm}^3} \left| \frac{981 \text{ cm}}{\text{s}^2} \right| \frac{h \text{ (mm)}}{} \left| \frac{1 \text{ cm}}{10 \text{ mm}} \right| \frac{1 \text{ dyne}}{1 \text{ g}\cdot\text{cm/s}^2} \left| \frac{760 \text{ mm Hg}}{1.01325\times 10^6 \text{ dyne/cm}^2} \right.$$

$= 0.02274 \text{ h(mm)}$

$\dot{V}(\text{mL/s})$	62	87	107	123	138	151
$h(\text{mm})$	5	10	15	20	25	30
$\Delta P(\text{mm Hg})$	0.114	0.227	0.341	0.455	0.568	0.682

(b) $\ln\dot{V} = n\ln(\Delta P) + \ln K$
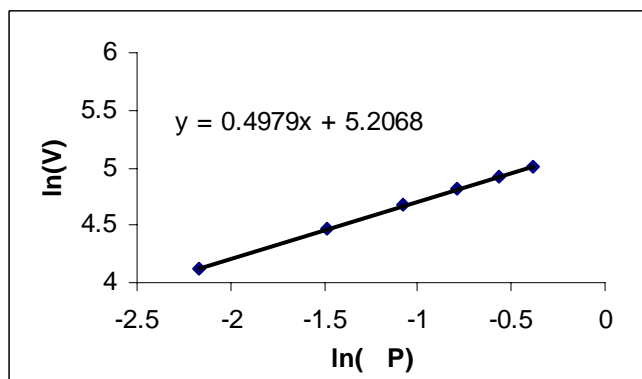
From the plot above, $\ln\dot{V} = 0.4979 \ln(\Delta P) + 5.2068$

$\Rightarrow \underline{\underline{n = 0.4979 \approx 0.5}}$, $\ln K = 5.2068 \Rightarrow \underline{\underline{K = 183 \frac{\text{ml/s}}{(\text{mm Hg})^{0.5}}}}$

3.47 (cont'd)

(c) $h = 23 \Rightarrow \Delta P = (0.02274)(23) = 0.523 \text{ mm Hg} \Rightarrow \dot{V} = 183(0.523)^{0.5} = \underline{\underline{132 \text{ mL/s}}}$

$$\frac{132 \text{ mL}}{\text{s}} \left| \frac{0.791 \text{ g}}{\text{mL}} = \underline{\underline{104 \text{ g/s}}} \qquad \frac{104 \text{ g}}{\text{s}} \right| \frac{1 \text{ mol}}{58.08 \text{ g}} = \underline{\underline{1.80 \text{ mol/s}}}$$

3.48 (a) $T = 85°\text{F} + 459.7 = \underline{\underline{544°\text{R}}} / 1.8 = \underline{\underline{303 \text{ K}}} - 273 = \underline{\underline{30°\text{C}}}$

(b) $T = -10°\text{C} + 273 = \underline{\underline{263 \text{ K}}} \times 1.8 = \underline{\underline{474°\text{R}}} - 460 = \underline{\underline{14°\text{F}}}$

(c) $\Delta T = \dfrac{85°\text{C}}{} \left| \dfrac{1.0°\text{K}}{1.0°\text{C}} = \underline{\underline{85°\text{K}}}; \qquad \dfrac{85°\text{C}}{} \right| \dfrac{1.8°\text{F}}{1°\text{C}} = \underline{\underline{153°\text{F}}}; \qquad \dfrac{85°\text{C}}{} \left| \dfrac{1.8°\text{R}}{1.0°\text{C}} = \underline{\underline{153°\text{R}}} \right.$

(d) $\dfrac{150°\text{R}}{} \left| \dfrac{1°\text{F}}{1°\text{R}} = \underline{\underline{150°\text{F}}}; \qquad \dfrac{150°\text{R}}{} \right| \dfrac{1.0°\text{K}}{1.8°\text{R}} = \underline{\underline{83.3°\text{K}}}; \qquad \dfrac{150°\text{R}}{} \left| \dfrac{1.0°\text{C}}{1.8°\text{R}} = \underline{\underline{83.3°\text{C}}} \right.$

3.49 (a) $T = 0.0940 \times 1000°\text{FB} + 4.00 = 98.0°\text{C} \Rightarrow \text{T} = 98.0 \times 1.8 + 32 = \underline{\underline{208°\text{F}}}$

(b) $\Delta T \, (°\text{C}) = 0.0940 \Delta T \, (°\text{FB}) = \underline{\underline{0.94°\text{C}}} \Rightarrow \Delta T \, (\text{K}) = \underline{\underline{0.94 \text{ K}}}$

$$\Delta T \, (°\text{F}) = \frac{0.94°\text{C}}{} \left| \frac{1.8°\text{F}}{1.0°\text{C}} = \underline{\underline{1.69°\text{F}}} \Rightarrow \Delta T \, (°\text{R}) = \underline{\underline{1.69°\text{R}}} \right.$$

(c) $T_1 = 15°\text{C} \Rightarrow 100°\text{L}; \quad T_2 = 43°\text{C} \Rightarrow 1000°\text{L}$

$T \, (°\text{C}) = aT \, (°\text{L}) + b$

$$a = \frac{(43 - 15)°\text{C}}{(1000 - 100)°\text{L}} = 0.0311 \left(\frac{°\text{C}}{°\text{L}} \right); \qquad b = 15 - 0.0311 \times 100 = 11.9°\text{C}$$

$\Rightarrow \quad \underline{\underline{T \, (°\text{C}) = 0.0311T \, (°\text{L}) + 11.9}} \quad \text{and}$

$$T \, (°\text{L}) = \frac{1}{0.0311} \left[0.0940T(°\text{FB}) + 4.00 - 11.9 \right] = \underline{\underline{3.023T(°\text{FB}) - 254}}$$

(d) $T_{bp} = -88.6°\text{C} \Rightarrow \underline{\underline{184.6 \text{ K}}} \Rightarrow \underline{\underline{332.3°\text{R}}} \Rightarrow \underline{\underline{-127.4°\text{F}}} \Rightarrow \underline{\underline{-985.1°\text{FB}}} \Rightarrow \underline{\underline{-3232°\text{L}}}$

(e) $\Delta T = 50.0°\text{L} \Rightarrow \underline{\underline{1.56°\text{C}}} \Rightarrow \underline{\underline{16.6°\text{FB}}} \Rightarrow \underline{\underline{1.56 \text{ K}}} \Rightarrow \underline{\underline{2.8°\text{F}}} \Rightarrow \underline{\underline{2.8°\text{R}}}$

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

(a) $V(mV) = aT(°C) + b$

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

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

$\Downarrow$

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

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

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

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

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

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

(c) Extrapolation error, thermocouple reading wrong.

3.52 (a) $PV = 0.08206nT$

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

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

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

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

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

3.52 (cont'd)

(b) $n'_{tot} = \dfrac{(500+14.696)\times 3.5}{10.73\times(85+459.7)} = \underline{\underline{0.308 \text{ lb-mole}}}$

$$m_{CO} = \dfrac{0.308 \text{ lb-mole}}{} \left| \dfrac{0.30 \text{ lb-mole CO}}{\text{lb-mole}} \right| \dfrac{28 \text{ lb}_m \text{ CO}}{\text{lb-mole CO}} = \underline{\underline{2.6 \text{ lb}_m \text{ CO}}}$$

(c) $T' = \dfrac{(3000+14.696)\times 3.5}{10.73\times 0.308} - 459.7 = \underline{\underline{2733^\circ \text{F}}}$

3.53 (a) $T(^\circ\text{C}) = a\times r(\text{ohms}) + b$

$\left.\begin{array}{l} 0 = 23.624a + b \\ 100 = 33.028a + b \end{array}\right\} \Rightarrow \begin{array}{l} a = 10.634 \\ b = -251.22 \end{array} \Rightarrow \underline{\underline{T(^\circ\text{C}) = 10.634r(\text{ohms}) - 251.22}}$

(b) $\dot{n}\left(\dfrac{\text{kmol}}{\text{s}}\right) = \dfrac{\dot{n}' \text{ (kmol)}}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} = \dfrac{\dot{n}'}{60}\right.$

$P(\text{atm}) = \dfrac{P'(\text{mm Hg})}{} \left| \dfrac{1 \text{ atm}}{760 \text{ mm Hg}} = \dfrac{P'}{760} \right.$, $T(\text{K}) = T'(^\circ\text{C}) + 273.16$

$\dot{V}\left(\dfrac{\text{m}^3}{\text{s}}\right) = \dot{V}' \dfrac{\text{m}^3}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} = \dfrac{\dot{V}'}{60} \right.$

$\dfrac{\dot{n}'}{60} = \dfrac{12.186}{} \left| \dfrac{P'}{760} \right| \dfrac{}{T'+273.16} \left| \dfrac{\dot{V}'}{60} \right. \Rightarrow \underline{\underline{\dot{n}' = \dfrac{0.016034 P'(\text{mm Hg})\dot{V}'(\text{m}^3/\text{min})}{T'(^\circ\text{C})+273.16}}}$

(c) $T = 10.634r - 251.22$

$$r_1 = 26.159 \Rightarrow \underline{\underline{T_1 = 26.95^\circ \text{C}}}$$
$$\Rightarrow r_2 = 26.157 \Rightarrow \underline{\underline{T_2 = 26.93^\circ \text{C}}}$$
$$r_3 = 44.789 \Rightarrow \underline{\underline{T_3 = 225.1^\circ \text{C}}}$$

$$P \text{ (mm Hg)} = h + P_{atm} = h + (29.76 \text{ in Hg})\left(\dfrac{760 \text{ mm Hg}}{29.92 \text{ in Hg}}\right) = h + 755.9$$

$$h_1 = 232 \text{ mm} \Rightarrow \underline{\underline{P_1 = 987.9 \text{ mm Hg}}}$$
$$\Rightarrow h_2 = 156 \text{ mm} \Rightarrow \underline{\underline{P_2 = 911.9 \text{ mm Hg}}}$$
$$h_3 = 74 \text{ mm} \Rightarrow \underline{\underline{P_3 = 829.9 \text{ mm Hg}}}$$

3.53 (cont'd)

(d) $\dot{n}_1 = \dfrac{(0.016034)(987.9)(947/60)}{26.95+273.16} = 0.8331 \text{ kmol } CH_4/\text{min}$

$\dot{n}_2 = \dfrac{(0.016034)(911.9)(195)}{26.93+273.16} = 9.501 \text{ kmol } air/\text{min}$

$\dot{n}_3 = \dot{n}_1 + \dot{n}_2 = \underline{\underline{10.33 \text{ kmol/min}}}$

(e) $V_3 = \dfrac{\dot{n}_3(T_2+273.16)}{0.016034\, P_3} = \dfrac{(10.33)(225.1+273.16)}{(0.016034)(829.9)} = \underline{\underline{387 \text{ m}^3/\text{min}}}$

(f) $\dfrac{0.8331 \text{ kmol } CH_4}{\text{min}} \left| \dfrac{16.04 \text{ kg } CH_4}{\text{kmol}} = 13.36\dfrac{\text{kg } CH_4}{\text{min}} \right.$

$\dfrac{0.21\times 9.501 \text{ kmol } O_2}{\text{min}} \left| \dfrac{32.0 \text{ kg } O_2}{\text{kmol } O_2} \right. + \dfrac{0.79\times 9.501 \text{ kmol } N_2}{\text{min}} \left| \dfrac{28.0 \text{ kg } N_2}{\text{kmol } N_2} = 274 \dfrac{\text{kg air}}{\text{min}} \right.$

$x_{CH_4} = \dfrac{13.36 \text{ kg } CH_4/\text{min}}{(13.36+274) \text{ kg } / \text{min}} = \underline{\underline{0.0465 \text{ kg } CH_4/\text{kg}}}$

3.54
```
REAL, MW, T, SLOPE, INTCPT, KO, E
REAL TIME (100), CA (100), TK (100), X (100), Y(100)
INTEGER IT, N, NT, J
READ (5,*) MW, NT
DO 10 IT=1, NT
    READ (5,*) TC, N
    TK(IT) = TC + 273.15
    READ (5,*) (TIME (J), CA (J), J = 1, N)
    DO 1 J=1, N
      CA(J) = CA(J) / MW
      X(J) = TIME(J)
      Y(J) = 1./CA(J)
1       CONTINUE
    CALL LS (X, Y, N, SLOPE, INTCPT)
    K(IT) = SLOPE
    WRITE (E, 2) TK (IT), (TIME (J), CA (J), J = 1, N)
    WRITE (6, 3) K (IT)
10  CONTINUE
    DO 4 J=1, NT
      X(J) = 1./TK(J)
      Y(J) = LOG(K(J))
```

3.54 (cont'd)

```
4   CONTINUE
    CALL LS (X, Y, NT, SLOPE, INTCPT)
    KO = EXP(INTCPT)

    E = –8.314 = SLOPE
    WRITE (6, 5) KO, E
2   FORMAT (' TEMPERATURE (K):  ', F6.2, /
        * ' TIME  CA', /,
        * ' (MIN)  (MOLES)', /
        * 100 (IX, F5.2, 3X, F7.4, /))
3   FORMAT (' K (L/MOL – MIN):  ', F5.3, //)
5   FORMAT (/, ' KO (L/MOL – MIN) : ', E 12.4, /, ' E (J/MOL):  ', E 12.4)
    END
    SUBROUTINE LS (X, Y, N, SLOPE, INTCPT)
    REAL X(100), Y(100), SLOPE, INTCPT, SX, SY, SXX, SXY, AN
    INTEGER N, J
    SX=0
    SY=0
    SXX=0
    SXY=0
    DO 10 J=1,N
        SX = SX + X(J)
        SY = SY + Y(J)
        SXX = SXX + X(J)**2
        SXY = SXY + X(J)*Y(J)
10  CONTINUE
    AN = N
    SX = SX/AN
    SY = SY/AN
    SXX = SXX/AN
    SXY = SXY/AN
    SLOPE = (SXY – SX*SY)/(SXX – SX**2)
    INTCPT = SY – SLOPE*SX
    RETURN
    END
```

$ DATA		[OUTPUT]
65.0	4	TEMPERATURE (K): 367.15
94.0	6	TIME CA
10.0	8.1	(MIN) (MOLS/L)
20.0	4.3	10.00 0.1246
30.0	3.0	20.00 0.0662
40.0	2.2	30.00 0.0462
50.0	1.8	40.00 0.0338

3.54 (cont'd)

60.0	1.5	50.00 0.0277
		60.00 0.0231

$$K(L/MOL \cdot MIN): \ 0.707 \quad (\text{at } 94°C)$$

110.	6
10.0	3.5
20.0	1.8
30.0	1.2
40.0	0.92
50.0	0.73
60.0	0.61
127.	6

TEMPERATURE (K): 383.15

⋮

$$K(L/MOL \cdot MIN): \ 1.758$$

⋮

⋮

⋮ ETC

$$K0(L/MOL-MIN): \ 0.2329E+10$$

$$E (J/MOL): \ 0.6690E+05$$

CHAPTER FOUR

4.1 **a.** <u>Continuous, Transient</u>

b. Input – Output = Accumulation
No reactions $\Rightarrow$ Generation = 0, Consumption = 0

$$6.00\frac{kg}{s} - 3.00\frac{kg}{s} = \frac{dn}{dt} \Rightarrow \underline{\frac{dn}{dt} = 3.00\frac{kg}{s}}$$

c.
$$t = \frac{1.00\,m^3}{}\left|\frac{1000\,kg}{1\,m^3}\right|\frac{1\,s}{3.00\,kg} = \underline{\underline{333\,s}}$$

4.2 **a.** <u>Continuous, Steady State</u>

b. $k = 0 \Rightarrow \underline{C_A = C_{A0}}$ $k = \infty \Rightarrow \underline{C_A = 0}$

c. Input – Output – Consumption = 0
Steady state $\Rightarrow$ Accumulation = 0
A is a reactant $\Rightarrow$ Generation = 0

$$\dot{V}\left(\frac{m^3}{s}\right)C_{A0}\left(\frac{mol}{m^3}\right) = \dot{V}\left(\frac{m^3}{s}\right)C_A\left(\frac{mol}{m^3}\right) + kVC_A\left(\frac{mol}{s}\right) \Rightarrow \underline{\underline{C_A = \frac{C_{A0}}{1 + \frac{kV}{\dot{V}}}}}$$

4.3 **a.**

$$\begin{array}{l}
100\,kg/h \\
0.550\,kg\,B/kg \\
0.450\,kg\,T/kg
\end{array}
\quad\rightarrow\quad
\begin{array}{l}
\dot{m}_v\,(kg/h) \\
0.850\,kg\,B/kg \\
0.150\,kg\,T/kg \\
\dot{m}_l\,(kg/h) \\
0.106\,kg\,B/kg \\
0.894\,kg\,T/kg
\end{array}$$

Input – Output = 0
Steady state $\Rightarrow$ Accumulation = 0
No reaction $\Rightarrow$ Generation = 0, Consumption = 0
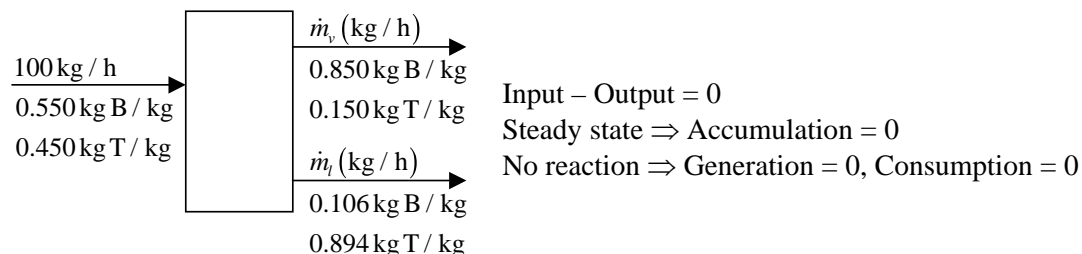
(1) Total Mass Balance: $100.0\ kg/h = \dot{m}_v + \dot{m}_l$

(2) Benzene Balance: $[0.550 \times 100.0]\ kg\,B/h = 0.850\dot{m}_v + 0.106\dot{m}_l$

Solve (1) & (2) simultaneously $\Rightarrow \underline{\dot{m}_v = 59.7\,kg/h,\ \dot{m}_l = 40.3\,kg/h}$

b. The flow chart is identical to that of (a), except that mass flow rates (kg/h) are replaced by masses (kg). The balance equations are also identical (initial input = final output).

c. Possible explanations $\Rightarrow$ a chemical reaction is taking place, the process is not at steady state, the feed composition is incorrect, the flow rates are not what they are supposed to be, other species are in the feed stream, measurement errors.

4.4 **b.** $\dfrac{n\,(\text{mol})}{\substack{\text{0.500 mol N}_2/\text{mol}\\ \text{0.500 mol CH}_4/\text{mol}}}\longrightarrow$

$\dfrac{0.500n\,(\text{mol N}_2)}{}\left|\dfrac{28\text{ g N}_2}{\text{mol N}_2}\right|\dfrac{1\,\text{kg}}{1000\,\text{g}}=\underline{\underline{0.014n\,(\text{kg N}_2)}}$

c. $\dfrac{100.0\text{ g / s}}{\substack{x_E\,(\text{g C}_2\text{H}_6/\text{g})\\ x_P\,(\text{g C}_3\text{H}_8/\text{g})\\ x_B\,(\text{g C}_4\text{H}_{10}/\text{g})}}\longrightarrow$

$\dot{n}_E=\dfrac{100x_E\,(\text{g C}_2\text{H}_6)}{\text{s}}\left|\dfrac{1\text{ lb}_m}{453.593\,\text{g}}\right|\dfrac{\text{lb - mole C}_2\text{H}_6}{30\,\text{lb}_m\ \text{C}_2\text{H}_6}\left|\dfrac{3600\text{ s}}{\text{h}}\right.$

$\qquad=\underline{\underline{26.45x_E\,(\text{lb - mole C}_2\text{H}_6\,/\,\text{h})}}$

d. $\dfrac{\dot{n}_1\,(\text{lb - mole H}_2\text{O/s})}{\left\{\substack{\dot{n}_2\,(\text{lb - mole DA/s})\\ 0.21\ \text{lb - mole O}_2/\text{lb - mole DA}\\ 0.79\ \text{lb - mole N}_2/\text{lb - mole DA}}\right.}\longrightarrow$

$\dot{n}_{O_2}=\underline{\underline{0.21\dot{n}_2\,(\text{lb-mole O}_2\,/\,\text{s})}}$

$x_{\text{H}_2\text{O}}=\underline{\underline{\dfrac{\dot{n}_1}{\dot{n}_1+\dot{n}_2}\left(\dfrac{\text{lb-mole H}_2\text{O}}{\text{lb-mole}}\right)}}$

$x_{\text{O}_2}=\underline{\underline{\dfrac{0.21\dot{n}_2}{\dot{n}_1+\dot{n}_2}\left(\dfrac{\text{lb-mole O}_2}{\text{lb-mole}}\right)}}$

e. $\dfrac{n\,(\text{mol})}{\substack{\text{0.400 mol NO/mol}\\ y_{\text{NO}_2}\,(\text{mol NO}_2/\text{mol})\\ 0.600-y_{\text{NO}_2}\,(\text{mol N}_2\text{O}_4/\text{mol})}}\longrightarrow$

$n_{\text{N}_2\text{O}_4}=n\left[0.600-y_{\text{NO}_2}\right](\text{mol N}_2\text{O}_4)$

4.5 **a.** Basis: 1000 lb$_m$ C$_3$H$_8$ / h fresh feed
(Could also take 1 h operation as basis -
flow chart would be as below except
that all / h would be deleted.)

Note: the compressor and the off gas from
the absorber are not mentioned explicitly
in the process description, but their presence
should be inferred.
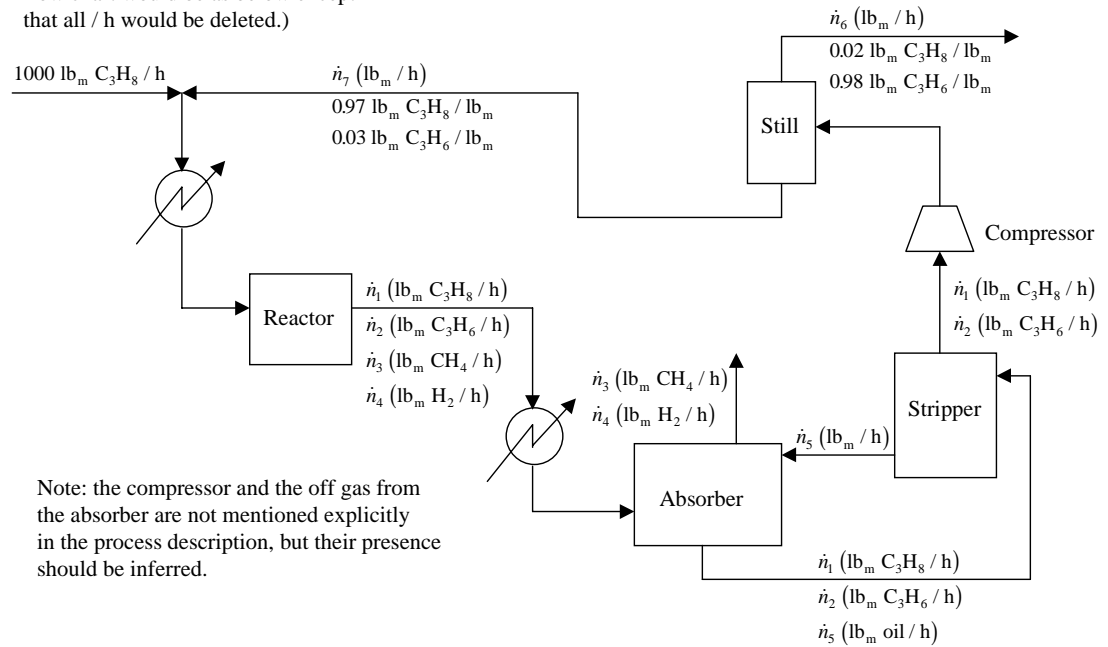
4.5 (cont'd)

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

4.6   **a.**   <u>3 independent balances</u> (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
         <u>– 2 mole fraction summations</u>
           2 unknowns must be specified

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

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

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

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

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

4.7   **a.**   <u>3 independent balances</u> (one for each species)

    b.
         <u>Water Balance</u>: $\dfrac{400\,g}{\text{min}} \bigg| \dfrac{0.885\,\text{g H}_2\text{O}}{g} = \dfrac{\underline{\underline{\dot{m}_R}}(g)}{(\text{min})} \bigg| \dfrac{0.995\,\text{g H}_2\text{O}}{g} \Rightarrow \underline{\underline{\dot{m}_R = 356\,g/\text{min}}}$

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

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

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

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

4.7 (cont'd)

    d.

4.8   **a.**
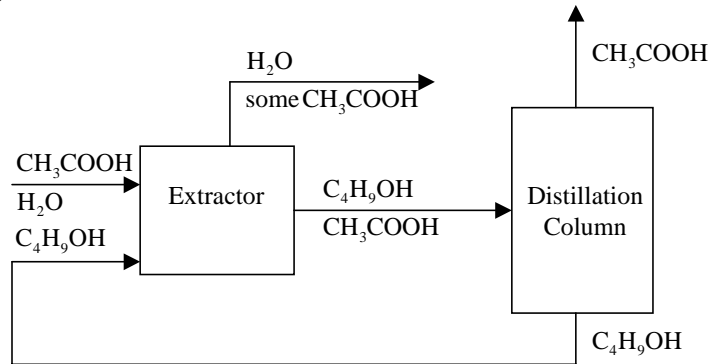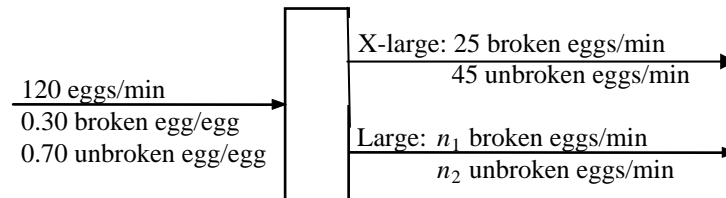
    b. $120 = 25 + 45 + n_1 + n_2 \ (\text{eggs}/\text{min}) \Rightarrow \underline{\underline{n_1 + n_2 = 50}}$ $\left.\begin{array}{c} \\ \\ \end{array}\right\}$ $\underline{\underline{n_1 = 11}}$

        $\underline{\underline{(0.30)(120) = 25 + n_1}}$ $\Rightarrow \underline{\underline{n_2 = 39}}$

    c. $n_1 + n_2 = \underline{\underline{50 \ \text{large eggs}/\text{min}}}$

        n_1 large eggs broken/50 large eggs $= (11/50) = \underline{\underline{0.22}}$

    d.   22% of the large eggs (right hand) and $(25/70) \Rightarrow 36\%$ of the extra-large eggs (left hand)

        are broken. Since it does not require much strength to break an egg, the left hand is probably

        poorly controlled (rather than strong) relative to the right. Therefore, Fred is <u>right-handed</u>.

4.9   **a.**
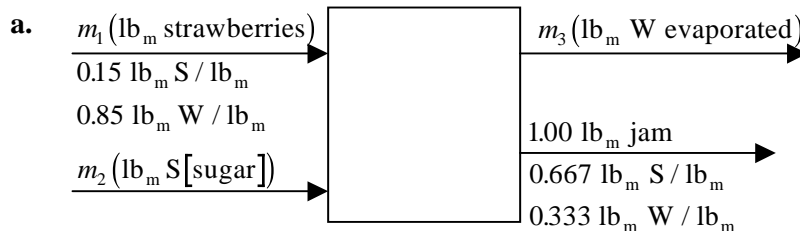
    b.   3 unknowns (m_1, m_2, m_3)

        – 2 balances

        <u>– 1 feed ratio</u>

          0 DF

    c.   Feed ratio: $m_1 / m_2 = 45/55$ (1)

        S balance: $0.15m_1 + m_2 = 0.667$ (2)

        Solve simultaneously $\Rightarrow m_1 = \underline{\underline{0.49 \ \text{lb}_m \ \text{strawberries}}}, \ m_2 = \underline{\underline{0.59 \ \text{lb}_m \ \text{sugar}}}$

4.10 a.

$$\begin{array}{l} \underline{300\,\text{gal}} \\ m_1\,(\text{lb}_\text{m}) \\ 0.750\,\text{lb}_\text{m}\,C_2H_5OH\,/\,\text{lb}_\text{m} \\ 0.250\,\text{lb}_\text{m}\,H_2O\,/\,\text{lb}_\text{m} \end{array}$$

$$\begin{array}{l} m_3\,(\text{lb}_\text{m}) \\ 0.600\,\text{lb}_\text{m}\,C_2H_5OH\,/\,\text{lb}_\text{m} \\ 0.400\,\text{lb}_\text{m}\,H_2O\,/\,\text{lb}_\text{m} \end{array}$$

$$\begin{array}{l} \underline{V_{40}\,(\text{gal})} \\ m_2\,(\text{lb}_\text{m}) \\ 0.400\,\text{lb}_\text{m}\,C_2H_5OH\,/\,\text{lb}_\text{m} \\ 0.600\,\text{lb}_\text{m}\,H_2O\,/\,\text{lb}_\text{m} \end{array}$$

4 unknowns (m_1, m_2, V_{40}, m_3)
$-$ 2 balances
$\underline{-\text{ 2 specific gravities}}$
0 DF

b.

$$m_1 = \frac{300\,\text{gal}}{}\left|\frac{1\,\text{ft}^3}{7.4805\,\text{gal}}\right|\frac{0.877 \times 62.4\,\text{lb}_\text{m}}{\text{ft}^3} = 2195\,\text{lb}_\text{m}$$

<u>Overall balance:</u> $m_1 + m_2 = m_3$ (1)

<u>C₂H₅OH balance:</u> $0.750m_1 + 0.400m_2 = 0.600m_3$ (2)

Solve (1) & (2) simultaneously $\Rightarrow m_2 = 1646\,\text{lb}_\text{m}, m_3 = 3841\,\text{lb}_\text{m}$

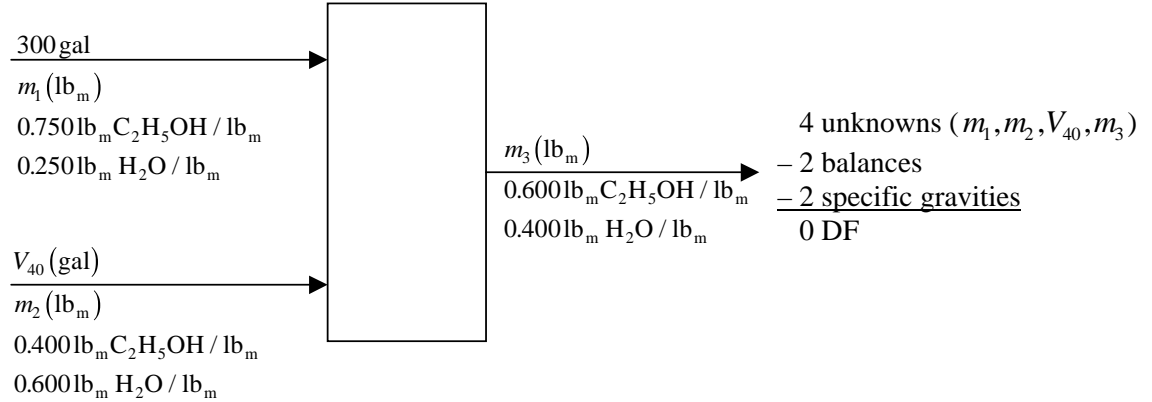$$V_{40} = \frac{1646\,\text{lb}_\text{m}}{}\left|\frac{\text{ft}^3}{0.952 \times 62.4\,\text{lb}_\text{m}}\right|\frac{7.4805\,\text{gal}}{1\,\text{ft}^3} = \underline{\underline{207\,\text{gal}}}$$

4.11 a.

$$\begin{array}{l} \underline{\dot{n}_1\,(\text{mol}/\text{s})} \\ 0.0403\,\text{mol}\,C_3H_8\,/\,\text{mol} \\ 0.9597\,\text{mol air}\,/\,\text{mol} \end{array}$$

$$\begin{array}{l} \dot{n}_3\,(\text{mol}/\text{s}) \\ 0.0205\,\text{mol}\,C_3H_8\,/\,\text{mol} \\ 0.9795\,\text{mol air}\,/\,\text{mol} \end{array}$$

$$\begin{array}{l} \underline{\dot{n}_2\,(\text{mol air}/\text{s})} \\ 0.21\,\text{mol}\,O_2\,/\,\text{mol} \\ 0.79\,\text{mol}\,N_2\,/\,\text{mol} \end{array}$$

3 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_3)$
$\underline{-\text{ 2 balances}}$
1 DF
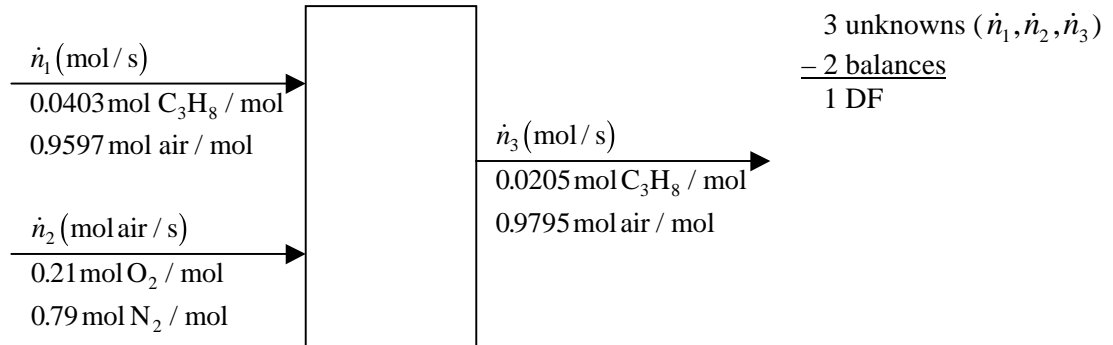
b. <u>Propane feed rate:</u> $0.0403\dot{n}_1 = 150 \Rightarrow \dot{n}_1 = 3722\,(\text{mol}/\text{s})$

<u>Propane balance:</u> $0.0403\dot{n}_1 = 0.0205\dot{n}_3 \Rightarrow \dot{n}_3 = 7317\,(\text{mol}/\text{s})$

<u>Overall balance:</u> $3722 + \dot{n}_2 = 7317 \Rightarrow \underline{\underline{\dot{n}_2 = 3600\,(\text{mol}/\text{s})}}$

c. $\underline{\geq}$. The dilution rate should be greater than the value calculated to ensure that ignition is not possible even if the fuel feed rate increases slightly.

4.12 a.

1000 kg / h
0.500 kg CH_3OH / kg
0.500 kg H_2O / kg

$\dot{m}$(kg / h)
0.960 kg CH_3OH / kg
0.040 kg H_2O / kg

673 kg / h
x (kg CH_3OH / kg)
$1-x$ (kg H_2O / kg)

2 unknowns ($\dot{m}, x$)
– 2 balances
0 DF
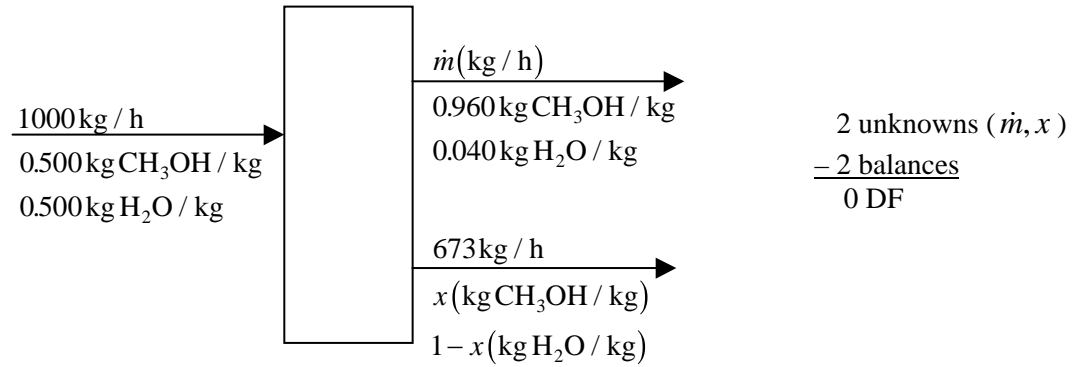
b. Overall balance: $1000 = \dot{m} + 673 \Rightarrow \dot{m} = 327$ kg / h

Methanol balance: $0.500(1000) = 0.960(327) + x(673) \Rightarrow x = 0.276$ kg CH_3OH / kg

Molar flow rates of methanol and water:

$$\frac{673\,kg}{h}\bigg|\frac{0.276\,kg\,CH_3OH}{kg}\bigg|\frac{1000\,g}{kg}\bigg|\frac{mol\,CH_3OH}{32.0\,g\,CH_3OH} = 5.80 \times 10^3 \text{ mol } CH_3OH / h$$

$$\frac{673\,kg}{h}\bigg|\frac{0.724\,kg\,H_2O}{kg}\bigg|\frac{1000\,g}{kg}\bigg|\frac{mol\,H_2O}{18\,g\,H_2O} = 2.71 \times 10^4 \text{ mol } H_2O / h$$

Mole fraction of Methanol:

$$\frac{5.80 \times 10^3}{5.80 \times 10^3 + 2.71 \times 10^4} = 0.176 \text{ mol } CH_3OH / mol$$

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.

Feed
2253 kg

Reactor

Reactor effluent
2253 kg
R = 388

Purifier

Product
1239 kg
R = 583

Waste
m_w (kg)
R = 140

Analyzer Calibration Data

$x_p = 0.000145R^{1.364546}$
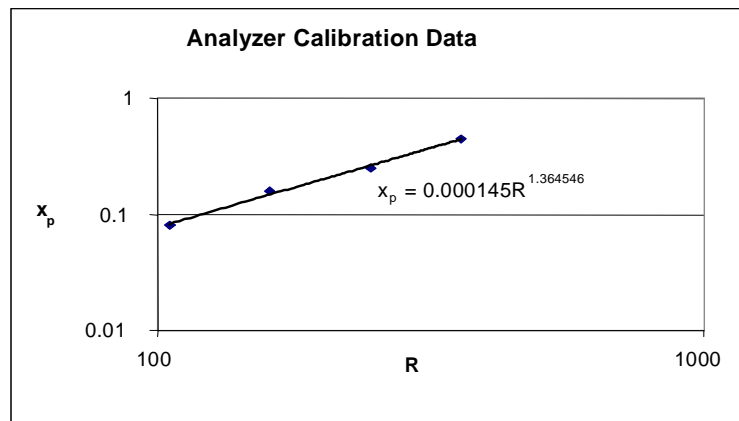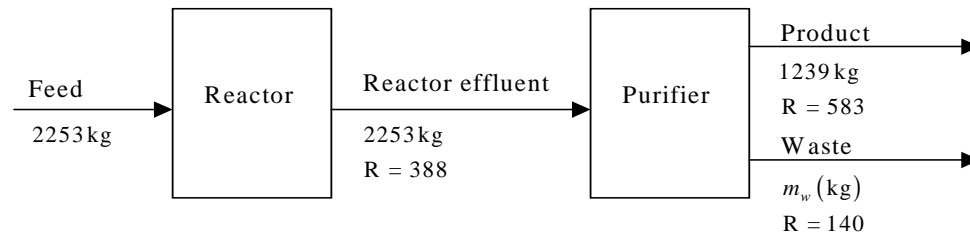
4.13 (cont'd)

b. Effluent: $x_p = 0.000145(388)^{1.3645} = 0.494\,\text{kg P} / \text{kg}$

Product: $x_p = 0.000145(583)^{1.3645} = 0.861\,\text{kg P} / \text{kg}$

Waste: $x_p = 0.000145(140)^{1.3645} = 0.123\,\text{kg P} / \text{kg}$

Efficiency $= \dfrac{0.861(1239)}{0.494(2253)} \times 100\% = 95.8\%$

c. Mass balance on purifier: $2253 = 1239 + m_w \Rightarrow m_w = 1014\,\text{kg}$
P balance on purifier:

Input: $(0.494\,\text{kg P} / \text{kg})(2253\,\text{kg}) = 1113\,\text{kg P}$

Output: $(0.861\,\text{kg P} / \text{kg})(1239\,\text{kg}) + (0.123\,\text{kg P} / \text{kg})(1014\,\text{kg}) = 1192\,\text{kg P}$

The P balance does not close . Analyzer readings are wrong; impure feed; extrapolation
beyond analyzer calibration data is risky -- recalibrate; get data for R > 583; not at steady
state; additional reaction occurs in purifier; normal data scatter.

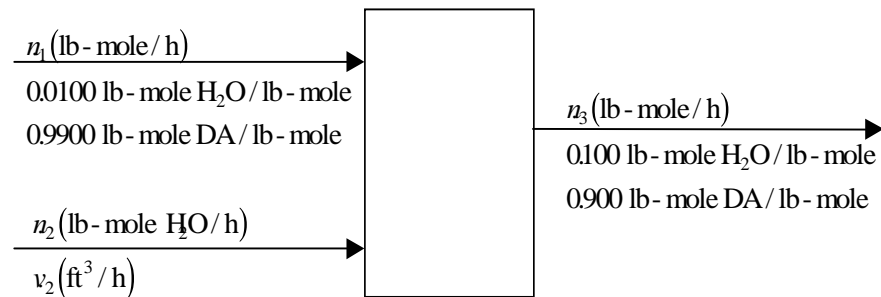**4.14   a.**

$n_1\,(\text{lb-mole}/\text{h})$
0.0100 lb-mole H_2O/lb-mole
0.9900 lb-mole DA/lb-mole

$n_2\,(\text{lb-mole } H_2O/\text{h})$
$v_2\,(\text{ft}^3/\text{h})$

$n_3\,(\text{lb-mole}/\text{h})$
0.100 lb-mole H_2O/lb-mole
0.900 lb-mole DA/lb-mole

4 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{v})$ – 2 balances – 1 density – 1 meter reading = 0 DF

Assume linear relationship: $\dot{v} = aR + b$

Slope: $a = \dfrac{\dot{v}_2 - \dot{v}_1}{R_2 - R_1} = \dfrac{96.9 - 40.0}{50 - 15} = 1.626$

Intercept: $b = \dot{v}_a - aR_1 = 40.0 - 1.626(15) = 15.61$

$\dot{v}_2 = 1.626(95) + 15.61 = 170\,(\text{ft}^3 / \text{h})$

$\dot{n}_2 = \dfrac{170\,\text{ft}^3}{\text{h}}\left|\dfrac{62.4\,\text{lb}_m}{\text{ft}^3}\right|\dfrac{\text{lb-mol}}{18.0\,\text{lb}_m} = 589\,(\text{lb-moles } H_2O / \text{h})$

DA balance: $0.9900\dot{n}_1 = 0.900\dot{n}_3$ (1)
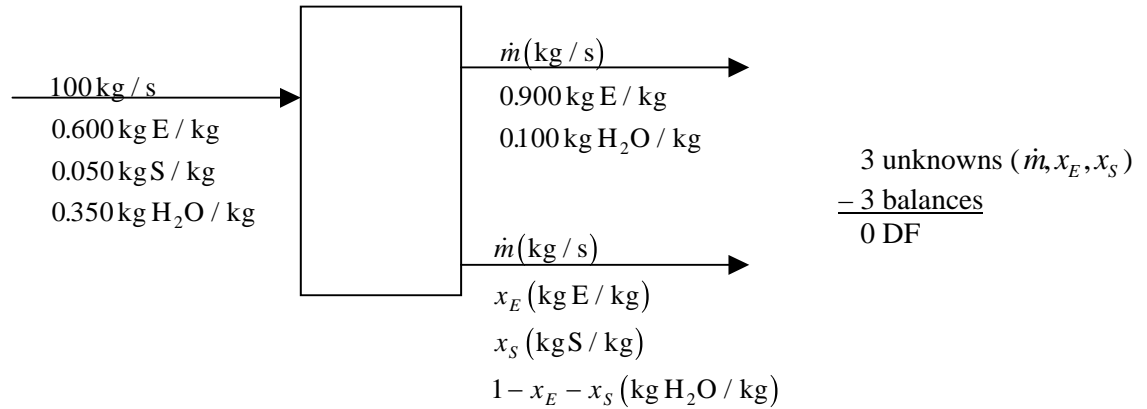
Overall balance: $\dot{n}_1 + \dot{n}_2 = \dot{n}_3$ (2)

Solve (1) & (2) simultaneously $\Rightarrow \dot{n}_1 = 5890\,\text{lb-moles} / \text{h}, \; \dot{n}_3 = 6480\,\text{lb-moles} / \text{h}$

b. Bad calibration data, not at steady state, leaks, 7% value is wrong, $\dot{v} - R$ relationship is not
linear, extrapolation of analyzer correlation leads to error.

4.15 **a.**

$$\dot{m}\,(\text{kg}/\text{s})$$
$$0.900 \text{ kg E} / \text{kg}$$
$$0.100 \text{ kg H}_2\text{O} / \text{kg}$$

$$\underline{100 \text{ kg} / \text{s}}$$
$$0.600 \text{ kg E} / \text{kg}$$
$$0.050 \text{ kg S} / \text{kg}$$
$$0.350 \text{ kg H}_2\text{O} / \text{kg}$$

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

$$\dot{m}\,(\text{kg}/\text{s})$$
$$x_E\,(\text{kg E} / \text{kg})$$
$$x_S\,(\text{kg S} / \text{kg})$$
$$1 - x_E - x_S\,(\text{kg H}_2\text{O} / \text{kg})$$

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

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

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

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

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

$$b = \frac{\ln(x_2 / x_1)}{\ln(R_2 / R_1)} = \frac{\ln(0.400 / 0.100)}{\ln(38 / 15)} = 1.491$$
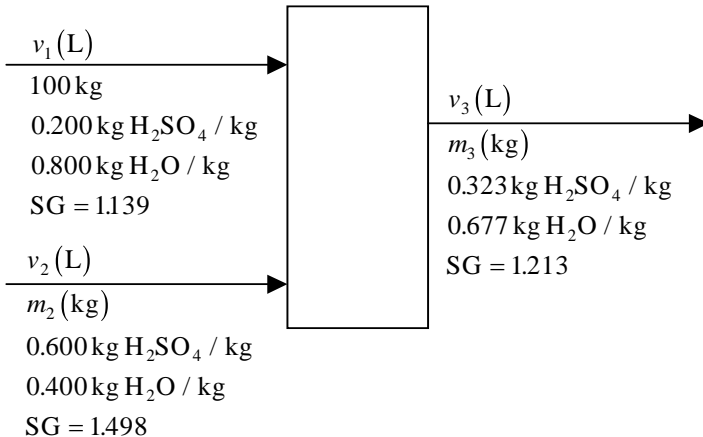
$$\ln(a) = \ln(x_1) - b\ln(R_1) = \ln(0.100) - 1.491\ln(15) = -6.340 \Rightarrow a = 1.764 \times 10^{-3}$$

$$\underline{\underline{x = 1.764 \times 10^{-3} R^{1.491}}}$$

$$R = \left(\frac{x}{a}\right)^{\frac{1}{b}} = \left(\frac{0.900}{1.764 \times 10^{-3}}\right)^{\frac{1}{1.491}} = \underline{\underline{65.5}}$$

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.

4.16 a.

$$\frac{4.00\,\text{mol H}_2\text{SO}_4}{\text{L of solution}}\bigg|\frac{0.098\,\text{kg H}_2\text{SO}_4}{\text{mol H}_2\text{SO}_4}\bigg|\frac{\text{L of solution}}{1.213\,\text{kg solution}} = \underline{\underline{0.323\left(\text{kg H}_2\text{SO}_4\,/\,\text{kg solution}\right)}}$$

b.

$v_1(\text{L})$
100 kg
0.200 kg H$_2$SO$_4$ / kg
0.800 kg H$_2$O / kg
SG = 1.139

$v_2(\text{L})$
$m_2(\text{kg})$
0.600 kg H$_2$SO$_4$ / kg
0.400 kg H$_2$O / kg
SG = 1.498

$v_3(\text{L})$
$m_3(\text{kg})$
0.323 kg H$_2$SO$_4$ / kg
0.677 kg H$_2$O / kg
SG = 1.213

5 unknowns (v_1, v_2, v_3, m_2, m_3)
– 2 balances
– 3 specific gravities
0 DF

Overall mass balance: $100 + m_2 = m_3$

Water balance: $0.800(100) + 0.400 m_2 = 0.677 m_3$ $\Rightarrow$ $m_2 = 44.4\,\text{kg}$, $m_3 = 144\,\text{kg}$

$$v_1 = \frac{100\,\text{kg}}{}\bigg|\frac{\text{L}}{1.139\,\text{kg}} = 87.80\,\text{L}\,20\%\,\text{solution}$$

$$v_2 = \frac{44.4\,\text{kg}}{}\bigg|\frac{\text{L}}{1.498\,\text{kg}} = 29.64\,\text{L}\,60\%\,\text{solution}$$

$$\frac{v_1}{v_2} = \frac{87.80}{29.64} = \underline{\underline{2.96\frac{\text{L 20\% solution}}{\text{L 60\% solution}}}}$$

c.

$$\frac{1250\,\text{kg P}}{\text{h}}\bigg|\frac{44.4\,\text{kg 60\% solution}}{144\,\text{kg P}}\bigg|\frac{\text{L}}{1.498\,\text{kg solution}} = \underline{\underline{257\,\text{L}\,/\,\text{h}}}$$

4.17

$m_1(\text{kg})$ @ \$18 / kg
0.25 kg P / kg
0.75 kg H$_2$O / kg

$m_2(\text{kg})$ @ \$10 / kg
0.12 kg P / kg
0.88 kg H$_2$O / kg

1.00 kg
0.17 kg P / kg
0.83 kg H$_2$O / kg

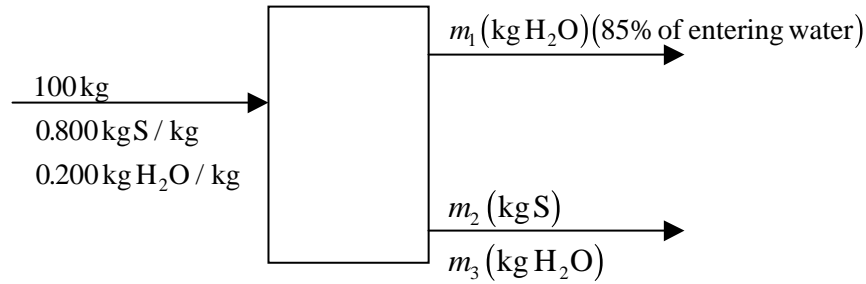Overall balance: $m_1 + m_2 = 1.00$ (1)

Pigment balance: $0.25 m_1 + 0.12 m_2 = 0.17(1.00)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow m_1 = 0.385\,\text{kg}\,25\%\,\text{paint}, m_2 = 0.615\,\text{kg}\,12\%\,\text{paint}$

Cost of blend: $0.385(\$18.00) + 0.615(\$10.00) = \$13.08\,\text{per kg}$

Selling price: $1.10(\$13.08) = \underline{\underline{\$14.39\,\text{per kg}}}$

4.18 **a.**

85% drying: $m_1 = 0.850(0.200)(100) = 17.0 \, kg \, H_2O$

Sugar balance: $m_2 = 0.800(100) = 80.0 \, kg \, S$

Overall balance: $100 = 17 + 80 + m_3 \Rightarrow m_3 = 3 \, kg \, H_2O$

$$x_w = \frac{3 \, kg \, H_2O}{(3+80) \, kg} = 0.0361 \, kg \, H_2O / kg$$

$$\frac{m_1}{m_2 + m_3} = \frac{17 \, kg \, H_2O}{(80+3) \, kg} = 0.205 \, kg \, H_2O / kg \, wet \, sugar$$

b.

$$\frac{1000 \, tons \, wet \, sugar}{day} \left| \frac{3 \, tons \, H_2O}{100 \, tons \, wet \, sugar} \right. = 30 \, tons \, H_2O / day$$

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

c.

$$\bar{x}_w = \frac{1}{10}(x_{w1} + x_{w2} + \ldots + x_{w10}) = 0.0504 \, kg \, H_2O / kg$$

$$SD = \sqrt{\frac{1}{9}\left[(x_{w1} - \bar{x}_w)^2 + \ldots + (x_{w10} - \bar{x}_w)^2\right]} = 0.00181 \, kg \, H_2O / kg$$

Endpoints $= 0.0504 \pm 3(0.00181)$

Lower limit $= 0.0450$, 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
– 3 specific gravities
0 DF
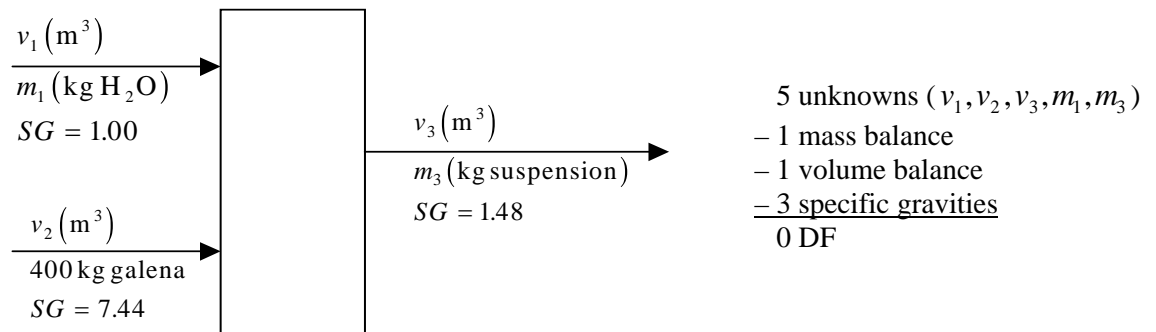
Total mass balance: $m_1 + 400 = m_3$ (1)

4.19 (cont'd)

Assume volume additivity: $\dfrac{m_1(kg)}{}\left|\dfrac{m^3}{1000\,kg}\right. + \dfrac{400\,kg}{}\left|\dfrac{m^3}{7440\,kg}\right. = \dfrac{m_3(kg)}{}\left|\dfrac{m^3}{1480\,kg}\right.$ (2)

Solve (1) and (2) simultaneously $\Rightarrow m_1 = 668\,kg\,H_2O, m_3 = 1068\,kg\,suspension$

$v_1 = \dfrac{668\,kg}{}\left|\dfrac{m^3}{1000\,kg}\right. = \underline{\underline{0.668\,m^3\,water\,fed\,to\,tank}}$

b. Specific gravity of coal $< 1.48 <$ Specific gravity of slate

c. The suspension begins to settle. Stir the suspension. $1.00 <$ Specific gravity of coal < 1.48

4.20 a.

$\dot{n}_1(mol/h)$
$\overline{0.040\,mol\,H_2O/mol}$
$0.960\,mol\,DA/mol$

$\dot{n}_2(mol/h)$
$\overline{x(mol\,H_2O/mol)}$
$1 - x(mol\,DA/mol)$

$\dot{n}_3(mol\,H_2O\,adsorbed/h)$
$97\%\,of\,H_2O\,in\,feed$
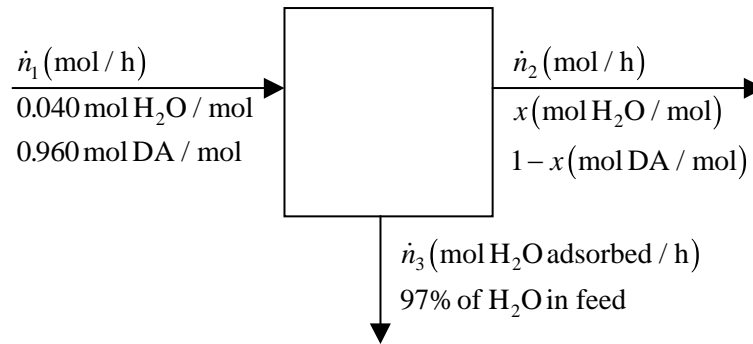
Adsorption rate: $\dot{n}_3 = \dfrac{(3.54 - 3.40)\,kg}{5\,h}\left|\dfrac{mol\,H_2O}{0.0180\,kg\,H_2O}\right. = 1.556\,mol\,H_2O/h$

97% adsorbed: $1.56 = 0.97(0.04\dot{n}_1) \Rightarrow \dot{n}_1 = \underline{\underline{40.1\,mol/h}}$

Total mole balance: $\dot{n}_1 = \dot{n}_2 + \dot{n}_3 \Rightarrow \dot{n}_2 = 40.1 - 1.556 = 38.54\,mol/h$

Water balance: $0.040(40.1) = 1.556 + x(38.54) \Rightarrow x = \underline{\underline{1.2 \times 10^{-3}\,(mol\,H_2O/mol)}}$

b. The calcium chloride pellets have reached their saturation limit. Eventually the mole fraction will reach that of the inlet stream, i.e. 4%.

4.21 a.

$300\,lb_m/h$
$\overline{0.55\,lb_m\,H_2SO_4/lb_m}$
$0.45\,lb_m\,H_2O/lb_m$

$\dot{m}_B(lb_m/h)$
$\overline{0.90\,lb_m\,H_2SO_4/lb_m}$
$0.10\,lb_m\,H_2O/lb_m$

$\dot{m}_C(lb_m/h)$
$\overline{0.75\,lb_m\,H_2SO_4/lb_m}$
$0.25\,lb_m\,H_2O/lb_m$
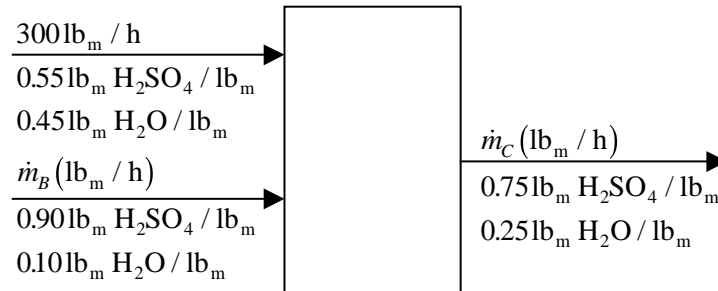
Overall balance: $300 + \dot{m}_B = \dot{m}_C$ (1)

H₂SO₄ balance: $0.55(300) + 0.90\dot{m}_B = 0.75\dot{m}_C$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{m}_B = \underline{\underline{400\,lb_m/h}}, \dot{m}_C = \underline{\underline{700\,lb_m/h}}$

4.21 (cont'd)

b.

$$\dot{m}_A - 150 = \frac{500-150}{70-25}(R_A - 25) \Rightarrow \underline{\underline{\dot{m}_A = 7.78R_A - 44.4}}$$

$$\dot{m}_B - 200 = \frac{800-200}{60-20}(R_B - 20) \Rightarrow \underline{\underline{\dot{m}_B = 15.0R_B - 100}}$$

$$\ln x - \ln 20 = \frac{\ln 100 - \ln 20}{10-4}(R_x - 4) \Rightarrow \ln x = 0.2682R_x + 1.923 \Rightarrow \underline{\underline{x = 6.841e^{0.2682R_x}}}$$

$$m_A = 300 \Rightarrow R_A = \frac{300+44.4}{7.78} = \underline{\underline{44.3}}, m_B = 400 \Rightarrow R_B = \frac{400+100}{15.0} = \underline{\underline{33.3}},$$

$$x = 55\% \Rightarrow R_x = \frac{1}{0.268}\ln\left(\frac{55}{6.841}\right) = \underline{\underline{7.78}}$$

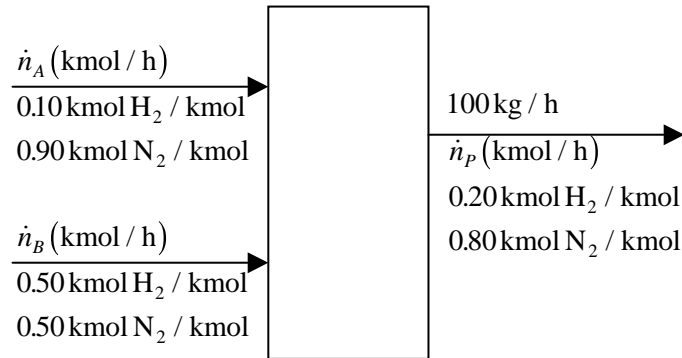**c.** <u>Overall balance</u>: $\dot{m}_A + \dot{m}_B = \dot{m}_C$

<u>H$_2$SO$_4$ balance</u>: $0.01x\dot{m}_A + 0.90\dot{m}_B = 0.75\dot{m}_C = 0.75(\dot{m}_A + \dot{m}_B) \Rightarrow \dot{m}_B = \frac{(0.75 - 0.01x)\dot{m}_A}{0.15}$

$$\Rightarrow 15.0R_B - 100 = \frac{\left[0.75 - 0.01\left(6.841e^{0.2682R_x}\right)\right](7.78R_A - 44.4)}{0.15}$$

$$\Rightarrow \underline{\underline{R_B = \left(2.59 - 0.236e^{0.2682R_x}\right)R_A + 1.35e^{0.2682R_x} - 8.13}}$$

<u>Check</u>: $R_A = 44.3, R_x = 7.78 \Rightarrow R_B = \left(2.59 - 0.236e^{0.2682(7.78)}\right)44.3 + 1.35e^{0.2682(7.78)} - 8.13 = 33.3$

4.22 **a.**

$$\dot{n}_A (\text{kmol} / \text{h})$$
$$0.10\,\text{kmol}\,H_2 / \text{kmol}$$
$$0.90\,\text{kmol}\,N_2 / \text{kmol}$$

$$100\,\text{kg} / \text{h}$$
$$\dot{n}_P (\text{kmol} / \text{h})$$
$$0.20\,\text{kmol}\,H_2 / \text{kmol}$$
$$0.80\,\text{kmol}\,N_2 / \text{kmol}$$

$$\dot{n}_B (\text{kmol} / \text{h})$$
$$0.50\,\text{kmol}\,H_2 / \text{kmol}$$
$$0.50\,\text{kmol}\,N_2 / \text{kmol}$$

$$\overline{MW} = 0.20(2.016) + 0.80(28.012) = 22.813\,\text{kg} / \text{kmol}$$

$$\Rightarrow \dot{n}_P = \frac{100\,\text{kg}}{\text{h}}\left|\frac{\text{kmol}}{22.813\,\text{kg}}\right. = 4.38\,\text{kmol} / \text{h}$$

<u>Overall balance</u>: $\dot{n}_A + \dot{n}_B = 4.38$ (1)

<u>H$_2$ balance</u>: $0.10\dot{n}_A + 0.50\dot{n}_B = 0.20(4.38)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n}_A = \underline{\underline{3.29\,\text{kmol} / \text{h}}}, \dot{n}_B = \underline{\underline{1.10\,\text{kmol} / \text{h}}}$

4.22 (cont'd)

b.

$$\dot{n}_P = \frac{\dot{m}_P}{22.813}$$

Overall balance: $\dot{n}_A + \dot{n}_B = \dfrac{\dot{m}_P}{22.813}$

H$_2$ balance: $x_A \dot{n}_A + x_B \dot{n}_B = \dfrac{x_P \dot{m}_P}{22.813}$

$$\Rightarrow \quad \dot{n}_A = \frac{\dot{m}_P}{22.813} \frac{(x_B - x_P)}{(x_B - x_A)} \qquad\qquad \dot{n}_B = \frac{\dot{m}_P}{22.813} \frac{(x_P - x_A)}{(x_B - x_A)}$$
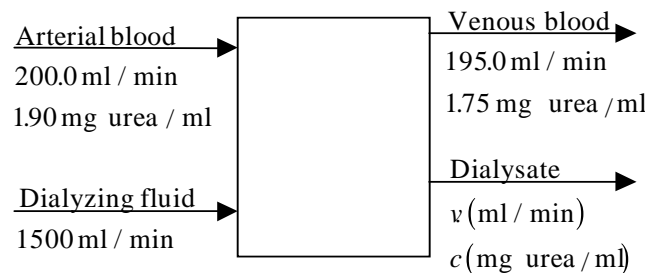
c.

Trial	X_A	X_B	X_P	m_P	n_A	n_B
1	0.10	0.50	0.10	100	4.38	0.00
2	0.10	0.50	0.20	100	3.29	1.10
3	0.10	0.50	0.30	100	2.19	2.19
4	0.10	0.50	0.40	100	1.10	3.29
5	0.10	0.50	0.50	100	0.00	4.38
6	**0.10**	**0.50**	**0.60**	**100**	**-1.10**	**5.48**
7	0.10	0.50	0.10	250	10.96	0.00
8	0.10	0.50	0.20	250	8.22	2.74
9	0.10	0.50	0.30	250	5.48	5.48
10	0.10	0.50	0.40	250	2.74	8.22
11	0.10	0.50	0.50	250	0.00	10.96
12	**0.10**	**0.50**	**0.60**	**250**	**-2.74**	**13.70**

The results of trials 6 and 12 are impossible since the flow rates are negative. You cannot blend a 10% H$_2$ mixture with a 50% H$_2$ mixture and obtain a 60% H$_2$ mixture.
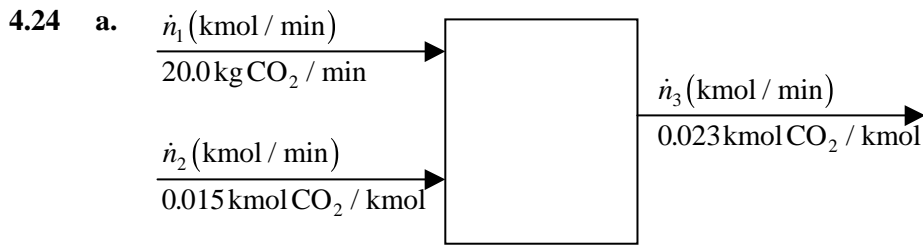
d. Results are the same as in part c.

4.23

Arterial blood
200.0 ml / min
1.90 mg urea / ml

Venous blood
195.0 ml / min
1.75 mg urea /ml

Dialyzing fluid
1500 ml / min

Dialysate
v (ml / min)
c (mg urea / ml)

a. Water removal rate: $200.0 - 195.0 = \underline{5.0 \text{ ml / min}}$

Urea removal rate: $1.90(200.0) - 1.75(195.0) = \underline{\underline{38.8 \text{ mg urea / min}}}$

b. $\dot{v} = 1500 + 5.0 = 1505 \text{ ml / min}$

$$c = \frac{38.8 \text{ mg urea/min}}{1505 \text{ ml/min}} = \underline{\underline{0.0258 \text{ mg urea/ml}}}$$

c. $\dfrac{(2.7 - 1.1) \text{ mg removed}}{\text{ml}} \left|\, \dfrac{1 \text{ min}}{38.8 \text{ mg removed}} \,\right| \dfrac{10^3 \text{ ml}}{1 \text{ L}} \left|\, \dfrac{5.0 \text{ L}}{} = \underline{\underline{206 \text{ min}}} \text{ (3.4 h)}\right.$

4.24 **a.**

$\dot{n}_1 \, (\text{kmol / min})$

$20.0 \, \text{kg CO}_2 \, / \, \text{min}$

$\dot{n}_2 \, (\text{kmol / min})$

$0.015 \, \text{kmol CO}_2 \, / \, \text{kmol}$

$\dot{n}_3 \, (\text{kmol / min})$

$0.023 \, \text{kmol CO}_2 \, / \, \text{kmol}$

$$\dot{n}_1 = \frac{20.0 \, \text{kg CO}_2}{\text{min}} \left| \frac{\text{kmol}}{44.0 \, \text{kg CO}_2} \right. = 0.455 \, \text{kmol CO}_2 \, / \, \text{min}$$

Overall balance: $0.455 + \dot{n}_2 = \dot{n}_3$ (1)

$\underline{\text{CO}_2 \text{ balance}}$: $0.455 + 0.015\dot{n}_2 = 0.023\dot{n}_3$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n}_2 = \underline{55.6 \, \text{kmol / min}}, \dot{n}_3 = 56.1 \, \text{kmol / min}$

b.

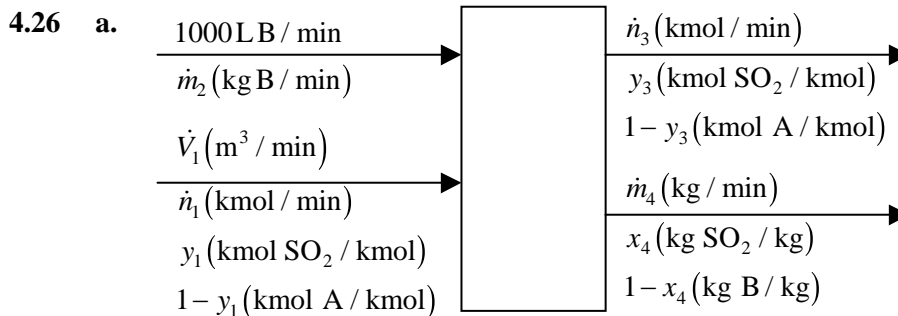$$u = \frac{150 \, \text{m}}{18 \, \text{s}} = \underline{\underline{8.33 \, \text{m / s}}}$$

$$A = \frac{1}{4} \pi D^2 = \frac{56.1 \, \text{kmol}}{\text{min}} \left| \frac{\text{m}^3}{0.123 \, \text{kmol}} \right| \frac{1 \, \text{min}}{60 \, \text{s}} \left| \frac{\text{s}}{8.33 \, \text{m}} \right. \Rightarrow D = \underline{\underline{1.08 \, \text{m}}}$$

4.25

$\underline{\text{Spectrophotometer calibration}}$: $C = kA \underset{\substack{A=0.9 \\ C=3}}{====>} C \, (\mu\text{g / L}) = 3.333A$

$\underline{\text{Dye concentration}}$: $A = 0.18 \Rightarrow C = (3.333)(0.18) = 0.600 \, \mu\text{g / L}$

$$\underline{\text{Dye injected}} = \frac{0.60 \, \text{cm}^3}{} \left| \frac{1 \, \text{L}}{10^3 \, \text{cm}^3} \right| \frac{5.0 \, \text{mg}}{1 \, \text{L}} \left| \frac{10^3 \, \mu\text{g}}{1 \, \text{mg}} \right. = 3.0 \, \mu\text{g}$$

$$\Rightarrow (3.0 \, \mu\text{g}) / V(\text{L}) = 0.600 \, \mu\text{g / L} \Rightarrow \underline{\underline{V = 5.0 \, \text{L}}}$$

4.26 **a.**

$1000 \, \text{L B / min}$

$\dot{m}_2 \, (\text{kg B / min})$

$\dot{V}_1 \, (\text{m}^3 / \text{min})$

$\dot{n}_1 \, (\text{kmol / min})$

$y_1 \, (\text{kmol SO}_2 \, / \, \text{kmol})$

$1 - y_1 \, (\text{kmol A / kmol})$

$\dot{n}_3 \, (\text{kmol / min})$

$y_3 \, (\text{kmol SO}_2 \, / \, \text{kmol})$

$1 - y_3 \, (\text{kmol A / kmol})$

$\dot{m}_4 \, (\text{kg / min})$

$x_4 \, (\text{kg SO}_2 \, / \, \text{kg})$

$1 - x_4 \, (\text{kg B / kg})$

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
<u>– 1 specific gravity</u>
  0 DF

b. <u>Orifice meter calibration:</u>

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

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

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

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

<u>Analyzer calibration:</u>

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

$$\left. \begin{array}{l} b = \dfrac{\ln(y_2/y_1)}{R_2 - R_1} = \dfrac{\ln(0.1107/0.00166)}{90 - 20} = 0.0600 \\[2mm] \ln a = \ln y_1 - bR_1 = \ln(0.00166) - 0.0600(20) = -7.60 \\[2mm] \qquad\qquad \Downarrow \\[2mm] a = 5.00 \times 10^{-4} \end{array} \right\} \Rightarrow \underline{\underline{y = 5.00 \times 10^{-4} e^{0.0600R}}}$$

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

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

$$\Downarrow$$

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

$$R_1 = 82.4 \Rightarrow y_1 = 5.00 \times 10^{-4} \exp(0.0600 \times 82.4) = 0.0702 \text{ kmol } SO_2/\text{kmol}$$

$$R_3 = 11.6 \Rightarrow y_3 = 5.00 \times 10^{-4} \exp(0.0600 \times 11.6) = 0.00100 \text{ kmol } SO_2/\text{kmol}$$

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

4.26 (cont'd)

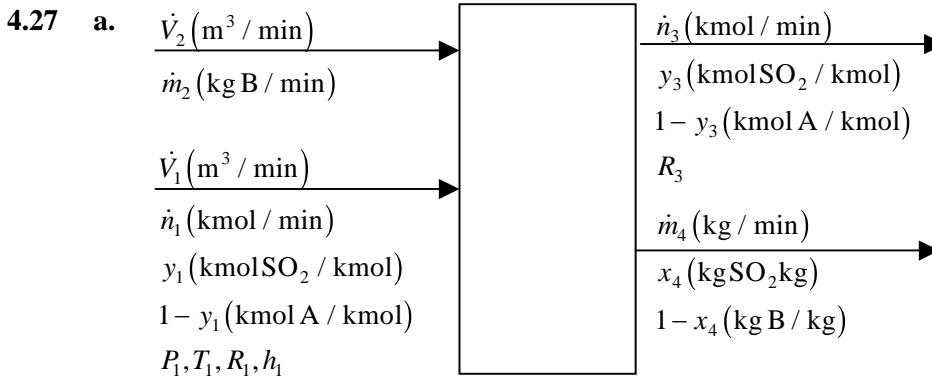A balance: $(1-0.0702)(95.34)=(1-0.00100)n_3 \Rightarrow n_3 = 88.7$ kmol/min

SO_2 balance: $(0.0702)(95.34)(64.0 \text{ kg}/\text{kmol})=(0.00100)(88.7)(64)+\dot{m}_4 x_4$ (1)

B balance: $1300 = \dot{m}_4(1-x_4)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{m}_4 = 1723$ kg/min, $x_4 = \underline{0.245 \text{ kg } SO_2 \text{ absorbed}/\text{kg}}$

$\underline{SO_2 \text{ removed}} = \dot{m}_4 x_4 = \underline{\underline{422 \text{ kg } SO_2/\text{min}}}$

d. Decreasing the bubble size increases the bubble surface-to-volume ratio, which results in a higher rate of transfer of SO_2 from the gas to the liquid phase.

4.27 a.

$\dot{V}_2 \left(\text{m}^3/\text{min}\right)$

$\dot{m}_2 \left(\text{kg B}/\text{min}\right)$

$\dot{V}_1 \left(\text{m}^3/\text{min}\right)$

$\dot{n}_1 \left(\text{kmol}/\text{min}\right)$

$y_1 \left(\text{kmol SO}_2/\text{kmol}\right)$

$1-y_1 \left(\text{kmol A}/\text{kmol}\right)$

P_1, T_1, R_1, h_1

$\dot{n}_3 \left(\text{kmol}/\text{min}\right)$

$y_3 \left(\text{kmol SO}_2/\text{kmol}\right)$

$1-y_3 \left(\text{kmol A}/\text{kmol}\right)$

R_3

$\dot{m}_4 \left(\text{kg}/\text{min}\right)$

$x_4 \left(\text{kg SO}_2 \text{kg}\right)$

$1-x_4 \left(\text{kg B}/\text{kg}\right)$

b. 14 unknowns ($\dot{n}_1, \dot{V}_1, y_1, P_1, T_1, R_1, h_1, \dot{V}_2, \dot{m}_2, \dot{n}_3, y_3, R_3, \dot{m}_4, x_4$)

– 3 material balances
– 3 analyzer and orifice meter readings
– 1 gas density formula (relates $\dot{n}_1$ and $\dot{V}_1$)
– 1 specific gravity (relates $\dot{m}_2$ and $\dot{V}_2$)
  6 DF

A balance: $(1-y_1)\dot{n}_1 = (1-y_3)\dot{n}_3$ (1)

SO_2 balance: $y_1 \dot{n}_1 = y_3 \dot{n}_3 + \dfrac{x_4 \dot{m}_4}{64 \text{ kg SO}_2/\text{kmol}}$ (2)

B balance: $\dot{m}_2 = (1-x_4)\dot{m}_4$ (3)

Calibration formulas: $y_1 = 5.00 \times 10^{-4} e^{0.060 R_1}$ (4)

                                 $y_3 = 5.00 \times 10^{-4} e^{0.060 R_3}$ (5)

                                 $\dot{V}_1 = 13.2 h_1^{0.515}$ (6)

Gas density formula: $\dot{n}_1 = \dfrac{12.2\left[(P_1+14.7)/14.7\right]}{\left[(T_1+460)/1.8\right]}\dot{V}_1$ (7)

Liquid specific gravity: $SG = 1.30 \Rightarrow \dot{V}_2 = \dfrac{\dot{m}_2 \left(\text{kg}\right)}{\text{h}} \left|\dfrac{\text{m}^3}{1300 \text{ kg}}\right.$ (8)

4-16

4.27 (cont'd)

c.

T_1	75	°F	y_1	0.07	kmol SO_2/kmol
P_1	150	psig	V_1	207	m3/h
h_1	210	torr	n_1	95.26	kmol/h
R_1	82.4				

Trial	x_4 (kg SO_2/kg)	y_3 (kmol SO_2/kmol)	V_2 (m_3/h)	n_3 (kmol/h)	m_4 (kg/h)	m_2 (kg/h)
1	0.10	0.050	0.89	93.25	1283.45	1155.11
2	0.10	0.025	1.95	90.86	2813.72	2532.35
3	0.10	0.010	2.56	89.48	3694.78	3325.31
4	0.10	0.005	2.76	89.03	3982.57	3584.31
5	0.10	0.001	2.92	88.68	4210.72	3789.65
6	0.20	0.050	0.39	93.25	641.73	513.38
7	0.20	0.025	0.87	90.86	1406.86	1125.49
8	0.20	0.010	1.14	89.48	1847.39	1477.91
9	0.20	0.005	1.23	89.03	1991.28	1593.03
10	0.20	0.001	1.30	88.68	2105.36	1684.29
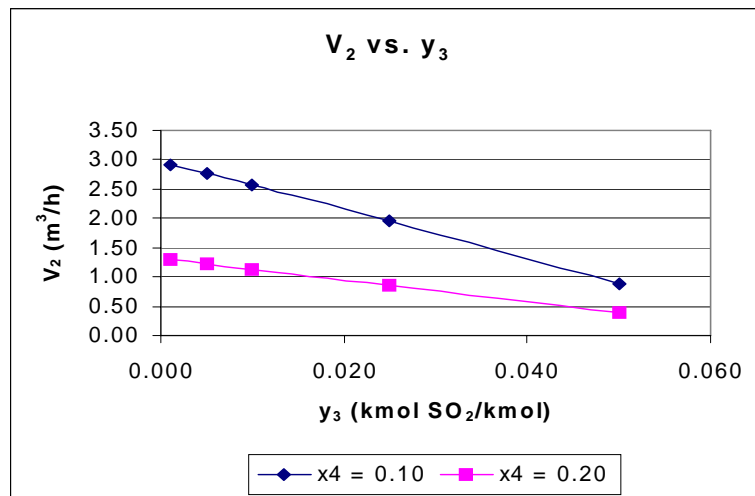
For a given SO_2 feed rate removing more SO_2 (lower y_3) requires a higher solvent feed rate ($\dot{V}_2$).

For a given SO_2 removal rate (y_3), a higher solvent feed rate ($\dot{V}_2$) tends to a more dilute SO_2 solution at the outlet (lower x_4).

d. Answers are the same as in part c.

4.28 <u>Maximum balances:</u> Overall - 3, Unit 1 - 2; Unit 2 - 3; Mixing point - 3

Overall mass balance $\Rightarrow \dot{m}_3$
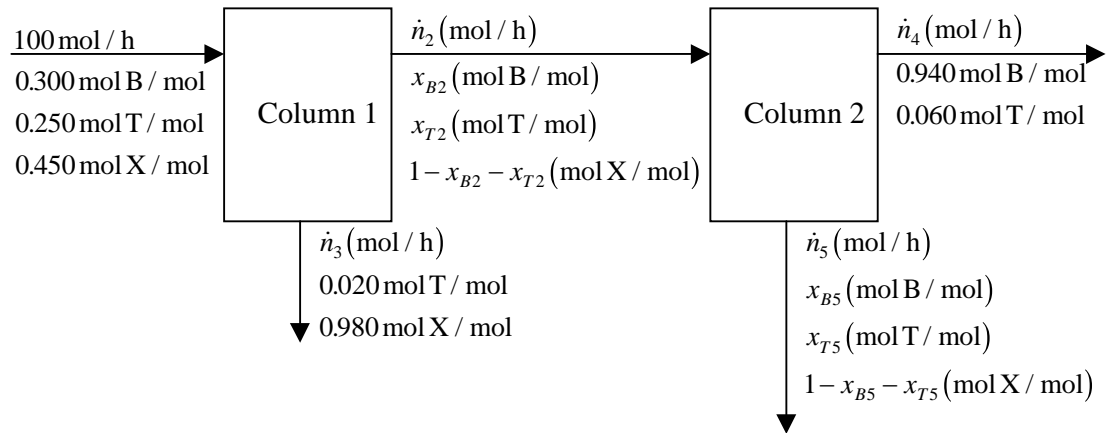Mass balance - Unit 1 $\Rightarrow \dot{m}_1$
A balance - Unit 1 $\Rightarrow x_1$
Mass balance - mixing point $\Rightarrow \dot{m}_2$
A balance - mixing point $\Rightarrow x_2$
C balance - mixing point $\Rightarrow y_2$

4.29 **a.**

Column 1
  4 unknowns $(\dot{n}_2, \dot{n}_3, x_{B2}, x_{T2})$
  –3 balances
  – 1 recovery of X in bot. (96%)
    0 DF

Column 2:
  4 unknowns $(\dot{n}_3, \dot{n}_4, \dot{n}_5, y_x)$
  – 3 balances
  – 1 recovery of B in top (97%)
    0 DF

Column 1
  96% X recovery: $0.96(0.450)(100) = 0.98\dot{n}_3$ (1)

  Total mole balance: $100 = \dot{n}_2 + \dot{n}_3$ (2)

  B balance: $0.300(100) = x_{B2}\dot{n}_2$ (3)

  T balance: $0.250(100) = x_{T2}\dot{n}_2 + 0.020\dot{n}_3$ (4)

Column 2
  97% B recovery: $0.97x_{B2}\dot{n}_2 = 0.940\dot{n}_4$ (5)

  Total mole balance: $\dot{n}_2 = \dot{n}_4 + \dot{n}_5$ (6)

  B balance: $x_{B2}\dot{n}_2 = 0.940\dot{n}_4 + x_{B5}\dot{n}_5$ (7)

  T balance: $x_{T2}\dot{n}_2 = 0.060\dot{n}_4 + x_{T5}\dot{n}_5$ (8)

b. $(1) \Rightarrow \dot{n}_3 = 44.1\,\text{mol / h}$ $(2) \Rightarrow \dot{n}_2 = 55.9\,\text{mol / h}$

    $(3) \Rightarrow x_{B2} = 0.536\,\text{mol B / mol}$ $(4) \Rightarrow x_{T2} = 0.431\,\text{mol T / mol}$

    $(5) \Rightarrow \dot{n}_4 = 30.95\,\text{mol / h}$ $(6) \Rightarrow \dot{n}_5 = 24.96\,\text{mol / h}$

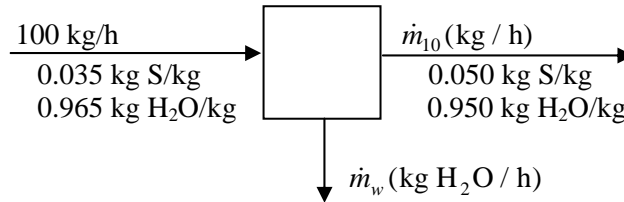 $(7) \Rightarrow x_{B5} = 0.036\,\text{mol B / mol}$ $(8) \Rightarrow x_{T5} = 0.892\,\text{mol T / mol}$

    Overall benzene recovery: $\dfrac{0.940(30.95)}{0.300(100)} \times 100\% = \underline{\underline{97\%}}$

    Overall toluene recovery: $\dfrac{0.892(24.96)}{0.250(100)} \times 100 = \underline{\underline{89\%}}$
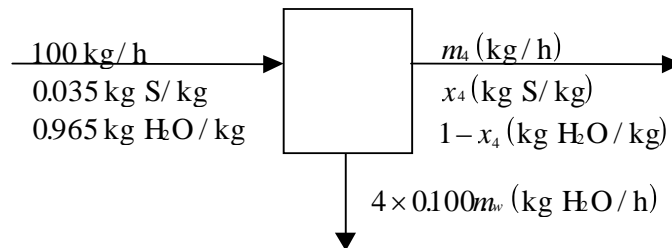
4.30   a.
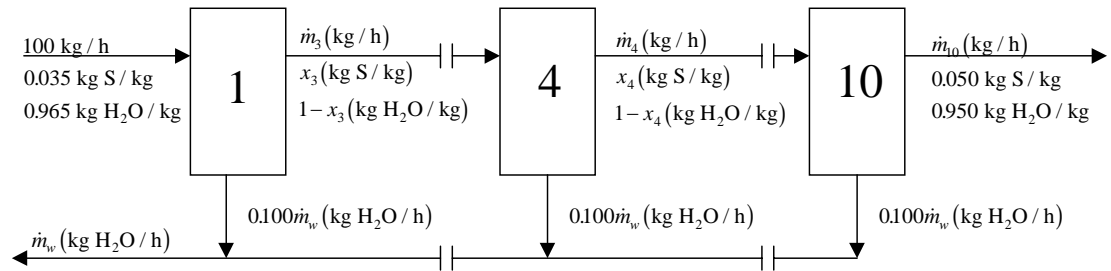
b.   Overall process

Salt balance: $0.035(100) = 0.050\underline{\underline{\dot{m}_{10}}}$

Overall balance: $100 = \underline{\underline{\dot{m}_w}} + \dot{m}_{10}$

H₂O yield: $\underline{\underline{Y_w}} = \dfrac{\dot{m}_w \left(\text{kg H}_2\text{O recovered}\right)}{96.5\left(\text{kg H}_2\text{O in fresh feed}\right)}$

First 4 evaporators

Overall balance: $100 = 4(0.100)\dot{m}_w + \underline{\underline{\dot{m}_4}}$

Salt balance: $0.035(100) = \underline{\underline{x_4 \dot{m}_4}}$

c. $\underline{\underline{Y_w = 0.31}}$

$\underline{\underline{x_4 = 0.0398}}$

4.31   a.
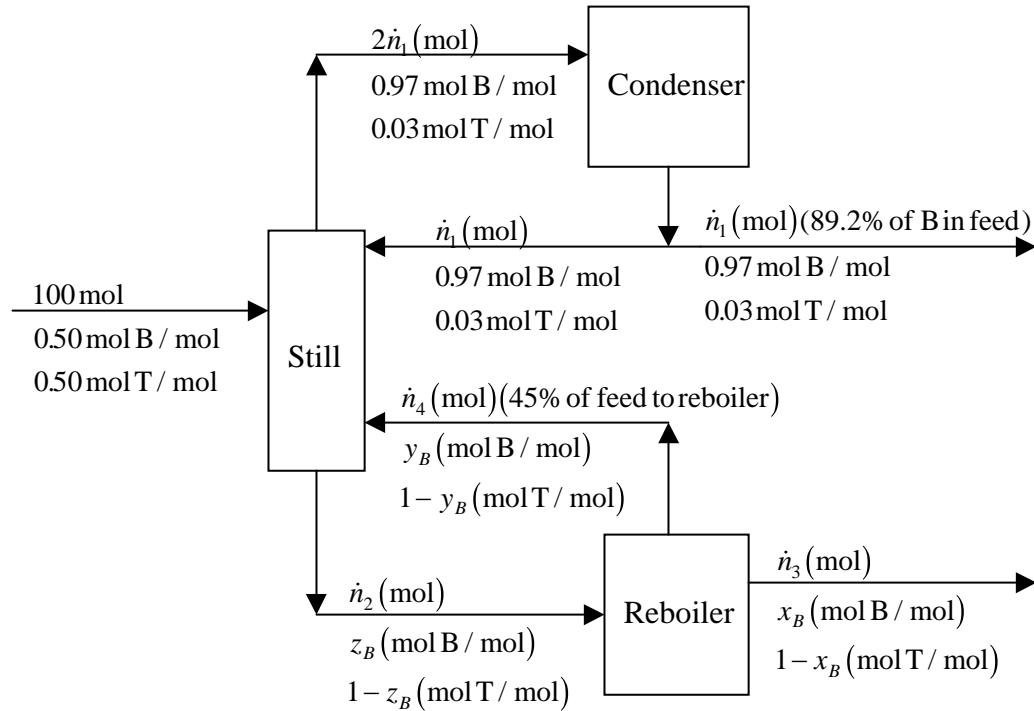
Overall process: 3 unknowns $(\dot{n}_1, \dot{n}_3, x_B)$ Still: 5 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_4, y_B, z_B)$
                – 2 balances   – 2 balances
                – 1 relationship (89.2% recovery)   3 DF
                   0 DF

Condenser: 1 unknown $(\dot{n}_1)$ Reboiler: 6 unknowns $(\dot{n}_2, \dot{n}_3, \dot{n}_4, x_B, y_B, z_B)$
             – 0 balances   – 2 balances
              1 DF   – 2 relationships (2.25 ratio & 45% vapor)
                         3 DF

Begin with overall process.

b.   Overall process

    89.2% recovery: $0.892(0.50)(100) = 0.97\dot{n}_1$

    Overall balance: $100 = \dot{n}_1 + \dot{n}_3$

    B balance: $0.50(100) = 0.97\dot{n}_1 + x_B\dot{n}_3$

Reboiler

    Composition relationship: $\dfrac{y_B / (1 - y_B)}{x_B / (1 - x_B)} = 2.25$

    Percent vaporized: $\dot{n}_4 = 0.45\dot{n}_2$ (1)

    Mole balance: $\dot{n}_2 = \dot{n}_3 + \dot{n}_4$ (2)

    (Solve (1) and (2) simultaneously.)

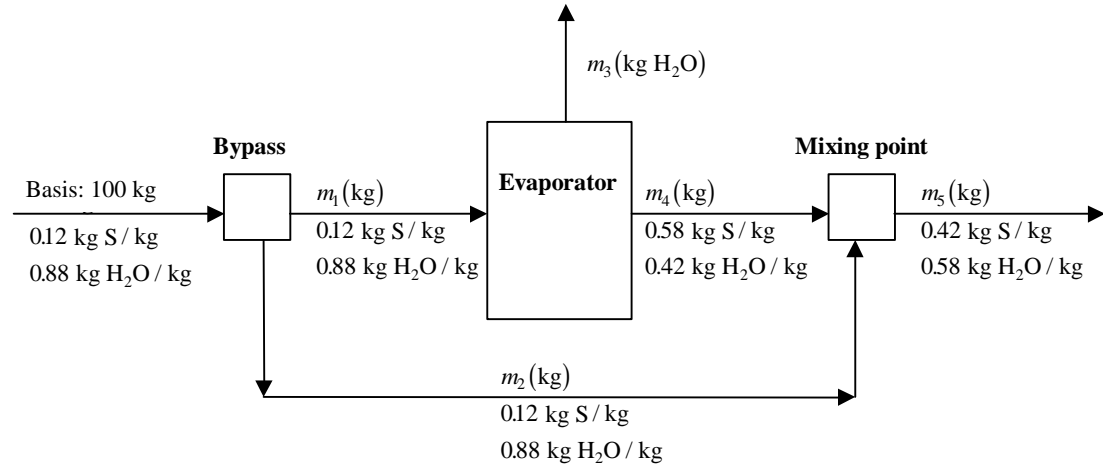   B balance: $z_B\dot{n}_2 = x_B\dot{n}_3 + y_B\dot{n}_4$

4.31 (cont'd)

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

     <u>Moles of overhead</u>: $\dot{n}_1 = \underline{\underline{46.0}}\,\text{mol}$ <u>Moles of bottoms</u>: $\dot{n}_3 = \underline{\underline{54.0}}\,\text{mol}$

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

4.32 **a.**

     <u>Overall process</u>: 2 unknowns (m_3, m_5) <u>Bypass</u>: 2 unknowns (m_1, m_2)
                         $-$ 2 balances $-$ 1 independent balance
                           0 DF   1 DF

     <u>Evaporator</u>: 3 unknowns (m_1, m_3, m_4) <u>Mixing point</u>: 3 unknowns (m_2, m_4, m_5)
                      $-$ 2 balances $-$ 2 balances
                         1 DF   1 DF

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

     <u>Overall mass balance</u>: $100 = \underline{\underline{m_3}} + m_5$

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

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

     Solve (1) and (2) simultaneously
     <u>Bypass mass balance</u>: $100 = \underline{\underline{m_1}} + m_2$

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

     <u>Bypass fraction</u>: $\dfrac{m_2}{100} = \underline{\underline{0.095}}$

   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 **a.**

$$\dot{m}_4 \,(\text{kg Cr} / \text{h})$$

$\dot{m}_1\,(\text{kg}/\text{h})$	$\dot{m}_2\,(\text{kg}/\text{h})$		$\dot{m}_5\,(\text{kg}/\text{h})$	$\dot{m}_6\,(\text{kg}/\text{h})$
0.0515 kg Cr / kg	0.0515 kg Cr / kg	Treatment	$x_5\,(\text{kg Cr} / \text{kg})$	$x_6\,(\text{kg Cr} / \text{kg})$
0.9485 kg W / kg	0.9485 kg W / kg	Unit	$1 - x_5\,(\text{kg W} / \text{kg})$	$1 - x_6\,(\text{kg W} / \text{kg})$

$$\dot{m}_3\,(\text{kg}/\text{h})$$
0.0515 kg Cr / kg
0.9485 kg W / kg
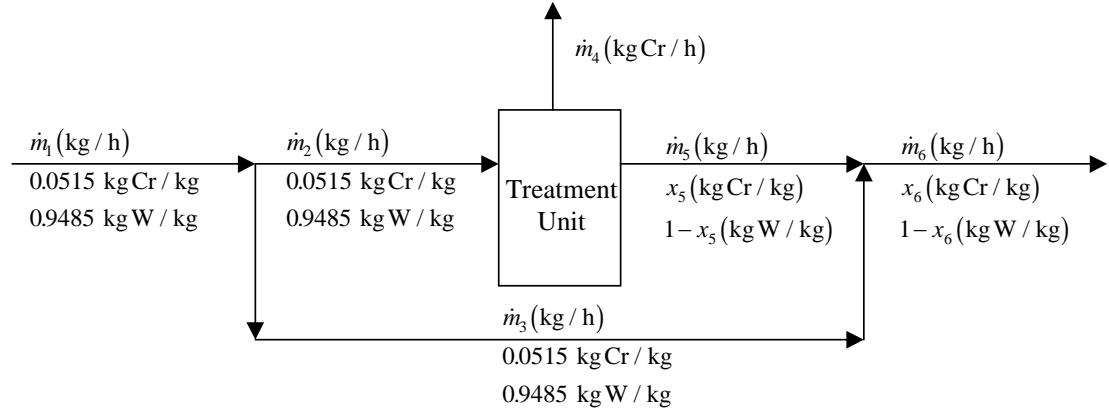
b. $\dot{m}_1 = 6000 \text{ kg} / \text{h} \Rightarrow \dot{m}_2 = 4500 \text{ kg} / \text{h} \,\left(\text{maximum allowed value}\right)$

<u>Bypass point mass balance:</u> $\dot{m}_3 = 6000 - 4500 = 1500 \text{ kg} / \text{h}$

<u>95% Cr removal:</u> $\dot{m}_4 = 0.95(0.0515)(4500) = 220.2 \text{ kg Cr} / \text{h}$

<u>Mass balance on treatment unit:</u> $\dot{m}_5 = 4500 - 220.2 = 4279.8 \text{ kg} / \text{h}$

<u>Cr balance on treatment unit:</u> $x_5 = \dfrac{0.0515(4500) - 220.2}{4779.8} = 0.002707 \text{ kg Cr} / \text{kg}$

<u>Mixing point mass balance:</u> $\dot{m}_6 = 1500 + 4279.8 = \underline{\underline{5779.8 \text{ kg} / \text{h}}}$

<u>Mixing point Cr balance:</u> $x_6 = \dfrac{0.0515(1500) + 0.0002707(4279.8)}{5779.8} = \underline{\underline{0.0154 \text{ kg Cr} / \text{kg}}}$

c.

m_1 (kg/h)	m_2 (kg/h)	m_3 (kg/h)	m_4 (kg/h)	m_5 (kg/h)	x_5	m_6 (kg/h)	x_6
1000	1000	0	48.9	951	0.00271	951	0.00271
2000	2000	0	97.9	1902	0.00271	1902	0.00271
3000	3000	0	147	2853	0.00271	2853	0.00271
4000	4000	0	196	3804	0.00271	3804	0.00271
5000	4500	500	220	4280	0.00271	4780	0.00781
6000	4500	1500	220	4280	0.00271	5780	0.0154
7000	4500	2500	220	4280	0.00271	6780	0.0207
8000	4500	3500	220	4280	0.00271	7780	0.0247
9000	4500	4500	220	4280	0.00271	8780	0.0277
10000	4500	5500	220	4280	0.00271	9780	0.0301

4.33 (cont'd)

m_1 vs. x_6
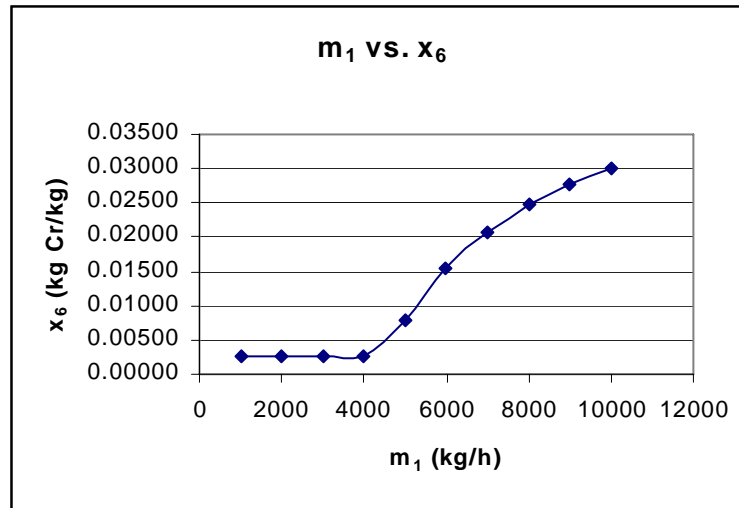
d. Cost of additional capacity – installation and maintenance, revenue from additional recovered Cr, anticipated wastewater production in coming years, capacity of waste lagoon, regulatory limits on Cr emissions.

4.34   a.

175 kg H_2O / s $\left(45\% \text{ of water fed to evaporator}\right)$

$\dot{m}_1$ (kg / s)
0.196 kg K_2SO_4 / kg
0.804 kg H_2O / kg

$\dot{m}_4 \left(\text{kg } K_2SO_4 \text{ / s}\right)$
$\dot{m}_5 \left(\text{kg } H_2O \text{ / s}\right)$

Evaporator

$\dot{m}_6 \left(\text{kg } K_2SO_4 \text{ / s}\right)$
$\dot{m}_7 \left(\text{kg } H_2O \text{ / s}\right)$

Crystallizer Filter

Filter cake
$10\dot{m}_2 \left(\text{kg } K_2SO_4 \text{ / s}\right)$
$\dot{m}_2$ (kg soln / s)
$\left\{ \begin{array}{l} 0.400 \text{ kg } K_2SO_4 \text{ / kg} \\ 0.600 \text{ kg } H_2O \text{ / kg} \end{array} \right\}$

Filtrate

$\dot{m}_3$ (kg / s)
0.400 kg K_2SO_4 / kg
0.600 kg H_2O / kg
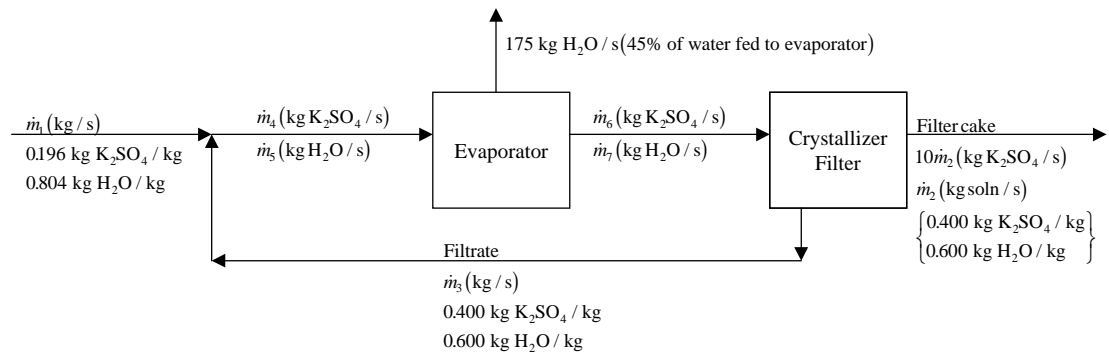
Let K = K_2SO_4, W = H_2 <u>Basis</u>: 175 kg W evaporated/s

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

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

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

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

<u>Strategy</u>:   Overall balances $\Rightarrow \dot{m}_1, \dot{m}_2$ ⎫ verify that each
    % evaporation $\Rightarrow \dot{m}_5$ ⎪ chosen subsystem involves
    Balances around mixing point $\Rightarrow \dot{m}_3, \dot{m}_4$ ⎬ no more than two
    Balances around evaporator $\Rightarrow \dot{m}_6, \dot{m}_7$ ⎭ unknown variables

4.34 (cont'd)

Overall mass balance: $\dot{m}_1 = 175 + 10\dot{m}_2 + \dot{m}_2$

Overall K balance: $0.196\dot{m}_1 = 10\dot{m}_2 + 0.400\dot{m}_2$

Production rate of crystals $= 10\dot{m}_2$

45% evaporation: 175 kg evaporated/min $= 0.450\dot{m}_5$

W balance around mixing point: $0.804\dot{m}_1 + 0.600\dot{m}_3 = \dot{m}_5$

Mass balance around mixing point: $\dot{m}_1 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5$

K balance around evaporator: $\dot{m}_6 = \dot{m}_4$

W balance around evaporator: $\dot{m}_5 = 175 + \dot{m}_7$

Mole fraction of K in stream entering evaporator $= \dfrac{\dot{m}_4}{\dot{m}_4 + \dot{m}_5}$

b. Fresh feed rate: $\dot{m}_1 = 221$ kg / s

Production rate of crystals $= 10\dot{m}_2 = 41.6$ kg K(s)/s

Recycle ratio: $\dfrac{\dot{m}_3(\text{kg recycle/s})}{\dot{m}_1(\text{kg fresh feed/s})} = \dfrac{352.3}{220.8} = 1.60\dfrac{\text{kg recycle}}{\text{kg fresh feed}}$

c. Scale to 75% of capacity.
Flow rate of stream entering evaporator $= 0.75(398 \text{ kg / s}) = 299 \text{ kg / s}$

46.3% K, 53.7% W

d. Drying . Principal costs are likely to be the heating cost for the evaporator and the dryer and the cooling cost for the crystallizer.

4.35 **a.** Overall objective: Separate components of a CH_4-CO_2 mixture, recover CH_4, and discharge CO_2 to the atmosphere.
Absorber function: Separates CO_2 from CH_4.
Stripper function: Removes dissolved CO_2 from CH_3OH so that the latter can be reused.

b. The top streams are liquids while the bottom streams are gases. The liquids are heavier than the gases so the liquids fall through the columns and the gases rise.

c.
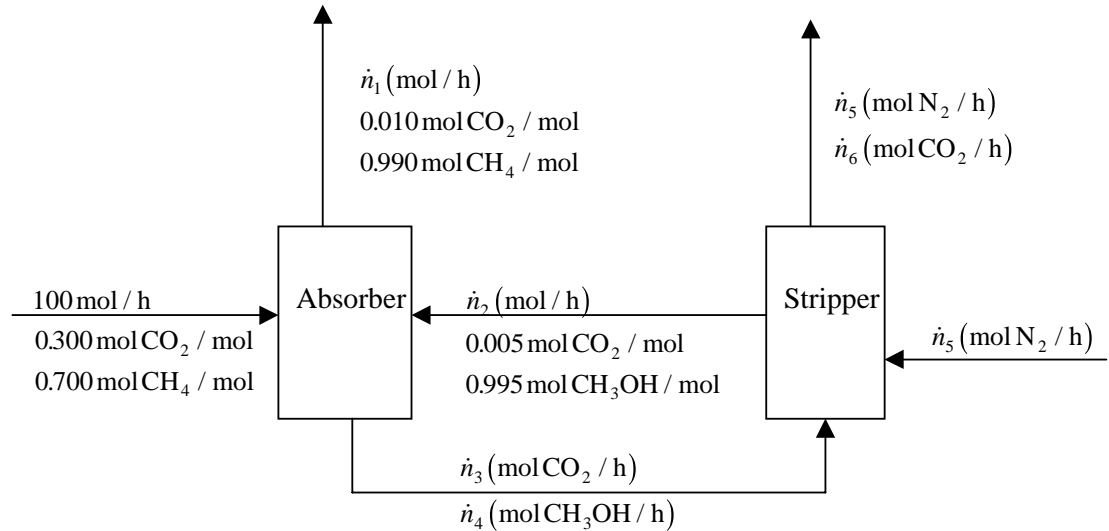
Overall: 3 unknowns ($\dot{n}_1, \dot{n}_5, \dot{n}_6$)   Absorber: 4 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4$)
          − 2 balances   − 3 balances
            1 DF   1 DF

Stripper: 4 unknowns ($\dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_5$)
          − 2 balances
          − 1 percent removal (90%)
            1 DF

Overall CH_4 balance: $\left[(0.700)(100)\right]\left(mol\,CH_4\,/\,h\right) = 0.990\underline{\underline{\dot{n}_1}}$

Overall mole balance: $100\left(mol\,/\,h\right) = \dot{n}_1 + \underline{\underline{\dot{n}_6}}$

Percent CO_2 stripped: $0.90\underline{\underline{\dot{n}_3}} = \dot{n}_6$

Stripper CO_2 balance: $\dot{n}_3 = \dot{n}_6 + 0.005\underline{\underline{\dot{n}_2}}$

Stripper CH_3OH balance: $\underline{\underline{\dot{n}_4}} = 0.995\dot{n}_2$

d. $\dot{n}_1 = 70.71\,mol\,/\,h, \dot{n}_2 = 651.0\,mol\,/\,h, \dot{n}_3 = 32.55\,mol\,CO_2\,/\,h, \dot{n}_4 = 647.7\,mol\,CH_3OH\,/\,h,$
$\dot{n}_6 = 29.29\,mol\,CO_2\,/\,h$

Fractional CO_2 absorption: $f_{CO_2} = \dfrac{30.0 - 0.010\dot{n}_1}{30.0} = \underline{\underline{0.976\,mol\,CO_2\,absorbed\,/\,mol\,fed}}$

4.35 (cont'd)

Total molar flow rate of liquid feed to stripper and mole fraction of CO_2:

$$\dot{n}_3 + \dot{n}_4 = \underline{\underline{680\,\text{mol}\,/\,\text{h}}}, \; x_3 = \frac{\dot{n}_3}{\dot{n}_3 + \dot{n}_4} = \underline{\underline{0.0478\,\text{mol}\,CO_2\,/\,\text{mol}}}$$

e.   Scale up to 1000 kg/h ($=10^6$ g/h) of product gas:

$$\overline{MW}_1 = 0.01(44\,\text{g}\,CO_2\,/\,\text{mol}) + 0.99(16\,\text{g}\,CH_4\,/\,\text{mol}) = 16.28\,\text{g}\,/\,\text{mol}$$

$$(\dot{n}_1)_{new} = (1.0 \times 10^6\,\text{g}\,/\,\text{h})(16.28\,\text{g}\,/\,\text{mol}) = 6.142 \times 10^4\;\text{mol}\,/\,\text{h}$$

$$(\dot{n}_{feed})_{new} = (100\,\text{mol}\,/\,\text{h})\left[(6.142 \times 10^4\;\text{mol}\,/\,\text{h})\,/\,(70.71\,\text{mol}\,/\,\text{h})\right] = \underline{\underline{8.69 \times 10^4\;\text{mol}\,/\,\text{h}}}$$

f. $T_a < T_s$ The higher temperature in the stripper will help drive off the gas.
    $P_a > P_s$ The higher pressure in the absorber will help dissolve the gas in the liquid.

g.   The methanol must have a high solubility for CO_2, a low solubility for CH_4, and a low
    volatility at the stripper temperature.

4.36   a.   <u>Basis</u>: 100 kg beans fed
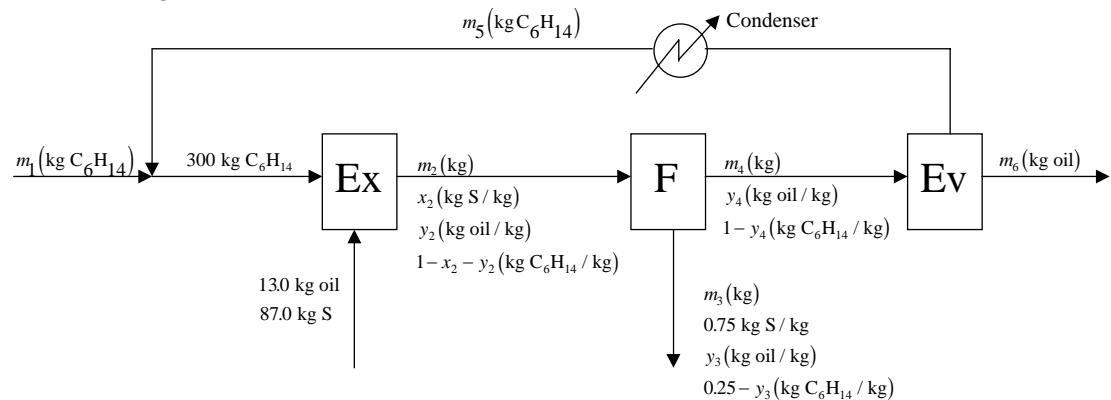
<u>Overall:</u>   4 unknowns (m_1, m_3, m_6, y_3)   <u>Extractor:</u>   3 unknowns (m_2, x_2, y_2)
        $-$ 3 balances $-$ 3 balances
          1 DF   0 DF

<u>Mixing Pt:</u>   2 unknowns (m_1, m_5)   <u>Evaporator:</u>   4 unknowns (m_4, m_5, m_6, y_4)
          $-$ 1 balance $-$ 2 balances
            1 DF   2 DF

<u>Filter:</u>   7 unknowns ($m_2, m_3, m_4, x_2, y_2, y_3, y_4$)
            $-$ 3 balances
            $-$ 1 oil/hexane ratio
              3 DF

Start with extractor (0 degrees of freedom)

<u>Extractor mass balance</u>: $[300 + 87.0 + 13.0]\,\text{kg} = \underline{\underline{m_2}}$

4.36 (cont'd)

Extractor S balance: $87.0 \text{ kg S} = \underline{\underline{x_2 m_2}}$

Extractor oil balance: $13.0 \text{ kg oil} = \underline{\underline{y_2 m_2}}$

Filter S balance: $87.0 \text{ kg S} = 0.75\underline{\underline{m_3}}$

Filter mass balance: $m_2 (\text{kg}) = m_3 + \underline{\underline{m_4}}$ Oil / hexane ratio in filter cake:

$$\frac{\underline{\underline{y_3}}}{0.25 - \underline{\underline{y_3}}} = \frac{y_2}{1 - x_2 - y_2}$$

Filter oil balance: $13.0 \text{ kg oil} = y_3 m_3 + \underline{\underline{y_4 m_4}}$

Evaporator hexane balance: $(1 - y_4) m_4 = \underline{\underline{m_5}}$

Mixing pt. Hexane balance: $\underline{\underline{m_1}} + m_5 = 300 \text{ kg C}_6\text{H}_{14}$

Evaporator oil balance: $y_4 m_4 = \underline{\underline{m_6}}$

b.

$$\underline{\text{Yield}} = \frac{m_6}{100} = \frac{11.8 \text{ kg oil}}{100 \text{ kg beans fed}} = \underline{\underline{0.118 (\text{kg oil / kg beans fed})}}$$

$$\underline{\text{Fresh hexane feed}} = \frac{m_1}{100} = \frac{28 \text{ kg C}_6\text{H}_{14}}{100 \text{ kg beans fed}} = \underline{\underline{0.28 (\text{kg C}_6\text{H}_{14} / \text{kg beans fed})}}$$

$$\text{Recycle ratio} = \frac{m_5}{m_1} = \frac{272 \text{ kg C}_6\text{H}_{14} \text{ recycled}}{28 \text{ kg C}_6\text{H}_{14} \text{ fed}} = \underline{\underline{9.71 (\text{kg C}_6\text{H}_{14} \text{ recycled / kg C}_6\text{H}_{14} \text{ fed})}}$$

c.   Lower heating cost for the evaporator and lower cooling cost for the condenser.

4.37
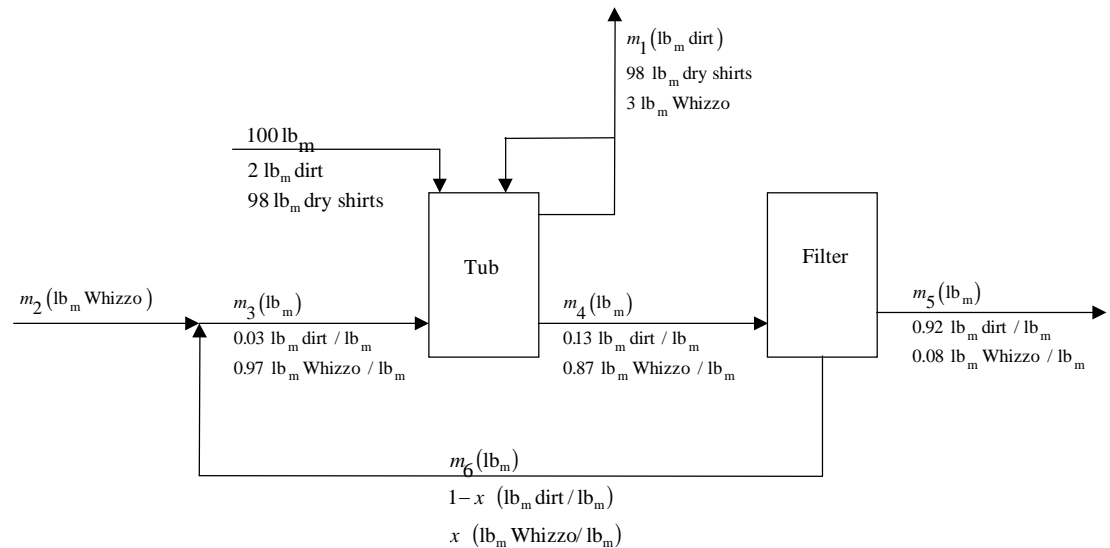
Strategy

95% dirt removal $\Rightarrow m_1$ ($= 5\%$ of the dirt entering)

Overall balances: 2 allowed (we have implicitly used a clean shirt balance in labeling the chart) $\Rightarrow m_2, m_5$ (solves Part (a))

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. 95% dirt removal: $m_1 = (0.05)(2.0) = 0.10 \text{ lb}_m$ dirt

Overall dirt balance: $2.0 = 0.10 + (0.92)m_5 \Rightarrow m_5 = 2.065 \text{ lb}_m$ dirt

Overall Whizzo balance: $m_2 = \left[3 + (0.08)(2.065)\right](\text{lb}_m \text{ Whizzo}) = \underline{\underline{3.17 \text{ lb}_m}}$ Whizzo

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

Tub Whizzo balance: $0.97m_3 = 3 + 0.87m_4$ (2)

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

Mixing pt. mass balance: $3.17 + m_6 = 20.4 \text{ lb}_m \Rightarrow m_6 = 17.3 \text{ lb}_m$

Mixing pt. Whizzo balance:

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

4.38 a.
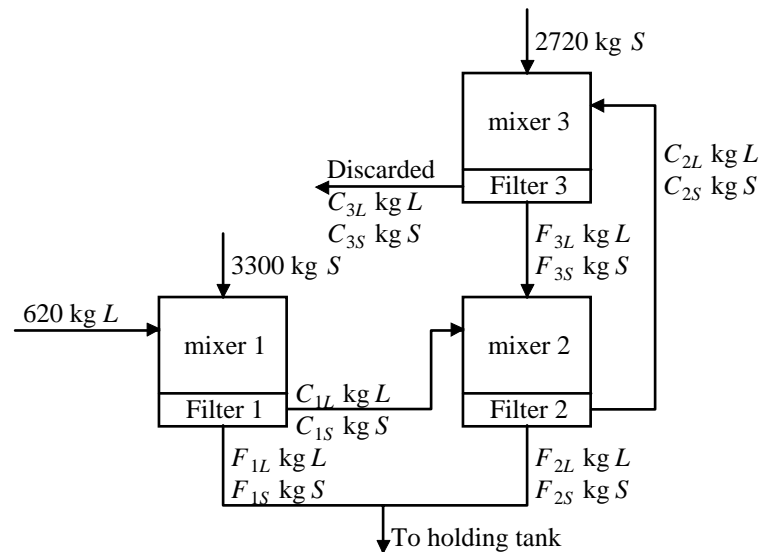
mixer/filter 1: $0.01(620) = F_{1L} \Rightarrow$ $F_{1L} = 6.2 \text{ kg L}$

     balance: $620 = 6.2 + C_{1L} \Rightarrow$ $C_{1L} = 613.8 \text{ kg L}$

mixer/filter 2: $0.01(613.8 + F_{3L}) = F_{2L}$ $F_{2L} = 6.2 \text{ kg L}$

     balance: $613.8 + F_{3L} = F_{2L} + C_{3L} \Rightarrow$ $C_{2L} = 613.7 \text{ kg L}$

mixer/filter 3: $0.01C_{2L} = F_{3L}$ $F_{3L} = 6.1 \text{ kg L}$

     balance: $613.7 = 6.1 + C_{3L} \Rightarrow$ $C_{3L} = 607.6 \text{ kg L}$

4.38 (cont'd)

Solvent

m/f 1: $\quad 0.15(3300) = C_{1S} \Rightarrow \quad C_{1S} = 495$ kg S

balance: $\quad 3300 = 495 + F_{1S} \Rightarrow \quad F_{1S} = 2805$ kg S

m/f 2: $\quad 0.15(495 + F_{3S}) = C_{2S}$ ⎫ $\quad C_{2S} = 482.6$ kg S

balance: $\quad 495 + F_{3S} = C_{2S} + F_{2S}$ ⎪ $\quad F_{2S} = 2734.6$ kg S

m/f 3: $\quad 0.15(2720 + C_{2S}) = C_{3S}$ ⎬ $\Rightarrow \quad C_{3S} = 480.4$ kg S

balance: $\quad 2720 + C_{2S} = F_{3S} + C_{3S}$ ⎭ $\quad F_{3S} = 2722.2$ kg S

<u>Holding Tank Contents</u>

$6.2 + 6.2 = \underline{\underline{12.4 \text{ kg leaf}}}$

$2805 + 2734.6 = \underline{\underline{5540 \text{ kg solvent}}}$

b.

$\quad$ 5540 kg S
$\quad$ 0.165 kg E / kg
$\quad$ 0.835 kg W / kg

| | Extraction Unit | Q_R (kg) 0.13 kg E / kg 0.15 kg F / kg 0.855 kg W / kg | Steam Stripper | Q_0 (kg) 0.200 kg E / kg 0.026 kg F / kg 0.774 kg W / kg |

Q_D (kg D)
Q_F (kg F)

Q_E (kg E)
Q_D (kg D)
Q_F (kg F)

Q_B (kg)
0.013 kg E / kg
0.987 kg W / kg

Q_3 (kg steam)
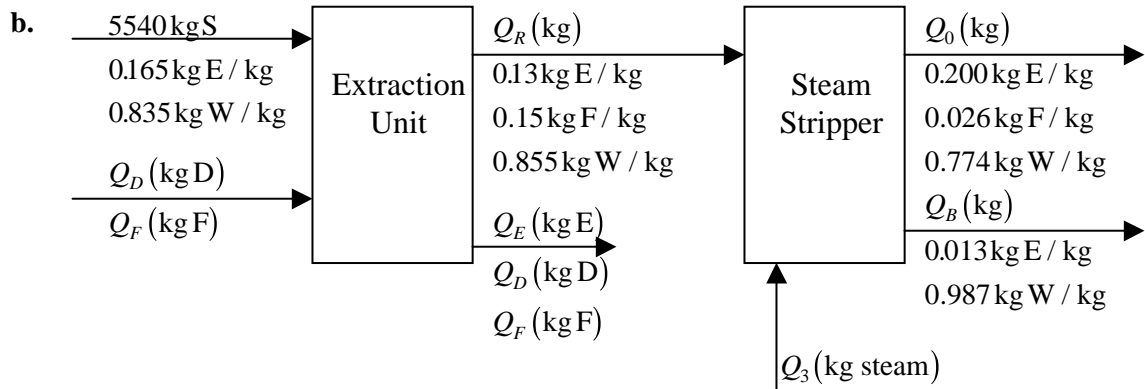
<u>Mass of D in Product:</u> $\dfrac{1 \text{ kg D}}{1000 \text{ kg leaf}} \bigg| \dfrac{620 \text{ kg leaf}}{} = \underline{\underline{0.62 \text{ kg D}}} = Q_D$

<u>Water balance around extraction unit:</u> $0.835(5540) = 0.855Q_R \Rightarrow Q_R = \underline{\underline{5410 \text{ kg}}}$

<u>Ethanol balance around extraction unit:</u>

$0.165(5540) = 0.13(5410) + Q_E \Rightarrow Q_E = \underline{\underline{211 \text{ kg}}}$ (ethanol in extract)

c. <u>F balance around stripper</u>

$\quad 0.015(5410) = 0.026Q_0 \Rightarrow Q_0 = \underline{\underline{3121 \text{ kg}}}$ (mass of stripper overhead product)

<u>E balance around stripper</u>

$\quad 0.13(5410) = 0.200(3121) + 0.013Q_B \Rightarrow Q_B = \underline{\underline{6085 \text{ kg}}}$ (mass of stripper bottom product)

<u>W balance around stripper</u>

$\quad 0.855(5410) + Q_S = 0.774(3121) + 0.987(6085) \Rightarrow Q_S = \underline{\underline{3796 \text{ kg steam fed to stripper}}}$

4.39 **a.** $C_2H_2 + 2H_2 \rightarrow C_2H_6$

$\underline{\underline{2 \text{ mol } H_2 \text{ react / mol } C_2H_2 \text{ react}}}$

$\underline{\underline{0.5 \text{ kmol } C_2H_6 \text{ formed / kmol } H_2 \text{ react}}}$

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.

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

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

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.

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

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

c.

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

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

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

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

$$\underline{\text{Required } NH_3}: \frac{3.125 \text{ kmol } O_2}{} \bigg| \frac{4 \text{ kmol } NH_3}{5 \text{ kmol } O_2} = 2.50 \text{ kmol } NH_3$$

$$\underline{\% \text{ excess } NH_3} = \frac{2.94 - 2.50}{2.50} \times 100\% = \underline{\underline{17.6\% \text{ excess } NH_3}}$$
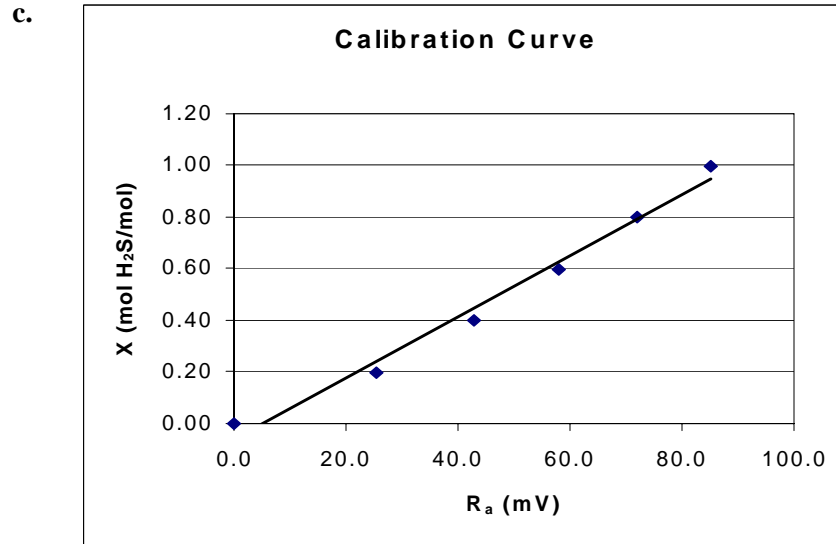
$$\underline{\text{Extent of reaction}}: n_{O_2} = \left(n_{O_2}\right)_0 - v_{O_2}\xi \Rightarrow 0 = 3.125 - (-5)\xi \Rightarrow \xi = 0.625 \text{ kmol} = \underline{\underline{625 \text{ mol}}}$$

$$\underline{\text{Mass of NO}}: \frac{3.125 \text{ kmol } O_2}{} \bigg| \frac{4 \text{ kmol NO}}{5 \text{ kmol } O_2} \bigg| \frac{30.0 \text{ kg NO}}{1 \text{ kmol NO}} = \underline{\underline{75.0 \text{ kg NO}}}$$

4.41 a. By adding the feeds in stoichometric 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.
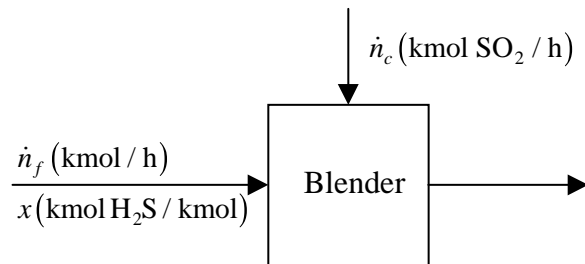
4.41 (cont'd)

b.

$$\dot{n}_c = \frac{3.00 \times 10^2 \text{ kmol}}{\text{h}} \left| \frac{0.85 \text{ kmol H}_2\text{S}}{\text{kmol}} \right| \frac{1 \text{ kmol SO}_2}{2 \text{ kmol H}_2\text{S}} = \underline{\underline{127.5 \text{ kmol SO}_2 \text{ / h}}}$$

c.

Calibration Curve

$$\underline{\underline{X = 0.0199 R_a - 0.0605}}$$

d.

$\dot{n}_c \left(\text{kmol SO}_2 \text{ / h} \right)$

$\dfrac{\dot{n}_f \left(\text{kmol / h} \right)}{x \left(\text{kmol H}_2\text{S / kmol} \right)}$

Blender

Flowmeter calibration: $\left. \begin{array}{l} \dot{n}_f = aR_f \\ \dot{n}_f = 100 \text{ kmol / h}, R_f = 15 \text{ mV} \end{array} \right\} \dot{n}_f = \dfrac{20}{3} R_f$

Control valve calibration: $\left. \begin{array}{l} \dot{n}_c = 25.0 \text{ kmol / h}, \text{R}_c = 10.0 \text{ mV} \\ \dot{n}_c = 60.0 \text{ kmol / h}, \text{R}_c = 25.0 \text{ mV} \end{array} \right\} \dot{n}_c = \dfrac{7}{3} R_c + \dfrac{5}{3}$

Stoichiometric feed: $\dot{n}_c = \dfrac{1}{2} \dot{n}_f x \Rightarrow \dfrac{7}{3} R_c + \dfrac{5}{3} = \dfrac{1}{2} \left(\dfrac{20}{3} R_f \right) (0.0119 R_a - 0.0605)$

$$\Rightarrow \underline{\underline{R_c = \dfrac{10}{7} R_f (0.0119 R_a - 0.0605) - \dfrac{5}{7}}}$$

$$\dot{n}_f = 3.00 \times 10^2 \text{ kmol / h} \Rightarrow R_f = \dfrac{3}{20} \dot{n}_f = 45 \text{ mV}$$

4-31

4.41 (cont'd)

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

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

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

4.42

$$
\begin{array}{l}
\underline{165\,\text{mol / s}} \\
x\,(\text{mol } C_2H_4 \text{ / mol}) \\
1 - x\,(\text{mol HBr / mol})
\end{array}
\qquad\longrightarrow\qquad
\begin{array}{l}
\underline{\dot{n}\,(\text{mol / s})} \\
0.310\,\text{mol } C_2H_4 \text{ / mol} \\
0.173\,\text{mol HBr / mol} \\
0.517\,\text{mol } C_2H_5Br \text{ / mol}
\end{array}
$$

$$C_2H_4 + HBr \rightarrow C_2H_5Br$$
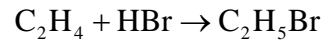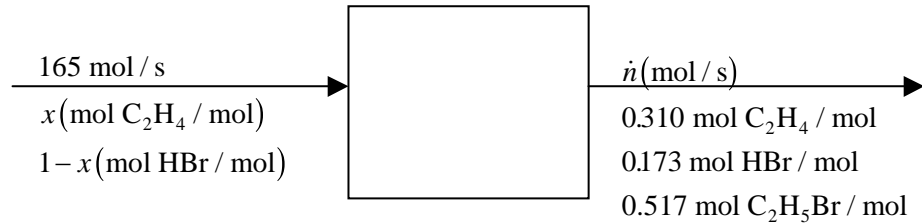
C balance: $\dfrac{165\,\text{mol}}{s}\left|\dfrac{x\,(\text{mol } C_2H_4)}{\text{mol}}\right|\dfrac{2\,\text{mol C}}{\text{mol } C_2H_4} = \dot{n}(0.310)(2) + \dot{n}(0.517)(2)$ \hfill (1)

Br balance: $165(1-x)(1) = \dot{n}(0.173)(1) + \dot{n}(0.517)(1)$ \hfill (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), HBr is the limiting reactant .

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

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

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

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

% excess of $C_2H_4 = \dfrac{89.93 - 75.08}{75.08} = 19.8\%$

Extent of reaction: $\dot{n}_{C_2H_5Br} = \left(\dot{n}_{C_2H_5Br}\right)_0 + v_{C_2H_5Br}\xi \Rightarrow (108.8)(0.517) = 0 + (1)\xi \Rightarrow \xi = 56.2\,\text{mol/s}$

4.43 **a.** $2HCl + \dfrac{1}{2}O_2 \rightarrow Cl_2 + H_2O$ Basis: 100 mol HCl fed to reactor

100 mol HCl		$n_2\,(mol\,HCl)$
		$n_3\,(mol\,O_2)$
$n_1\,(mol\,air)$		$n_4\,(mol\,N_2)$
0.21 mol O_2 / mol		$n_5\,(mol\,Cl_2)$
0.79 mol N_2 / mol		$n_6\,(mol\,H_2O)$
35% excess		
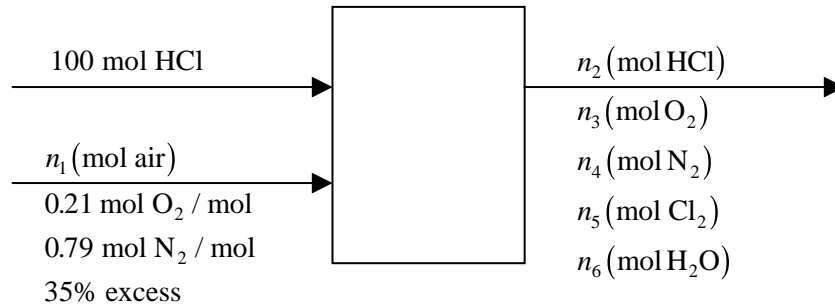
$$(O_2)_{stoic} = \frac{100\ \text{mol HCl}\ \big|\ 0.5\ \text{mol O}_2}{\big|\ 2\ \text{mol HCl}} = 25\ \text{mol O}_2$$

<u>35% excess air:</u> $0.21n_1(\text{mol O}_2\ \text{fed}) = 1.35 \times 25 \Rightarrow n_1 = 160.7\ \text{mol air fed}$

<u>85% conversion</u> $\Rightarrow 85\ \text{mol HCl react} \Rightarrow n_2 = 15\ \text{mol HCl}$

$$n_5 = \frac{85\ \text{mol HCl react}\ \big|\ 1\ \text{mol Cl}_2}{\big|\ 2\ \text{mol HCl}} = 42.5\ \text{mol Cl}_2$$

$n_6 = (85)(1/2) = 42.5\ \text{mol H}_2O$

<u>N_2 balance:</u> $(160.7)(0.79) = n_4 \Rightarrow n_4 = 127\ \text{mol N}_2$

<u>O balance:</u>

$$\frac{(160.7)(0.21)\ \text{mol O}_2\ \big|\ 2\ \text{mol O}}{\big|\ 1\ \text{mol O}_2} = 2n_3 + \frac{42.5\ \text{mol H}_2O\ \big|\ 1\ \text{mol O}}{\big|\ 1\ \text{mol H}_2O} \Rightarrow n_3 = 12.5\ \text{mol O}_2$$

<u>Total moles:</u>

$$\sum_{j=2}^{5} n_j = 239.5\ \text{mol} \Rightarrow \frac{15\ \text{mol HCl}}{239.5\ \text{mol}} = 0.063\ \frac{\text{mol HCl}}{\text{mol}},\ 0.052\ \frac{\text{mol O}_2}{\text{mol}},\ 0.530\ \frac{\text{mol N}_2}{\text{mol}},$$

$$0.177\ \frac{\text{mol Cl}_2}{\text{mol}},\ 0.177\ \frac{\text{mol H}_2O}{\text{mol}}$$

b. As before, $n_1 = 160.7\ \text{mol air fed}$, $n_2 = 15\ \text{mol HCl}$

$$2HCl + \frac{1}{2}O_2 \rightarrow Cl_2 + H_2O$$
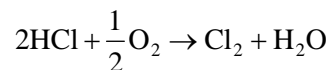
$$n_i = (n_i)_0 + v_i \xi$$
$$\Downarrow$$

<u>HCl:</u> $15 = 100 - 2\xi \Rightarrow \xi = 42.5\ \text{mol}$

4.43 (cont'd)

$$O_2: \quad n_3 = 0.21(160.7) - \frac{1}{2}\xi = \underline{\underline{12.5 \text{ mol } O_2}}$$

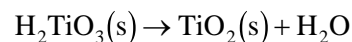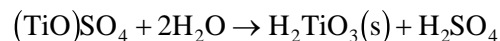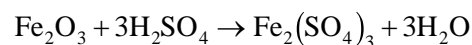$$N_2: \quad n_4 = 0.79(160.7) = \underline{\underline{127 \text{ mol } N_2}}$$

$$Cl_2: \quad n_5 = \xi = \underline{\underline{42.5 \text{ mol } Cl_2}}$$

$$H_2O: \quad n_6 = \xi = \underline{\underline{42.5 \text{ mol } H_2O}}$$

These molar quantities are the same as in part (a), so the mole fractions would also be the same.

c. Use of pure O_2 would eliminate the need for an extra process to remove the N_2 from the product gas, but O_2 costs much more than air. The cheaper process will be the process of choice.

4.44

$$FeTiO_3 + 2H_2SO_4 \rightarrow (TiO)SO_4 + FeSO_4 + 2H_2O$$

$$Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 3H_2O$$

$$(TiO)SO_4 + 2H_2O \rightarrow H_2TiO_3(s) + H_2SO_4$$

$$H_2TiO_3(s) \rightarrow TiO_2(s) + H_2O$$

Basis: 1000 kg TiO_2 produced

$$\frac{1000 \text{ kg } TiO_2}{} \left| \frac{\text{kmol } TiO_2}{79.90 \text{ kg } TiO_2} \right| \frac{1 \text{ kmol } FeTiO_3}{1 \text{ kmol } TiO_2} = 12.52 \text{ kmol } FeTiO_3 \text{ decomposes}$$

$$\frac{12.52 \text{ kmol } FeTiO_3 \text{ dec.}}{} \left| \frac{1 \text{ kmol } FeTiO_3 \text{ feed}}{0.89 \text{ kmol } FeTiO_3 \text{ dec.}} = 14.06 \text{ kmol } FeTiO_3 \text{ fed}$$

$$\frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{1 \text{ kmol } Ti}{1 \text{ kmol } FeTiO_3} \right| \frac{47.90 \text{ kg } Ti}{\text{kmol } Ti} = 673.5 \text{ kg } Ti \text{ fed}$$

$$673.5 \text{ kg } Ti \text{ / } M \text{ (kg ore)} = 0.243 \Rightarrow M = \underline{\underline{2772 \text{ kg ore fed}}}$$

Ore is made up entirely of 14.06 kmol $FeTiO_3$ + n(kmol Fe_2O_3) (Assumption!)

$$n = 2772 \text{ kg ore} - \frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{151.74 \text{ kg } FeTiO_3}{\text{kmol } FeTiO_3} = 638.1 \text{ kg } Fe_2O_3 \right.$$

$$\frac{638.1 \text{ kg } Fe_2O_3}{} \left| \frac{\text{kmol } Fe_2O_3}{159.69 \text{ kg } Fe_2O_3} = 4.00 \text{ kmol } Fe_2O_3 \right.$$

$$\frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{2 \text{ kmol } H_2SO_4}{1 \text{ kmol } FeTiO_3} + \frac{4.00 \text{ kmol } FeTiO_3}{} \right| \frac{3 \text{ kmol } H_2SO_4}{1 \text{ kmol } Fe_2O_3} = 40.12 \text{ kmol } H_2SO_4$$

50% excess: $1.5(40.12 \text{ kmol } H_2SO_4) = 60.18 \text{ kmol } H_2SO_4 \text{ fed}$

Mass of 80% solution: $\dfrac{60.18 \text{ kmol } H_2SO_4}{} \left| \dfrac{98.08 \text{ kg } H_2SO_4}{1 \text{ kmol } H_2SO_4} = 5902.4 \text{ kg } H_2SO_4 \right.$

$$5902.4 \text{ kg } H_2SO_4 \text{ / } M_a \text{ (kg soln)} = 0.80 \Rightarrow M_a = \underline{\underline{7380 \text{ kg } 80\% \text{ } H_2SO_4 \text{ feed}}}$$

4.45 **a.** Plot C (log scale) vs. R (linear scale) on semilog paper, get straight line through

$$\left(R_1 = 10, \ \ C_1 = 0.30 \ \text{g}/\text{m}^3 \right) \text{ and } \left(R_2 = 48, \ \ C_2 = 2.67 \ \text{g}/\text{m}^3 \right)$$

$$\ln C = bR + \ln a \Leftrightarrow C = ae^{br}$$

$$b = \frac{\ln(2.67/0.30)}{48 - 10} = 0.0575 \ , \ \ \ln a = \ln(2.67) - 0.0575(48) = -1.78 \Rightarrow a = e^{-1.78} = 0.169$$

$$\Rightarrow \ C = 0.169e^{0.0575R}$$

$$C\left(\text{g}/\text{m}^3\right) = \frac{C'(\ \text{lb}_m)}{\text{ft}^3} \ \left| \ \frac{453.6 \ \text{g}}{1 \ \text{lb}_m} \ \right| \ \frac{35.31 \ \text{ft}^3}{1 \ \text{m}^3} = 16{,}020C'$$

$$\Downarrow$$

$$16{,}020C' = 0.169e^{0.0575R} \Rightarrow \underline{\underline{C'\left(\text{lb}_m \ \text{SO}_2/\text{ft}^3\right) = 1.055 \times 10^{-5}\, e^{0.0575R}}}$$

b. $$\frac{\left(2867 \ \text{ft}^3/\text{s}\right)\left(60 \ \text{s}/\text{min}\right)}{1250 \ \text{lb}_m/\text{min}} = \underline{\underline{138 \ \text{ft}^3/\text{lb}_m \ \text{coal}}}$$

$$R = 37 \Rightarrow C'\left(\text{lb}_m \ \text{SO}_2/\text{ft}^3\right) = 1.055 \times 10^{-5}\, e^{(0.0575)(37)} = 8.86 \times 10^{-5} \ \text{lb}_m \ \text{SO}_2/\text{ft}^3$$

$$\frac{8.86 \times 10^{-5} \ \text{lb}_m \ \text{SO}_2}{\text{ft}^3} \ \left| \ \frac{138 \ \text{ft}^3}{1 \ \text{lb}_m \ \text{coal}} = 0.012 < 0.018 \frac{\text{lb}_m \ \text{SO}_2}{\text{lb}_m \ \text{coal}} \ \underline{\underline{\text{compliance achieved}}}$$

c. $$S + O_2 \rightarrow SO_2$$

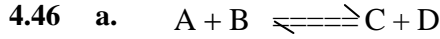$$\frac{1250 \ \text{lb}_m \ \text{coal}}{\text{min}} \ \left| \ \frac{0.05 \ \text{lb}_m \ \text{S}}{1 \ \text{lb}_m \ \text{coal}} \ \right| \ \frac{64.06 \ \text{lb}_m \ \text{SO}_2}{32.06 \ \text{lb}_m \ \text{S}} = 124.9 \ \text{lb}_m \ \text{SO}_2 \ \text{generated}/\text{min}$$

$$\frac{2867 \ \text{ft}^3}{\text{s}} \ \left| \ \frac{60 \ \text{s}}{1 \ \text{min}} \ \right| \ \frac{8.86 \times 10^{-5} \ \text{lb}_m \ \text{SO}_2}{\text{ft}^3} = 15.2 \ \text{lb}_m \ \text{SO}_2/\text{min} \ \text{in scrubbed gas}$$
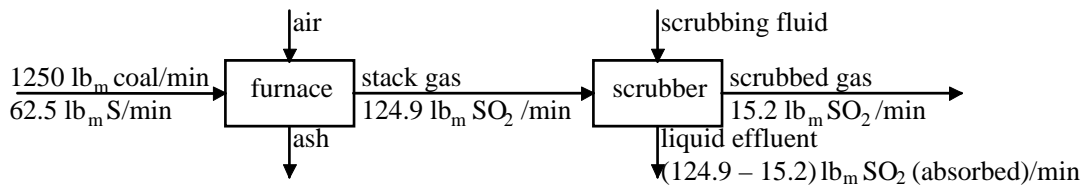
$$\underline{\text{\% removal}} = \frac{\left(124.9 - 15.2\right) \ \text{lb}_m \ \text{SO}_2 \ \text{scrubbed}/\text{min}}{124.9 \ \text{lb}_m \ \text{SO}_2 \ \text{fed to scrubber}/\text{min}} \times 100\% = \underline{\underline{88\%}}$$

d. The regulation was avoided by diluting the stack gas with fresh air before it exited from the stack. The new regulation prevents this since the mass of SO_2 emitted per mass of coal burned is independent of the flow rate of air in the stack.

4.46 **a.** $A + B \rightleftharpoons C + D$

$$\left. \begin{array}{l} n_A = n_{A_0} - \xi \\[6pt] n_B = n_{B_0} - \xi \\[6pt] n_C = n_{C_0} + \xi \\[6pt] n_D = n_{D_0} + \xi \\[6pt] \underline{n_I = n_{I_0}} \\[6pt] \text{Total } n_T = \sum n_i \end{array} \right\} \implies \begin{array}{l} y_A = \left(n_{A_0} - \xi\right)/n_T \\[6pt] y_B = \left(n_{B_0} - \xi\right)/n_T \\[6pt] y_C = \left(n_{C_0} + \xi\right)/n_T \\[6pt] y_D = \left(n_{D_0} + \xi\right)/n_T \end{array}$$

At equilibrium: $\dfrac{y_C y_D}{y_A y_B} = \dfrac{\left(n_{C0} + \xi_c\right)\left(n_{D0} + \xi_c\right)}{\left(n_{A0} - \xi_c\right)\left(n_{B0} - \xi_c\right)} = 4.87 \quad (n_T\text{'s cancel})$

$3.87\xi_c^2 - \left(n_{C0} + n_{D0} + 4.87\left(n_{A0} + n_{B0}\right)\right)\xi_c - \left(n_{C0}n_{D0} - 4.87 n_{A0}n_{B0}\right) = 0$

$[a\xi_c^2 + b\xi_c + c = 0]$

$$\therefore \xi_c = \frac{1}{2a}\left(-b \pm \sqrt{b^2 - 4ac}\right) \text{ where } \begin{array}{l} a = 3.87 \\[4pt] b = -\left[n_{C0} + n_{D0} + 4.87\left(n_{A0} + n_{B0}\right)\right] \\[4pt] c = -\left[n_{C0}n_{D0} - 4.87 n_{A0}n_{B0}\right] \end{array}$$

b. Basis: 1 mol A feed $\quad n_{A0} = 1 \quad n_{B0} = 1 \quad n_{C0} = n_{D0} = n_{I0} = 0$

Constants: $a = 3.87 \quad b = -9.74 \quad c = 4.87$

$\xi_e = \dfrac{1}{2(3.87)}\left(9.74 \pm \sqrt{(9.74)^2 - 4(3.87)(4.87)}\right) \Rightarrow \xi_{e1} = 0.688$

$\left(\xi_{e2} = 1.83 \text{ is also a solution but leads to a negative conversion}\right)$

Fractional conversion: $\underline{X_A \left(= X_B\right)} = \dfrac{n_{A0} - n_A}{n_{A0}} = \dfrac{\xi_{e1}}{n_{A0}} = \underline{\underline{0.688}}$

c. $n_{B0} = 80, n_{C0} = n_{D0} = n_{J0} = 0$

$n_C = 70 = n_{C0} + \xi_c \xRightarrow{\quad n_{C0} = 0 \quad} \xi_c = 70 \text{ mol}$

$n_A = n_{A0} - \xi_c = n_{A0} - 70 \text{ mol}$

$n_B = n_{B0} - \xi_c = 80 - 70 = 10 \text{ mol}$
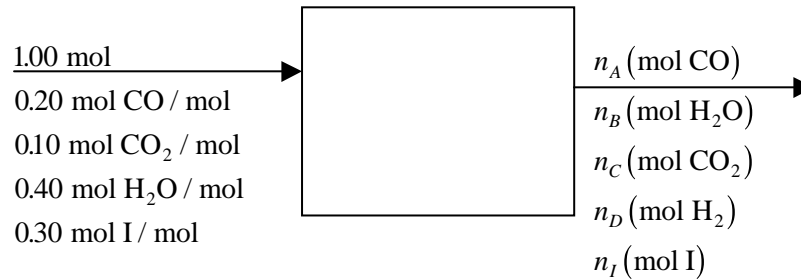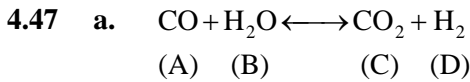
$n_C = n_{C0} + \xi_c = 70 \text{ mol}$

$n_D = n_{D0} + \xi_c = 70 \text{ mol}$

$4.87 = \dfrac{y_C y_D}{y_A y_B} = \dfrac{n_C n_D}{n_A n_B} \Rightarrow \dfrac{(70)(70)}{(n_{A0} - 70)(10)} = 4.87 \Rightarrow \underline{\underline{n_{A0} = 170.6 \text{ mol methanol fed}}}$

4.46 (cont'd)

Product gas $n_A = 170.6 - 70 = 100.6$ mol
$\quad\quad\quad n_B = 10$ mol
$\quad\quad\quad n_C = 70$ mol
$\quad\quad\quad n_D = 70$ mol
$\quad\quad\quad \overline{n_{total} = 250.6\,\text{mol}}$

$\Rightarrow$

$y_A = 0.401$ mol $CH_3OH/$mol
$y_B = 0.040$ mol $CH_3COOH/$mol
$y_C = 0.279$ mol $CH_3COOCH_3/$mol
$y_D = 0.279$ mol $H_2O/$mol

d. Cost of reactants, selling price for product, market for product, rate of reaction, need for heating or cooling, and many other items.

4.47 **a.** $CO + H_2O \longleftrightarrow CO_2 + H_2$

$\quad$ (A)$\quad$ (B)$\quad\quad\quad$ (C)$\quad$ (D)

1.00 mol
0.20 mol CO / mol
0.10 mol CO_2 / mol
0.40 mol H_2O / mol
0.30 mol I / mol

n_A (mol CO)
n_B (mol H_2O)
n_C (mol CO_2)
n_D (mol H_2)
n_I (mol I)

<u>Degree of freedom analysis:</u>$\quad$ 6 unknowns ($n_A, n_B, n_C, n_D, n_I, \xi$)

$\quad\quad\quad$ – 4 expressions for $n_i(\xi)$
$\quad\quad\quad$ – 1 balance on I
$\quad\quad\quad$ – 1 equilibrium relationship
$\quad\quad\quad\quad$ 0 DF

b. Since two moles are prodcued for every two moles that react,

$(n_{total})_{out} = (n_{total})_{in} = \underline{\underline{1.00\,(\text{mol})}}$

$n_A = 0.20 - \xi$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ (1)
$n_B = 0.40 - \xi$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ (2)
$n_C = 0.10 + \xi$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ (3)
$n_D = \xi$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ (4)
$\underline{n_I = 0.30}$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ (5)
$n_{tot} = 1.00\,\text{mol}$

At equilibrium: $\dfrac{y_C y_D}{y_A y_B} = \dfrac{n_C n_D}{n_A n_B} = \dfrac{(0.10 + \xi)(\xi)}{(0.20 - \xi)(0.40 - \xi)} = 0.0247 \exp\left(\dfrac{4020}{1123}\right) \Rightarrow \xi = 0.110$ mol

$y_D = n_D = \xi = \underline{\underline{0.110\,(\text{mol}\,H_2\,/\,\text{mol})}}$

c. The reaction has not reached equilibrium yet.

4.47 **(cont'd)**

d.

T (K)	x (CO)	x (H₂O)	x (CO₂)	Keq	Keq (Goal Seek)	Extent of Reaction	y (H₂)
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.** $A + 2B \rightarrow C$

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

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

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

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

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. Basis: 1 mol A (CO)

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

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

4.48 (cont'd)

(For this particular set of initial conditions, we get a quadratic equation. In general, the equation will be cubic.)

$\xi_e = 0.156$, ~~0.844~~   Reject the second solution, since it leads to a negative n_B.

$y_A = (1 - 0.156)/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_A = 0.500}}$

$y_B = (1 - 2(0.156))/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_B = 0.408}}$

$y_C = (0 + 0.156)/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_C = 0.092}}$

Fractional Conversion of CO $(A) = \dfrac{n_{A0} - n_A}{n_{A0}} = \dfrac{\xi}{n_{A0}} = \underline{\underline{0.156 \text{ mol } A \text{ reacted / mol } A \text{ feed}}}$

d.   Use the equations from part b.

i)   Fractional conversion decreases with increasing fraction of CO.
ii)   Fractional conversion decreases with increasing fraction of CH_3OH.
iii)   Fractional conversion decreases with increasing temperature.
iv)   Fractional conversion increases with increasing pressure.

```
     REAL TRU, A, E, YA0, YC0, T, P, KE, P2KE, C0, C1, C2, C3, EK, EKPI,
    *     FN, FDN, NT, CON, YA, YB, YC
     INTEGER NIT, INMAX
     TAU = 0.0001
     INMAX = 10
     A = 4.79E–13
     E = 11458.
     READ (5, *) YA0, YB0, YC0, T, P
     KE = A * EXP(E/T)
     P2KE = P*P*KE
     C0 = YC0 – P2KE * YA0 * YB0 * YB0
     C1 = 1. – 4. * YC0 + P2KE * YB0 * (YB0 + 4. * YA0)
     C2 = 4. * (YC0 –1. – P2KE * (YA0 + YB0))
     C3 = 4. * (1. + P2KE)
     EK = 0.0        (Assume an initial value ξe = 0.0)
     NIT = 0
1    FN = C0 + EK * (C1 + EK * (C2 + EK * C3))   FDN = C1 + EK * (2. * C2 +
     EK * 3. * C3)   EKPI = EK - FN/FDN   NIT = NIT + 1   IF (NIT.EQ.INMAX)
     GOTO 4   IF (ABS((EKPI – EK)/EKPI).LT.TAU) GOTO 2   EK =
     EKPI   GOTO 1
2    NT = 1. – 2. * EKPI
     YA = (YA0 – EKPI)/NT
     YB = (YB0 – 2. + EKPI)/NT
     YC = (YC0 + EKPI)/NT
```

4.48 (cont'd)

```
        CON = EKPI/YA0   WRITE (6, 3) YA, YB, YC, CON   STOP
4       WRITE (6, 5) INMAX, EKPI
3       FORMAT (' YA   YB   YC   CON', 1, 4(F6.3, 1X))   FORMAT ('DID NOT
        CONVERGE IN', I3, 'ITERATIONS',/,
    *              'CURRENT VALUE = ', F6.3)   END
$   DATA   0.5     0.5     0.0     423.    2.
```
RESULTS: YA = 0.500, YB = 0.408, YC = 0.092, CON = 0.156

Note: This will only find one root — there are two others that can only be found by choosing different initial values of ξ_a

4.49 a.

$$CH_4 + O_2 \longrightarrow HCHO + H_2O \qquad\qquad (1)$$

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad\qquad (2)$$

$$\underline{100 \text{ mol / s}}$$
$$0.50 \text{ mol } CH_4 \text{ / mol}$$
$$0.50 \text{ mol } O_2 \text{ / mol}$$

$\dot{n}_1 \left(\text{mol } CH_4 \text{ / s}\right)$

$\dot{n}_2 \left(\text{mol } O_2 \text{ / s}\right)$

$\dot{n}_3 \left(\text{mol HCHO / s}\right)$

$\dot{n}_4 \left(\text{mol } H_2O \text{ / s}\right)$

$\dot{n}_5 \left(\text{mol } CO_2 \text{ / s}\right)$
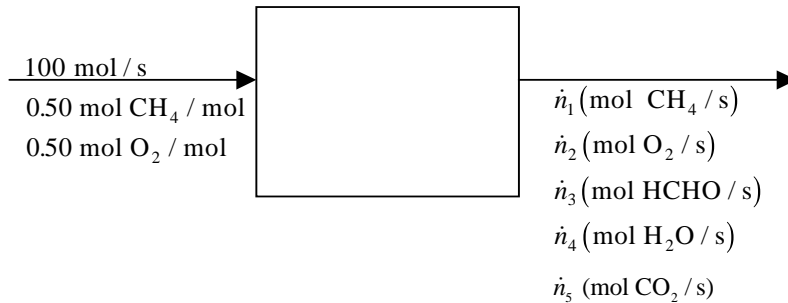
7 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_5, \dot{\xi}_1, \dot{\xi}_2$)

$\underline{-5 \text{ equations for } \dot{n}_i \left(\dot{\xi}_1, \dot{\xi}_2\right)}$

2 DF

b.

$$\dot{n}_1 = 50 - \dot{\xi}_1 - \dot{\xi}_2 \qquad\qquad (1)$$

$$\dot{n}_2 = 50 - \dot{\xi}_1 - 2\dot{\xi}_2 \qquad\qquad (2)$$

$$\dot{n}_3 = \dot{\xi}_1 \qquad\qquad (3)$$

$$\dot{n}_4 = \dot{\xi}_1 + 2\dot{\xi}_2 \qquad\qquad (4)$$

$$\dot{n}_5 = \dot{\xi}_2 \qquad\qquad (5)$$

c. Fractional conversion: $\dfrac{(50 - \dot{n}_1)}{50} = 0.900 \Rightarrow \dot{n}_1 = 5.00 \text{ mol } CH_4 \text{ / s}$

Fractional yield: $\dfrac{\dot{n}_3}{50} = 0.855 \Rightarrow \dot{n}_3 = 42.75 \text{ mol HCHO / s}$

Equation 3 $\Rightarrow \xi_1 = 42.75$ $y_{CH_4} = \underline{0.0500 \text{ mol } CH_4 \text{ / mol}}$

Equation 1 $\Rightarrow \xi_2 = 2.25$ $y_{O_2} = \underline{0.0275 \text{ mol } O_2 \text{ / mol}}$

Equation 2 $\Rightarrow \dot{n}_2 = 2.75$ $\Rightarrow y_{HCHO} = \underline{0.4275 \text{ mol HCHO / mol}}$

Equation 4 $\Rightarrow \dot{n}_4 = 47.25$ $y_{H_2O} = \underline{0.4725 \text{ mol } H_2O \text{ / mol}}$

Equation 5 $\Rightarrow \dot{n}_5 = 2.25$ $y_{CO_2} = \underline{0.0225 \text{ mol } CO_2 \text{ / mol}}$

Selectivity: $[(42.75 \text{ mol HCHO/s})/(2.25 \text{ mol } CO_2/s) = \underline{\underline{19.0 \text{ mol HCHO/mol } CO_2}}$

4.50 **a.** <u>Design for low conversion and feed ethane in excess.</u> Low conversion and excess ethane make the second reaction unlikely.
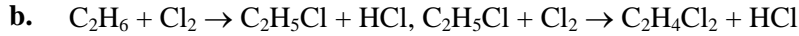
b. $C_2H_6 + Cl_2 \rightarrow C_2H_5Cl + HCl$, $C_2H_5Cl + Cl_2 \rightarrow C_2H_4Cl_2 + HCl$
<u>Basis</u>: 100 mol C_2H_5Cl produced

n_1 (mol C_2H_6)
n_2 (mol Cl_2)

100 mol C_2H_5Cl
n_3 (mol C_2H_6)
n_4 (mol HCl)
n_5 (mol $C_2H_5Cl_2$)

5 unknowns
<u>–3 atomic balances</u>
2 D.F.
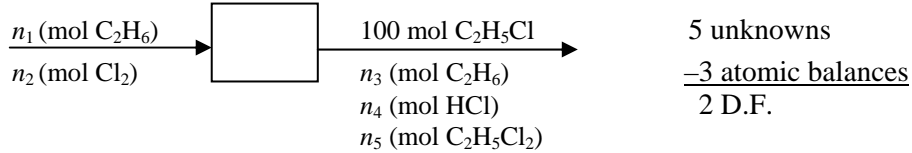
c. <u>Selectivity:</u> 100 mol $C_2H_5Cl = 14 n_5$ (mol $C_2H_4Cl_2$) $\Rightarrow n_5 = 7.143$ mol $C_2H_4Cl_2$

$\left.\begin{array}{l} \underline{15\% \text{ conversion:}} \ (1-0.15)n_1 = n_3 \\ \underline{\text{C balance:}} \quad\quad 2n_1 = 2(100) + 2n_3 + 2(7.143) \end{array}\right\} \Rightarrow \begin{array}{l} n_1 = 714.3 \text{ mol } C_2H_6 \text{ in} \\ n_3 = 114.3 \text{ mol } C_2H_6 \text{ out} \end{array}$

<u>H balance:</u> $6(714.3) = 5(100) + 6(114.3) + n_4 + 4(7.143) \Rightarrow n_4 = 607.1$ mol HCl

<u>Cl balance:</u> $2n_2 = 100 + 607.1 + 2(7.143) \Rightarrow n_2 = 114.3$ mol Cl_2

<u>Feed Ratio:</u> 114.3 mol Cl_2 / 714.3 mol $C_2H_6 = \underline{\underline{0.16 \text{ mol } Cl_2 \text{ / mol } C_2H_6}}$

<u>Maximum possible amount of C_2H_5Cl:</u>

$$n_{max} = \frac{114.3 \text{ mol } Cl_2}{} \left|\frac{1 \text{ mol } C_2H_5Cl}{1 \text{ mol } Cl_2}\right. = 114.3 \text{ mol } C_2H_5Cl$$

<u>Fractional yield of C_2H_5Cl:</u> $\dfrac{n_{C_2H_5Cl}}{n_{max}} = \dfrac{100 \text{ mol}}{114.3 \text{ mol}} = 0.875$

d. Some of the $C_2H_4Cl_2$ is further chlorinated in an undesired side reaction:
$C_2H_5Cl_2 + Cl_2 \rightarrow C_2H_4Cl_3 + HCl$
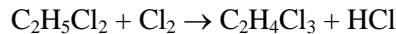
4.51 **a.** $C_2H_4 + H_2O \rightarrow C_2H_5OH$, $2 C_2H_5OH \rightarrow (C_2H_5)_2O + H_2O$

<u>Basis</u>: 100 mol effluent gas

n_1 (mol C_2H_4)
n_2 [mol H_2O (v)]
n_3 (mol I)

100 mol
0.433 mol C_2H_4 / mol
0.025 mol C_2H_5OH / mol
0.0014 mol $(C_2H_5)_2O$ / mol
0.093 mol I / mol
0.4476 mol H_2O (v) / mol

3 unknowns
-2 independent atomic balances
-1 I balance
0 D.F.
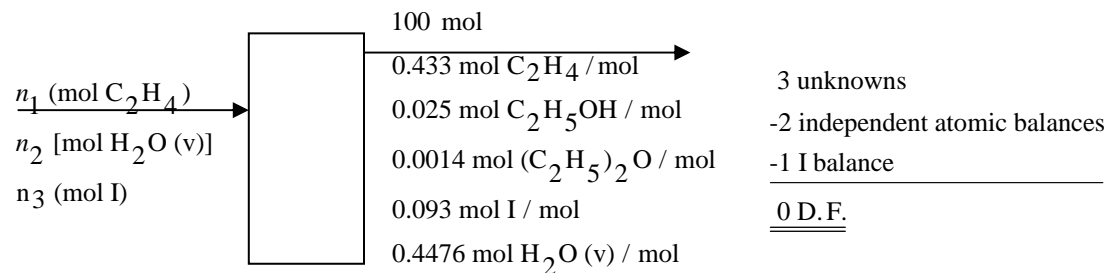
(1) C balance: $2n_1 = 100(2*0.433 + 2*0.025 + 4*0.0014)$

(2) H balance: $4n_1 + 2n_2 = 100(4*0.433 + 6*0.025 + 10*0.0014 + 2*0.4476)$

(3) O balance: $n_2 = 100(0.025 + 0.0014 + 0.4476)$

Note; *Eq.* (1)*2 + Eq. (3)*2 = Eq. (2) $\Rightarrow$ 2 independent atomic balances

(4) I balance: $n_3 = 9.3$

4.51 (cont'd)

    b.

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

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

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

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

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

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

    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 $CaF_2(s) + H_2SO_4(l) \rightarrow CaSO_4(s) + 2HF(g)$
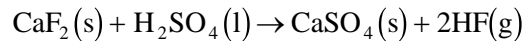
$$\dfrac{1 \text{ metric ton acid}}{} \left| \dfrac{1000 \text{ kg acid}}{1 \text{ metric ton acid}} \right| \dfrac{0.60 \text{ kg HF}}{1 \text{ kg acid}} = 600 \text{ kg HF}$$

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

100 kg Ore dissolved
0.96 kg CaF_2/kg
0.04 kg SiO_2/kg
n_A (kg 93% H_2SO_4)
0.93 H_2SO_4 kg/kg
0.07 H_2O kg/kg

n_1 (kg $CaSO_4$)
n_2 (kg HF)
n_3 (kg H_2SiF_6)
n_4 (kg H_2SO_4)
n_5 (kg H_2O)
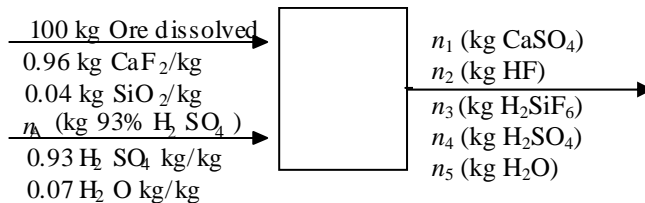
$\underline{\text{Atomic balance - Si:}}$

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

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

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

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

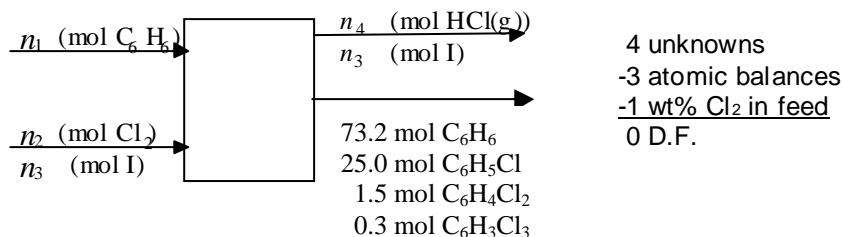$$\dfrac{600 \text{ kg HF}}{} \left| \dfrac{100 \text{ kg ore diss.}}{41.2 \text{ kg HF}} \right| \dfrac{1 \text{ kg ore feed}}{0.95 \text{ kg ore diss.}} = \underline{\underline{1533 \text{ kg ore}}}$$

4.53 **a.** $C_6H_6 + Cl_2 \rightarrow C_6H_5Cl + HCl$

$C_6H_5Cl + Cl_2 \rightarrow C_6H_4Cl_2 + HCl$

$C_6H_4Cl_2 + Cl_2 \rightarrow C_6H_3Cl_3 + HCl$
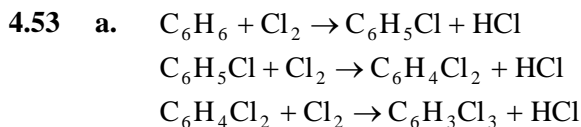
Convert output wt% to mol%: Basis 100 g output

species	g	Mol. Wt.	mol	mol %
C_6H_6	65.0	78.11	0.832	73.2
C_6H_5Cl	32.0	112.56	0.284	25.0
$C_6H_4Cl_2$	2.5	147.01	0.017	1.5
$C_6H_3Cl_3$	0.5	181.46	0.003	0.3
			total 1.136	

Basis: 100 mol output

n_1 (mol C_6H_6)

n_2 (mol Cl_2)
n_3 (mol I)

n_4 (mol HCl(g))
n_3 (mol I)

73.2 mol C_6H_6
25.0 mol C_6H_5Cl
1.5 mol $C_6H_4Cl_2$
0.3 mol $C_6H_3Cl_3$

4 unknowns
-3 atomic balances
-1 wt% Cl_2 in feed
0 D.F.

b. <u>C balance:</u> $6n_1 = 6(73.2 + 25.0 + 1.5 + 0.3) \Rightarrow n_1 = 100$ mol C_6H_6

<u>H balance:</u> $6(100) = 6(73.2) + 5(25.0) + 4(1.5) + 3(0.3) + n_4 \Rightarrow n_4 = 28.9$ mol HCl

<u>Cl balance:</u> $2n_2 = 28.9 + 25.0 + 2(1.5) + 3(0.3) \Rightarrow n_2 = 28.9$ mol Cl_2

<u>Theoretical C_6H_6</u> $= 28.9$ mol $Cl_2 (1$ mol $C_6H_6/1$ mol $Cl_2) = 28.9$ mol C_6H_6

<u>Excess C_6H_6:</u> $(100 - 28.9)/28.9 \times 100\% = \underline{\underline{246\% \text{ excess } C_6H_6}}$

<u>Fractional Conversion:</u> $(100 - 73.2)/100 = \underline{\underline{0.268 \text{ mol } C_6H_6 \text{ react/mol fed}}}$

<u>Yield:</u> $(25.0$ mol $C_6H_5Cl)/(28.9$ mol C_6H_5Cl maximum$) = \underline{\underline{0.865}}$

<u>Gas feed:</u> $\dfrac{28.9 \text{ mol } Cl_2}{}\left|\dfrac{70.91 \text{ g } Cl_2}{\text{mole } Cl_2}\right|\dfrac{1 \text{ g gas}}{0.98 \text{ g } Cl_2} = 2091$ g gas

<u>Liquid feed:</u> $(100$ mol $C_6H_6)\left(\dfrac{78.11 \text{ g } C_6H_6}{\text{mol } C_6H_6}\right) = 7811$ g liquid

$\Rightarrow 0.268\,\dfrac{\text{g gas}}{\text{g liquid}}$

c. Low conversion $\Rightarrow$ low residence time in reactor $\Rightarrow$ lower chance of 2nd and 3rd reactions occurring. Large excess of $C_6H_6 \Rightarrow Cl_2$ much more likely to encounter C_6H_6 than substituted $C_6H_6 \Rightarrow$ higher selectivity.

d. Dissolve in water to produce hydrochloric acid.

e. Reagent grade costs <u>much</u> more. Use only if impurities in technical grade mixture affect the reaction rate or desired product yield.

4.54 **a.** $2CO_2 \Leftrightarrow 2CO + O_2$ $\qquad\qquad$ $2A \Leftrightarrow 2B + C$

$O_2 + N_2 \Leftrightarrow 2NO$ $\qquad\qquad$ $C + D \Leftrightarrow 2E$
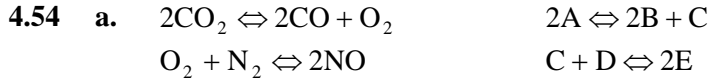
$$n_A = n_{A0} - 2\xi_{e1} \qquad\qquad y_A = (n_{A0} - 2\xi_{e1})/(n_{T0} + \xi_{e1})$$

$$n_B = n_{B0} + 2\xi_{e2} \qquad\qquad y_B = (n_{B0} + 2\xi_{e1})/(n_{T0} + \xi_{e1})$$

$$n_C = n_{C0} + \xi_{e1} - \xi_{e2} \Rightarrow y_C = (n_{C0} + \xi_{e1} - \xi_{e2})/(n_{T0} + \xi_{e1})$$

$$n_D = n_{D0} - \xi_{e2} \qquad\qquad y_D = (n_{D0} - 1\xi_{e2})/(n_{T0} + \xi_{e1})$$

$$\underline{n_E = n_{E0} + 2\xi_{e2}} \qquad\qquad y_E = (n_{E0} + 2\xi_{e2})/(n_{T0} + \xi_{e1})$$

$$n_{total} = n_{T0} + \xi_{e1} \qquad\qquad (n_{T0} = n_{A0} + n_{B0} + n_{C0} + n_{D0} + n_{E0})$$

<u>Equilibrium at 3000K and 1 atm</u>

$$\frac{y_B^2 y_C}{y_A^2} = \frac{(n_{B0} + 2\xi_{e1})^2 (n_{C0} + \xi_{e1} - \xi_{e2})}{(n_{A0} - 2\xi_{e1})^2 (n_{T0} + \xi_{e1})} = 0.1071$$

$$\frac{y_E^2}{y_C y_D} = \frac{(n_{E0} + 2\xi_{e2})^2}{(n_{A0} + \xi_{e1} - \xi_{e2})(n_{D0} - \xi_{e2})} = 0.01493$$

$\Downarrow$

$$\underline{\underline{f_1 = 0.1071(n_{A0} - 2\xi_{e1})^2 (n_{T0} + \xi_{e1}) - (n_{B0} + 2\xi_{e1})^2 (n_{C0} + \xi_{e1} - \xi_{e2}) = 0}}$$

$$\left.\underline{\underline{f_2 = 0.01493(n_{C0} + \xi_{e1} - \xi_{e2})(n_{D0} - \xi_{e2}) - (n_{E0} + 2\xi_{e2})^2 = 0}}\right\}$$
Defines functions $f_1(\xi_1, \xi_2)$ and $f_2(\xi_1, \xi_2)$

b. Given all n_{io}'s, solve above equations for ξ_{e1} and $\xi_{e2} \Rightarrow n_A, n_B, n_C, n_D, n_E \Rightarrow y_A, y_B, y_C, y_D, y_E$

c. $n_{A0} = n_{C0} = n_{D0} = 0.333$, $n_{B0} = n_{E0} = 0 \Rightarrow \xi_{e1} = 0.0593$, $\xi_{e2} = 0.0208$

$\Rightarrow \underline{y_A = 0.2027}, \underline{y_B = 0.1120}, \underline{y_C = 0.3510}, \underline{y_D = 0.2950}, \underline{y_E = 0.0393}$

d. $a_{11}d_1 + a_{12}d_2 = -f_1$ $\qquad\qquad$ $a_{21}d_1 + a_{22}d_2 = -f_2$

$$d_1 = \frac{a_{12}f_2 - a_{22}f_1}{a_{11}a_{22} - a_{12}a_{21}} \qquad\qquad d_2 = \frac{a_{21}f_1 - a_{11}f_2}{a_{11}a_{22} - a_{12}a_{21}}$$

$$(\xi_{e1})_{new} = \xi_{e1} + d_1 \qquad\qquad (\xi_{e2})_{new} = \xi_{e1} + d_2$$

(Solution given following program listing.)

```
.          IMPLICIT REAL * 4(N)
           WRITE (6, 1)
    1      FORMAT('1', 30X, 'SOLUTION TO PROBLEM 4.57'////)
    30     READ (5, *) NA0, NB0, NC0, ND0, NE0
           IF (NA0.LT.0.0)STOP
           WRITE (6, 2) NA0, NB0, NC0, ND0, NE0
```

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
```

4.54 (cont'd)

```
ITER = 4   X1A, X2A = 0.05437   0.02213        X1C, X2C = 0.05931      0.02086
ITER = 5   X1A, X2A = 0.05931   0.02086        X1C, X2C = 0.05930      0.02083
ITER = 6   X1A, X2A = 0.05930   0.02083        X1C, X2C = 0.05930      0.02083
YA, YB, YC, YD, YE =          2.0270E − 01   1.1197E − 01   3.5100E − 01
                              2.9501E − 01   3.9319E − 02
```

```
NA0, NB0, NC0, ND0, NE0 = 0.20   0.20   0.20   0.20   0.20
ITER = 1   X1A, X2A = 0.10000                0.10000   X1C, X2C = 0.00012      0.00037
           ↓
ITER = 7   X1A, X2A = −0.02244               −0.08339  X1C, X2C = −0.02244    −0.08339

YA, YB, YC, YD, YE=       2.5051E − 01   1.5868E − 01   2.6693E − 01
                         2.8989E − 01   3.3991E − 02
```

4.55 a.

(B)

$(1-f)\dot{m}_0$ (kg/h)

$x_R = 0$

(A)

$\dot{m}_0$ (kg/h)

x_{RA} (kg R/kg)

$(1-f)\dot{m}_0$ (kg/h)

x_{RA} (kg R/kg)

Reactor: 99% conv. of R

$\dot{m}_1$ (kg/h)

x_{R1} (kg R/kg)

(P)

$\dot{m}_P$ (kg/h)

0.0075 kg R/kg

$f\dot{m}_0$ (kg/h)

x_{RA} (kg R/kg)
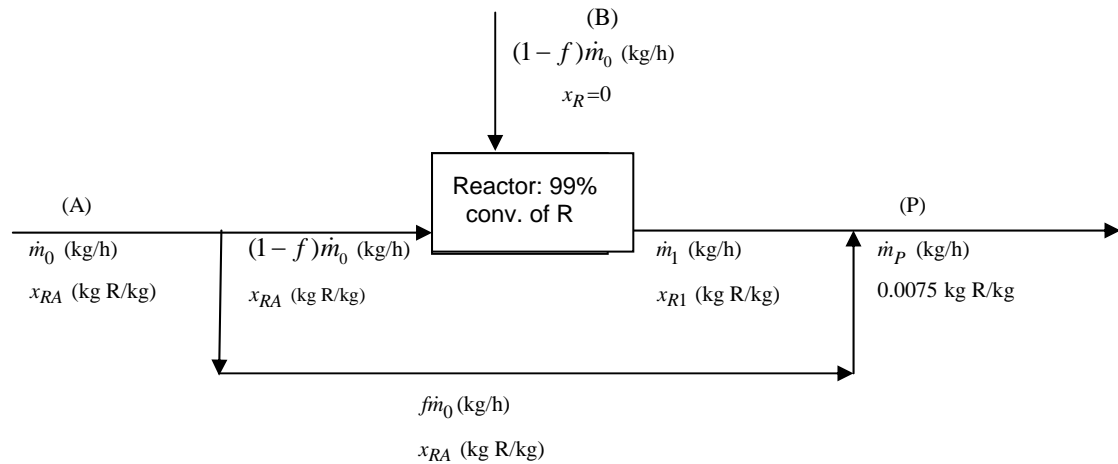
Mass balance on reactor: $\qquad 2(1-f)\dot{m}_0 = \dot{m}_1 \qquad\qquad$ (1)

99% conversion of R: $\qquad \dot{m}_1 x_{R1} = 0.01(1-f)\dot{m}_0 x_{RA} \qquad$ (2)

Mass balance on mixing point: $\qquad \dot{m}_1 + f\dot{m}_0 = \dot{m}_P \qquad\qquad$ (3)

R balance on mixing point: $\qquad \dot{m}_1 x_{R1} + f\dot{m}_0 x_{RA} = 0.0075\dot{m}_P \qquad$ (4)

The system has 6 unknowns $(\dot{m}_0, x_{RA}, f, \dot{m}_1, x_{R1}, \dot{m}_P)$ and four independent equations relating them, so there must be two degrees of freedom.

b.

$$2(1-f)\dot{m}_0 = \dot{m}_1$$
$$\dot{m}_1 x_{R1} = 0.01(1-f)\dot{m}_0 x_{RA}$$
$$\dot{m}_1 + f\dot{m}_0 = \dot{m}_P$$
$$\dot{m}_1 x_{R1} + f\dot{m}_0 x_{RA} = 0.0075\dot{m}_P$$
$$\dot{m}_P = 4850$$
$$x_{RA} = 0.0500$$

$\xrightarrow{\text{E-Z Solve}}$

$\dot{m}_0 = 2780$ kg/h

$f = 0.254$ kg bypassed/kg fresh feed

c.

m_P	x_{RA}	m_{A0}	m_{B0}	f
4850	0.02	3327	1523	0.54
4850	0.03	3022	1828	0.40
4850	0.04	2870	1980	0.31
4850	0.05	2778	2072	0.25
4850	0.06	2717	2133	0.21
4850	0.07	2674	2176	0.19
4850	0.08	2641	2209	0.16
4850	0.09	2616	2234	0.15
4850	0.10	2596	2254	0.13

m_P	x_{RA}	m_{A0}	m_{B0}	f
2450	0.02	1663	762	0.54
2450	0.03	1511	914	0.40
2450	0.04	1435	990	0.31
2450	0.05	1389	1036	0.25
2450	0.06	1359	1066	0.22
2450	0.07	1337	1088	0.19
2450	0.08	1321	1104	0.16
2450	0.09	1308	1117	0.15
2450	0.10	1298	1127	0.13

f vs. x_{RA}
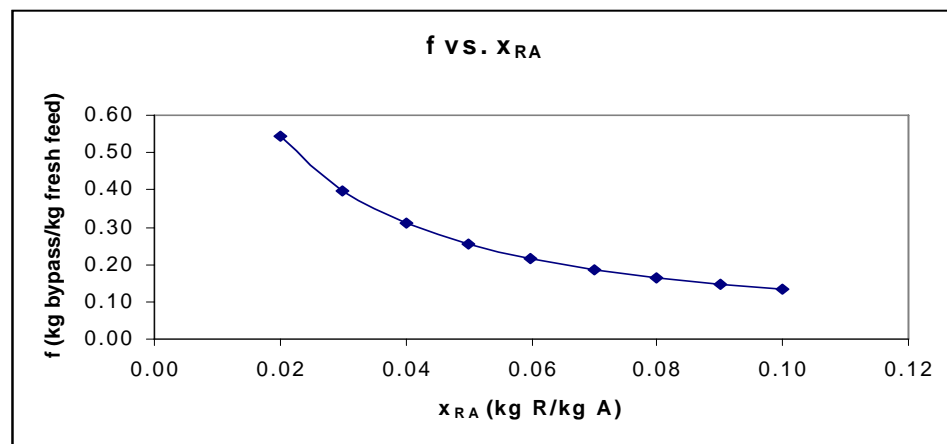
4.56 **a.**
$$\frac{900 \text{ kg HCHO}}{h} \left| \frac{1 \text{ kmol HCHO}}{30.03 \text{ kg HCHO}} \right. = 30.0 \text{ kmol HCHO / h}$$

n_1 (kmol CH_3OH / h)

30.0 kmol HCHO / h

n_2 (kmol H_2 /h)
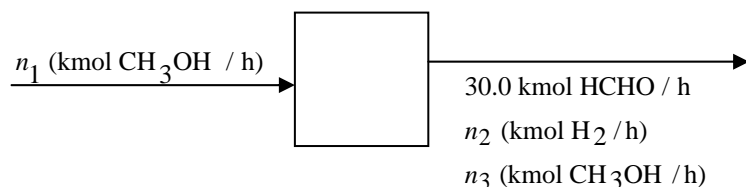
n_3 (kmol CH_3OH /h)

<u>% conversion:</u> $\dfrac{30.0}{n_1} = 0.60 \Rightarrow \underline{\underline{n_1 = 50.0 \text{ kmol } CH_3OH / h}}$

b.

n_1 (kmol CH_3OH / h)

30.0 kmol HCHO / h

n_2 (kmol H_2 /h)

n_3 (kmol CH_3OH /h)

30.0 kmol HCHO / h

n_2 (kmol H_2 /h)
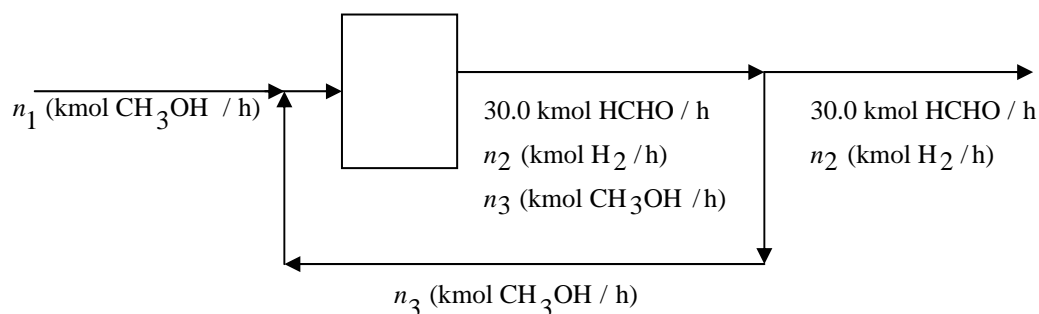
n_3 (kmol CH_3OH / h)

<u>Overall C balance:</u> $n_1 (1) = 30.0 (1) \Rightarrow n_1 = 30.0 \text{ kmol } CH_3OH/h$ (fresh feed)

<u>Single pass conversion:</u> $\dfrac{30.0}{n_1 + n_3} = 0.60 \Rightarrow \underline{\underline{n_3 = 20.0 \text{ kmol } CH_3OH / h}}$

$n_1 + n_3 = \underline{50.0 \text{ kmol } CH_3OH \text{ fed to reactor/h}}$

c. Increased x_{sp} will (1) require a larger reactor and so will increase the cost of the reactor and
(2) lower the quantities of unreacted methanol and so will decrease the cost of the
separation. The plot would resemble a concave upward parabola with a minimum
around $x_{sp} = 60\%$.

4.57 **a.** <u>Convert effluent composition to molar basis</u>. <u>Basis</u>: 100 g effluent:

$$\left. \begin{array}{l} \dfrac{10.6 \text{ g } H_2}{} \left| \dfrac{1 \text{ mol } H_2}{2.01 \text{ g } H_2} \right. = 5.25 \text{ mol } H_2 \\[4mm] \dfrac{64.0 \text{ g CO}}{} \left| \dfrac{1 \text{ mol CO}}{28.01 \text{ g CO}} \right. = 2.28 \text{ mol CO} \\[4mm] \dfrac{25.4 \text{ g } CH_3OH}{} \left| \dfrac{1 \text{ mol } CH_3OH}{32.04 \text{ g } CH_3OH} \right. \\[4mm] = 0.793 \text{ mol } CH_3OH \end{array} \right\} \Rightarrow$$

H_2: 0.631 mol H_2 / mol
CO: 0.274 mol CO / mol
CH_3OH: 0.0953 mol CH_3OH / mol

4.57 (cont'd)

$\dot{n}_4$ (mol/min)

0.004 mol CH$_3$OH(v)/mol

x (mol CO/mol)

$(0.896 - x)$ (mol H$_2$/mol)

```
                    ┌──────────┐                      ┌──────────┐
 $\dot{n}_1$ (mol CO/min) →│  Reactor │  350 mol/min   │   Cond.  │ $\dot{n}_3$ (mol CH$_3$OH(l)/min) →
 $\dot{n}_2$ (mol H$_2$/min) →│          │  0.631 mol CH$_3$OH(v)/mol │          │
                    └──────────┘  0.274 mol CO/mol     └──────────┘
         CO+H$_2$→CH$_3$OH   0.0953 mol H$_2$/mol
```

350 mol/min

0.631 mol CH$_3$OH(v)/mol

0.274 mol CO/mol

0.0953 mol H$_2$/mol

CO+H$_2$→CH$_3$OH
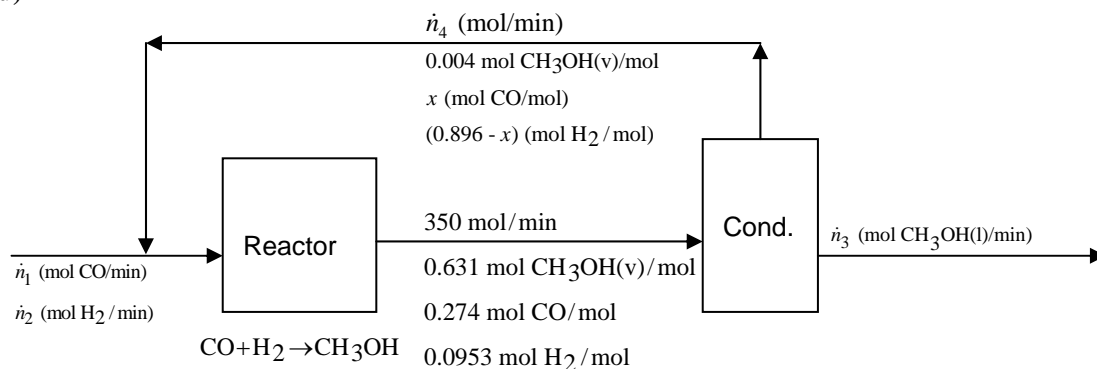
<u>Condenser</u>

  3 unknowns $(\dot{n}_3, \dot{n}_4, x)$

<u>–3 balances</u>

  0 degrees of freedom

<u>Overall process</u>

  2 unknowns $(\dot{n}_1, \dot{n}_2)$

<u>–2 independent atomic balances</u>

  0 degrees of freedom

<u>Balances around condenser</u>

$$\left.\begin{array}{l} \text{CO: } 350*0.274 = \dot{n}_4 * x \\ \text{H}_2: \ 350*0.631 = \dot{n}_4 *(0.996 - x) \\ \text{CH}_3\text{OH}: \ 350*0.0953 = \dot{n}_3 + 0.004 * \dot{n}_4 \end{array}\right\} \Rightarrow \begin{array}{l} \underline{\underline{\dot{n}_3 = 32.1 \text{ mol CH}_3\text{OH(l)/min}}} \\ \dot{n}_4 = 318.7 \text{ mol recycle/min} \\ x = .301 \text{ molCO/mol} \end{array}$$

<u>Overall balances</u>

$$\left.\begin{array}{l} \text{C: } \dot{n}_1 = \dot{n}_3 \\ \text{H: } 2\dot{n}_2 = 4\dot{n}_3 \end{array}\right\} \Rightarrow \begin{array}{l} \underline{\underline{\dot{n}_1 = 32.08 \text{ mol/min CO in feed}}} \\ \underline{\underline{\dot{n}_2 = 64.16 \text{ mol/min H}_2 \text{ in feed}}} \end{array}$$

<u>Single pass conversion of CO:</u> $\dfrac{(32.08 + 318.72 * 0.3009) - 350 * 0.274}{(32.08 + 318.72 * 0.3009)} \times 100\% = \underline{\underline{25.07\%}}$

<u>Overall conversion of CO:</u> $\dfrac{32.08 - 0}{32.08} \times 100\% = \underline{\underline{100\%}}$

b.   –   Reactor conditions or feed rates drifting. (Recalibrate measurement instruments.)

      –   Impurities in feed. (Re-analyze feed.)

      –   Leak in methanol outlet pipe before flowmeter. (Check for it.)

4.58 **a.** Basis: 100 kmol reactor feed/hr

n_3 (kmol CH$_4$ /h)

100 kmol /h

Reactor

Cond.

Absorb

Solvent

n_1 (kmol CH$_4$ /h) 80 kmol CH$_4$ /h
n_2 (kmol Cl$_2$ /h) 20 kmol Cl$_2$ /h

n_3 (kmol CH$_4$ /h)
n_4 (kmol HCl /h)
5n_5 (kmol CH$_3$Cl /h)
n_5 (kmol CH$_2$Cl$_2$ /h)

n_3 (kmol CH$_4$ /h)
n_4 (kmol HCl/h)

n_4 (kmol HCl/h)

5n_5 (kmol CH$_3$Cl /h)

Still

5n_5 (kmol CH$_3$Cl /h)
n_5 (kmol CH$_2$Cl$_2$ /h)

n_5 (kmol CH$_2$Cl$_2$ /h)
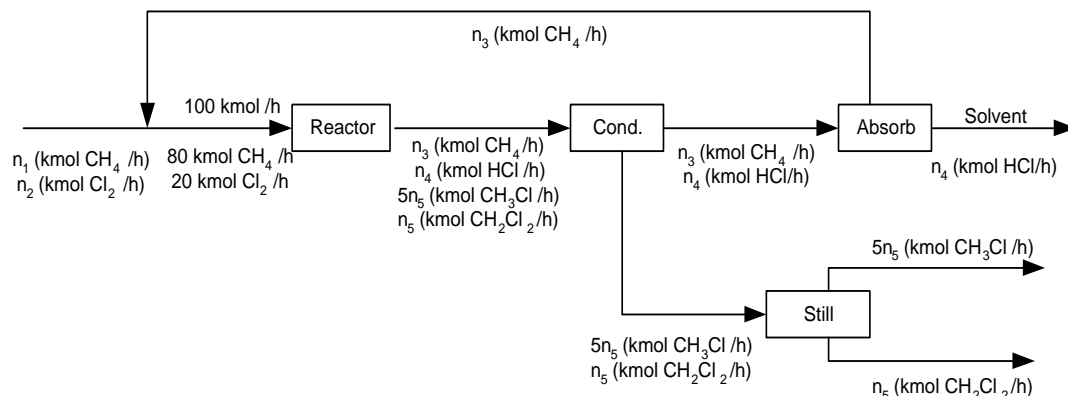
Overall process: 4 unknowns (n_1, n_2, n_4, n_5) -3 balances = 1 D.F.
Mixing Point: 3 unknowns (n_1, n_2, n_3) -2 balances = 1 D.F.
Reactor: 3 unknowns (n_3, n_4, n_5) -3 balances = 0 D.F.
Condenser: 3 unknowns (n_3, n_4, n_5) -0 balances = 3 D.F.
Absorption column: 2 unknowns (n_3, n_4) -0 balances = 2 D.F.
Distillation Column: 2 unknowns (n_4, n_5) -0 balances = 2 D.F.
Atomic balances around reactor:

$$\left.\begin{array}{l} 1)\,\text{C balance}:\ 80 = n_3 + 5n_5 + n_5 \\ 2)\,\text{H balance}:320 = 4n_3 + n_4 + 15n_5 + 2n_5 \\ 3)\,\text{Cl balance}:40 = n_4 + 5n_5 + 2n_5 \end{array}\right\} \Rightarrow \text{Solve for } n_3, n_4, n_5$$

CH$_4$ balance around mixing point: $n_1 = (80 - n_3)$ Solve for n_1
Cl$_2$ balance: $n_2 = 20$

b. For a basis of 100 kmol/h into reactor

n_1 = 17.1 kmol CH$_4$/h n_4 = 20.0 kmol HCl/h

n_2 = 20.0 kmol Cl$_2$/h   5n_5 = 14.5 kmol CH$_3$Cl/h

n_3 = 62.9 kmol CH$_4$/h

c. (1000 kg CH$_3$Cl/h)(1 kmol/50.49 kg) = 19.81 kmol CH$_3$Cl/h

$$\text{Scale factor} = \frac{19.81\,\text{kmol CH}_3\text{Cl/h}}{14.5\,\text{kmol CH}_3\text{Cl/h}} = 1.366$$

Fresh feed: $\left.\begin{array}{l} n_1 = (17.1)(1.366) = 23.3\,\text{kmol CH}_4\text{/h} \\ n_2 = (20.0)(1.366) = 27.3\,\text{kmol Cl}_2\text{/h} \end{array}\right\} \Rightarrow$ $\begin{array}{l} n_{tot} = 50.6\,\text{kmol/h} \\ 46.0\,\text{mol% CH}_4, 54.0\,\text{mole% Cl}_2 \end{array}$

Recycle: n_3 = (62.9)(1.366) = 85.9 kmol CH$_4$ recycled/h

4.59 **a.** Basis: 100 mol fed to reactor/h $\Rightarrow$ 25 mol O_2/h, 75 mol C_2H_4/h
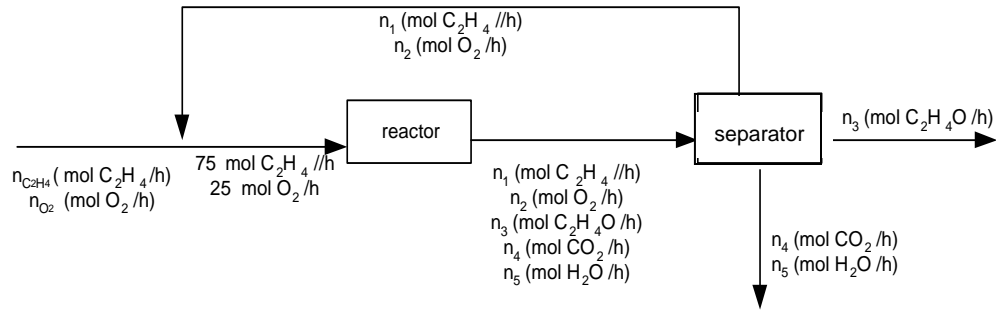
Reactor

      5 unknowns (n_1 - n_5)

      -3 atomic balances

      -1 - % yield

      <u>-1 - % conversion</u>

      0 D.F.

<u>Strategy:</u> 1. Solve balances around reactor to find n_1- n_5

          2. Solve balances around mixing point to find n_{O2}, n_{C2H4}

(1) % Conversion $\Rightarrow n_1 = .800 * 75$

(2) % yield: $(.200)(75)\,\mathrm{mol}\,C_2H_4 \times \dfrac{90\,\mathrm{mol}\,C_2H_4O}{100\,\mathrm{mol}\,C_2H_4} = n_3$ (production rate of C_2H_4O)

(3) C balance (reactor): $150 = 2\,n_1 + 2\,n_3 + n_4$

(4) H balance (reactor): $300 = 4\,n_1 + 4\,n_3 + 2\,n_5$

(5) O balance (reactor): $50 = 2\,n_2 + n_3 + 2\,n_4 + n_5$

(6) O_2 balance (mix pt): $n_{O2} = 25 - n_2$

(7) C_2H_4 balance (mix pt): $n_{C2H4} = 75 - n_1$

<u>Overall conversion of C_2H_4:</u> 100%

b. $n_1 = 60.0$ mol C_2H_4/h $n_5 = 3.00$ mol H_2O/h

      $n_2 = 13.75$ mol O_2 /h $n_{O2} = \underline{11.25\ \mathrm{mol}\ O_2/h}$

      $n_3 = \underline{13.5\ \mathrm{mol}\ C_2H_4O/h}$ $n_{C2H4} = \underline{15.0\ \mathrm{mol}\ C_2H_4/h}$

      $n_4 = 3.00$ mol CO_2/h   <u>100% conversion of C_2H_4</u>

c.

$$\underline{\text{Scale factor}} = \frac{2000\,\mathrm{lbm}\,C_2H_4O}{h}\left|\frac{1\,\mathrm{lb\text{-}mole}\,C_2H_4O}{44.05\,\mathrm{lbm}\,C_2H_4O}\right|\frac{h}{13.5\,\mathrm{mol}\,C_2H_4O} = 3.363\frac{\mathrm{lb-mol}/h}{\mathrm{mol}/h}$$

$n_{C2H4} = (3.363)(15.0) = \underline{50.4\ \mathrm{lb\text{-}mol}\ C_2H_4/h}$

$n_{O2} = (3.363)(11.25) = \underline{37.8\ \mathrm{lb\text{-}mol}\ O_2/h}$

4.60 **a.** Basis: 100 mol feed/h. Put dots above all n's in flow chart.
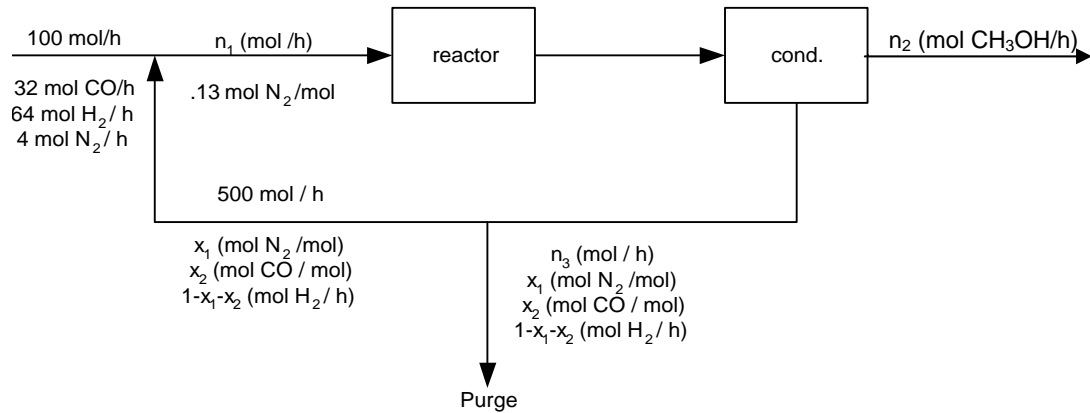
Mixing point balances:

total: $(100) + 500 = \dot{n}_1 \Rightarrow \dot{n}_1 = \underline{600\ mol/h}$

N_2: $4 + x_1 * 500 = .13 * 600 \Rightarrow x_1 = \underline{0.148\ mol\ N_2/mol}$

Overall system balances:

N_2: $4 = .148 * \dot{n}_3 \Rightarrow \dot{n}_3 = \underline{27\ mol/h}$

Atomic C: $32 = \dot{n}_2 + x_2 * 27$

Atomic H: $2 * 64 = 4 * 24.3 + 2 * (1 - 0.148 - x_2) * 27$

$\left.\begin{array}{c} \\ \\ \end{array}\right\} \Rightarrow$ $\dot{n}_2 = \underline{24.3\ mol\ CH_3OH/h}$

$x_2 = \underline{0.284\ mol\ CO/mol}$

Overall CO conversion: $100 * [32 - 0.284(27)]/32 = \underline{76\%}$

Single pass CO conversion: $24.3/(32 + .284 * 500) = \underline{14\%}$

b. Recycle: To recover unconsumed CO and H_2 and get a better overall conversion.

Purge: to prevent buildup of N_2.

4.61 **a.** $N_2 + 3H_2 \rightarrow 2NH_3$
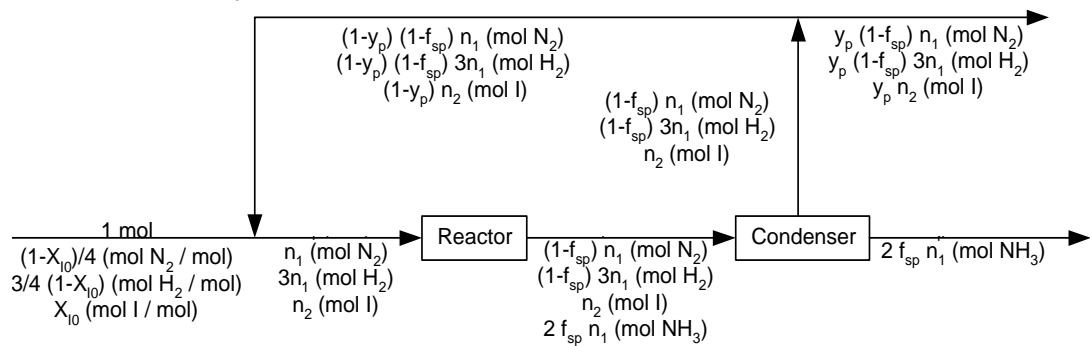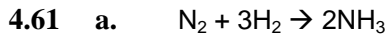
4.61 (cont'd)

At mixing point:

N_2: $(1-X_{I0})/4 + (1-y_p)(1-f_{sp}) n_1 = n_1$

I: $X_{I0} + (1-y_p) n_2 = n_2$

Total moles fed to reactor: $\underline{n_r = 4n_1 + n_2}$

Moles of NH_3 produced: $\underline{n_p = 2f_{sp}n_1}$

Overall N_2 conversion: $\dfrac{(1-X_{I0})/4 - y_p(1-f_{sp})n_1}{(1-X_{I0})/4} \times 100\%$

b. $X_{I0} = 0.01$ $f_{sp} = 0.20$ $y_p = 0.10$

$n_1 = 0.884$ mol N_2 $n_r = \underline{3.636 \text{ mol fed}}$

$n_2 = 0.1$ mol I $n_p = \underline{0.3536 \text{ mol } NH_3 \text{ produced}}$

                                    N_2 conversion = $\underline{71.4\%}$

c. Recycle: recover and reuse unconsumed reactants.

Purge: avoid accumulation of I in the system.

d. Increasing X_{I0} results in increasing n_r, decreasing n_p, and has no effect on f_{ov}. Increasing f_{sp} results in decreasing n_r, increasing n_p, and increasing f_{ov}.

Increasing y_p results in decreasing n_r, decreasing n_p, and decreasing f_{ov}.

Optimal values would result in a low value of n_r and f_{sp}, and a high value of n_p, this would give the highest profit.

X_{I0}	f_{sp}	y_p	n_r	n_p	f_{ov}
0.01	0.20	0.10	3.636	0.354	71.4%
0.05	0.20	0.10	3.893	0.339	71.4%
0.10	0.20	0.10	4.214	0.321	71.4%
0.01	0.30	0.10	2.776	0.401	81.1%
0.01	0.40	0.10	2.252	0.430	87.0%
0.01	0.50	0.10	1.900	0.450	90.9%
0.10	0.20	0.20	3.000	0.250	55.6%
0.10	0.20	0.30	2.379	0.205	45.5%
0.10	0.20	0.40	1.981	0.173	38.5%

4.62 **a.** $i\text{-}C_4H_{10} + C_4H_8 = C_8H_{18}$ <u>Basis</u>: 1-hour operation

Units of n: kmol
Units of m: kg
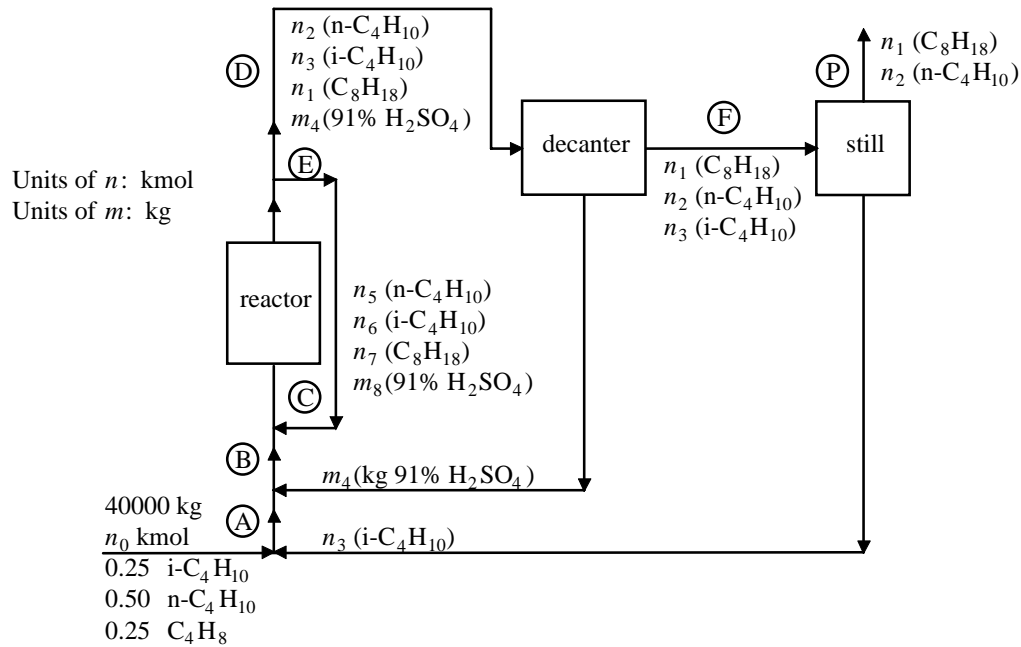
<u>Calculate moles of feed</u>

$$\overline{M} = 0.25M_{L-C_4H_{10}} + 0.50M_{n-C_4H_{10}} + 0.25M_{C_4H_8} = (0.75)(58.12) + (0.25)(56.10)$$
$$= 57.6 \text{ kg/kmol}$$

$$n_0 = (40000 \text{ kg})(1 \text{ kmol/57.6 kg}) = 694 \text{ kmol}$$

<u>Overall n - C_4H_{10} balance:</u> $n_2 = (0.50)(694) = \underline{\underline{347 \text{ kmol n - }C_4H_{10} \text{ in product}}}$

$\underline{C_8H_{18} \text{ balance:}}$

$$n_1 = \frac{(0.25)(694) \text{ kmol } C_4H_8 \text{ react}}{} \left| \frac{1 \text{ mol } C_8H_{18}}{1 \text{ mol } C_4H_8} \right. = \underline{\underline{173.5 \text{ kmol } C_8H_8 \text{ in product}}}$$

<u>At (A)</u>, 5 mol $i\text{-}C_4H_{10}/1$ mole $C_4H_8 \Rightarrow n(\text{mol } i\text{-}C_4H_{10})_A = \underbrace{(5)\underbrace{(0.25)(694)}_{\substack{\text{moles } C_4H_8 \text{ at} \\ A=173.5}}}_{} = \underbrace{867.5 \text{ kmol}}_{\substack{i\text{-}C_4H_{10} \text{ at} \\ (A) \text{ and } (B)}}$

Note: $n(\text{mol } C_4H_8) = 173.5$ at (A), (B) and (C) and in feed

$\underline{i\text{-}C_4H_{10} \text{ balance around first mixing point}} \Rightarrow (0.25)(694) + n_3 = 867.5$

$$\Rightarrow n_3 = \underline{\underline{694 \text{ kmol } i\text{-}C_4H_{10} \text{ recycled from still}}}$$

At C, 200 mol $i\text{-}C_4H_{10}/\text{mol } C_4H_8$

$$\Rightarrow n(\text{mol } i\text{-}C_4H_{10})_C = (200)(173.5) = 34{,}700 \text{ kmol } i\text{-}C_4H_{10}$$

4.62 (cont'd)

i - C_4H_{10} balance around second mixing point $\Rightarrow 867.5 + n_6 = 34,700$

$$\Rightarrow n_6 = \underline{\underline{33,800 \text{ kmol } C_4H_{10} \text{ in recycle E}}}$$

Recycle E: Since Streams (D) and (E) have the same composition,

$$\frac{n_5 \left(\text{moles n - } C_4H_{10}\right)_E}{n_2 \left(\text{moles n - } C_4H_{10}\right)_D} = \frac{n_6 \left(\text{moles } i\text{ - } C_4H_{10}\right)_E}{n_3 \left(\text{moles } i\text{ - } C_4H_{10}\right)_D} \Rightarrow n_5 = \underline{\underline{16,900 \text{ kmol n - } C_4H_{10}}}$$

$$\frac{n_7 \left(\text{moles } C_8H_{18}\right)_E}{n_1 \left(\text{moles } C_8H_{18}\right)_D} = \frac{n_6}{n_3} \Rightarrow n_7 = \underline{\underline{8460 \text{ kmol } C_4H_{18}}}$$

Hydrocarbons entering reactor:

$$\left[(347 + 16900)(\text{kmol n - } C_4H_{10})\right]\left(58.12 \ \frac{\text{kg}}{\text{kmol}}\right)$$

$$+ \left[(867.5 + 33800)(\text{kmol } i\text{ - } C_4H_{10})\right]\left(58.12 \ \frac{\text{kg}}{\text{kmol}}\right) + \left[173.5 \text{ kmol } C_4H_8\right]\left(56.10 \ \frac{\text{kg}}{\text{kmol}}\right)$$

$$+ \left[8460 \text{ kmol } C_8H_{18}\right]\left(114.22 \ \frac{\text{kg}}{\text{kmol}}\right) = 4.00 \times 10^6 \text{ kg} .$$

$$\frac{H_2SO_4 \text{ solution entering reactor}}{\left(\text{and leaving reactor}\right)} = \frac{4.00 \times 10^6 \ \text{kg HC} \ \bigg| \ 2 \text{ kg } H_2SO_4(\text{aq})}{\bigg| \ 1 \text{ kg HC}}$$

$$= 8.00 \times 10^6 \text{ kg } H_2SO_4(\text{aq})$$

$$\frac{m_8\left(H_2SO_4 \text{ in recycle}\right)}{8.00 \times 10^6 \left(H_2SO_4 \text{ leaving reactor}\right)} = \frac{n_5\left(\text{n - } C_4H_{10} \text{ in recycle}\right)}{n_2 + n_5\left(\text{n - } C_4H_{10} \text{ leaving reactor}\right)}$$

$$\Rightarrow m_8 = 7.84 \times 10^6 \text{ kg } H_2SO_4(\text{aq}) \text{ in recycle E}$$

$m_4 = H_2SO_4 \text{ entering reactor} - H_2SO_4 \text{ in E}$

$\quad = 1.6 \times 10^5 \text{ kg } H_2SO_4(\text{aq}) \text{ recycled from decanter}$

$\quad \Rightarrow \left[(1.6 \times 10^5)(0.91)\text{kg } H_2SO_4\right](1 \text{ kmol}/98.08 \text{ kg}) = 1480 \text{ kmol } H_2SO_4 \text{ in recycle}$

$\quad \left[(1.6 \times 10^5)(0.09)\text{kg } H_2O\right](1 \text{ kmol}/18.02 \text{ kg}) = 799 \text{ kmol } H_2O \text{ from decanter}$

Summary: (Change amounts to flow rates)

Product: 173.5 kmol C_8H_{18}/h, 347 kmol n - C_4H_{10}/h

Recycle from still: 694 kmol i - C_4H_{10}/h

Acid recycle: 1480 kmol H_2SO_4/h, 799 kmol H_2O/h

Recycle E: 16,900 kmol n - C_4H_{10}/h, 33,800 kmol L - C_4H_{10}/h, 8460 kmol C_8H_{18}/h,

7.84 $\times 10^6$ kg/h 91% $H_2SO_4 \Rightarrow$ 72,740 kmol H_2SO_4/h, 39,150 kmol H_2O/h

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

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.

k =	36.2	N	gamma	CA(N)	xA(N)
v =	5000	1	-5.670E-02	2.791E-02	0.5077
V =	2000	2	-2.791E-02	1.512E-02	0.7333
CA0 =	0.0567	3	-1.512E-02	8.631E-03	0.8478
CB0 =	0.1000	4	-8.631E-03	5.076E-03	0.9105
alpha =	14.48	5	-5.076E-03	3.038E-03	0.9464
beta =	1.6270	6	-3.038E-03	1.837E-03	0.9676
		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 $\Rightarrow N$ decreases (faster reaction $\Rightarrow$ fewer tanks)

(ii) $\dot{v}$ increases $\Rightarrow N$ increases (faster throughput $\Rightarrow$ less time spent in reactor

$\Rightarrow$ lower conversion per reactor)

(iii) V increases $\Rightarrow N$ decreases (larger reactor $\Rightarrow$ more time spent in reactor

$\Rightarrow$ higher conversion per reactor)

4.64 **a.** Basis: 1000 g gas

Species	m (g)	MW	n (mol)	**mole % (wet)**	**mole % (dry)**
C_3H_8	800	44.09	18.145	**77.2%**	**87.5%**
C_4H_{10}	150	58.12	2.581	**11.0%**	**12.5%**
H_2O	50	18.02	2.775	**11.8%**	
Total	1000		23.501	**100%**	**100%**

Total moles = 23.50 mol, Total moles (dry) = 20.74 mol

Ratio: 2.775 / 20.726 = 0.134 mol H_2O / mol dry gas

b. $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$, $C_4H_{10} + 13/2\ O_2 \rightarrow 4\ CO_2 + 5\ H_2O$

Theoretical O_2:

$$\underline{C_3H_8}: \ \frac{100\ \text{kg gas}}{h}\left|\frac{80\ \text{kg}\ C_3H_8}{100\ \text{kg gas}}\right|\frac{1\ \text{kmol}\ C_3H_8}{44.09\ \text{kg}\ C_3H_8}\left\|\frac{5\ \text{kmol}\ O_2}{1\ \text{kmol}\ C_3H_8}\right. = 9.07\ \text{kmol}\ O_2\ /\ h$$

$$\underline{C_4H_{10}}: \ \frac{100\ \text{kg gas}}{h}\left|\frac{15\ \text{kg}\ C_4H_{10}}{100\ \text{kg gas}}\right|\frac{1\ \text{kmol}\ C_4H_{10}}{58.12\ \text{kg}\ C_4H_{10}}\left|\frac{6.5\ \text{kmol}\ O_2}{1\ \text{kmol}\ C_4H_{10}}\right. = 1.68\ \text{kmol}\ O_2\ /\ h$$

Total: (9.07 + 1.68) kmol O_2/h = 10.75 kmol O_2/h

$$\underline{\text{Air feed rate}}: \ \frac{10.75\ \text{kmol}\ O_2}{h}\left|\frac{1\ \text{kmol Air}}{.21\ \text{kmol}\ O_2}\right|\frac{1.3\ \text{kmol air fed}}{1\ \text{kmol air required}} = \underline{66.5\ \text{kmol air}\ /\ h}$$

The answer does not change for incomplete combustion

4.65

$$\frac{5\ L\ C_6H_{14}}{}\left|\frac{0.659\ \text{kg}\ C_6H_{14}}{L\ C_6H_{14}}\right|\frac{1000\ \text{mol}\ C_6H_{14}}{86\ \text{kg}\ C_6H_{14}} = 38.3\ \text{mol}\ C_6H_{14}$$

$$\frac{4\ L\ C_7H_{16}}{}\left|\frac{0.684\ \text{kg}\ C_7H_{16}}{L\ C_7H_{16}}\right|\frac{1000\ \text{mol}\ C_7H_{16}}{100\ \text{kg}\ C_7H_{16}} = 27.36\ \text{mol}\ C_7H_{16}$$

$C_6H_{14} + 19/2\ O_2 \rightarrow 6\ CO_2 + 7\ H_2O$ $C_6H_{14} + 13/2\ O_2 \rightarrow 6\ CO + 7\ H_2O$

$C_7H_{16} + 11\ O_2 \rightarrow 7\ CO_2 + 8\ H_2O$ $C_7H_{16} + 15/2\ O_2 \rightarrow 7\ CO + 8\ H_2O$
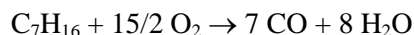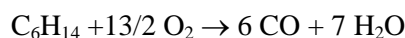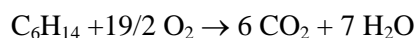
Theoretical oxygen:

$$\frac{38.3\ \text{mol}\ C_6H_{14}}{}\left|\frac{9.5\ \text{mol}\ O_2}{\text{mol}\ C_6H_{14}}\right. + \frac{27.36\ \text{mol}\ C_7H_{16}}{}\left|\frac{11\ \text{mol}\ O_2}{\text{mol}\ C_7H_{16}}\right. = 665\ \text{mol}\ O_2\ \text{required}$$

$\underline{O_2\ \text{fed}}$: (4000 mol air)(.21 mol O_2 / mol air) = 840 mol O_2 fed

$\underline{\text{Percent excess air}}$: $\dfrac{840-665}{665} \times 100\% = \underline{\underline{26.3\%\ \text{excess air}}}$

4.66

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad\qquad H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

175 kmol/h
0.500 kmol N_2/kmol
x (kmol CO/mol)
(0.500–x) (kmol H_2/kmol)

20% excess air
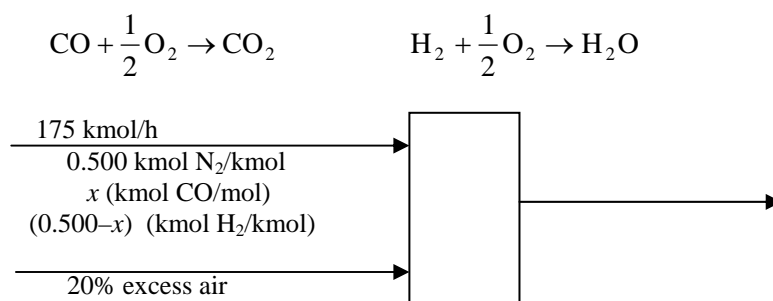
Note: Since CO and H_2 each require 0.5 mol O_2 / mol fuel for complete combustion, we can calculate the air feed rate without determining x_{CO}. We include its calculation for illustrative purposes.

A plot of x vs. R on log paper is a straight line through the points $(R_1 = 10.0, \, x_1 = 0.05)$ and $(R_2 = 99.7, \, x_2 = 1.0)$.

$\ln x = b \ln R + \ln a \qquad b = \ln(1.0/0.05)/\ln(99.7/10.0) = 1.303$

$\Updownarrow \qquad\qquad \ln a = \ln(1.0) - 1.303\ln(99.7) = -6.00 \quad \Rightarrow \underline{\underline{x = 2.49 \times 10^{-3} R^{1.303}}}$

$x = a R^b \qquad a = \exp(-6.00) = 2.49 \times 10^{-3}$

$R = 38.3 \Rightarrow x = 0.288 \dfrac{\text{moles CO}}{\text{mol}}$

$$\underline{\text{Theoretical } O_2}: \quad \frac{175 \text{ kmol}}{h} \left| \frac{0.288 \text{ kmol CO}}{\text{kmol}} \right| \frac{0.5 \text{ kmol } O_2}{\text{kmol CO}}$$

$$+ \frac{175 \text{ kmol}}{h} \left| \frac{0.212 \text{ kmol } H_2}{\text{kmol}} \right| \frac{0.5 \text{ kmol } O_2}{\text{kmol } H_2} = 43.75 \frac{\text{kmol } O_2}{h}$$

$$\underline{\text{Air fed:}} \quad \frac{43.75 \text{ kmol } O_2 \text{ required}}{h} \left| \frac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2} \right| \frac{1.2 \text{ kmol air fed}}{1 \text{ kmol air required}} = \underline{\underline{250 \frac{\text{kmol air}}{h}}}$$

4.67 a.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

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

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

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

100 kmol/h
0.944 CH_4
0.0340 C_2H_6
0.0060 C_3H_8
0.0050 C_4H_{10}

17% excess air
n_a (kmol air/h)
0.21 O_2
0.79 N_2
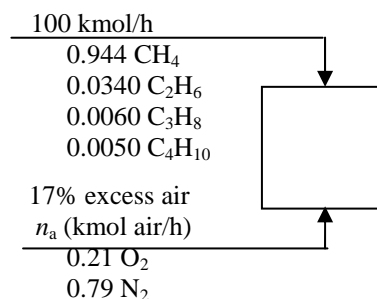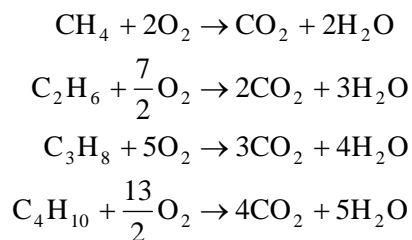
$$\underline{\text{Theoretical } O_2}: \frac{0.944(100)\text{kmol } CH_4}{h} \left| \frac{2 \text{ kmol } O_2}{1 \text{ kmol } CH_4} \right. + \frac{0.0340(100)\text{kmol } C_2H_6}{h} \left| \frac{3.5 \text{ kmol } O_2}{1 \text{ kmol } C_2H_6} \right.$$

$$+ \frac{0.0060(100)\text{kmol } C_3H_8}{h} \left| \frac{5 \text{ kmol } O_2}{1 \text{ kmol } C_3H_3} \right. + \frac{0.0050(100)\text{kmol } C_4H_{10}}{h} \left| \frac{6.5 \text{ kmol } O_2}{1 \text{ kmol } C_4H_{10}} \right.$$

$$= 207.0 \text{ kmol } O_2/h$$

4.67 (cont'd)

$$\text{Air feed rate: } n_f = \frac{207.0 \text{ kmol O}_2}{\text{h}} \left| \frac{1 \text{ kmol air}}{0.21 \text{ kmol O}_2} \right| \frac{1.17 \text{ kmol air fed}}{\text{kmol air req.}} = 1153 \text{ kmol air/h}$$

b. $\quad n_a = n_f \left(2x_1 + 3.5x_2 + 5x_3 + 6.5x_4\right)\left(1 + P_{xs}/100\right)\left(1/0.21\right)$

c. $\quad \dot{n}_f = aR_f, \; (\dot{n}_f = 75.0 \text{ kmol / h}, \; R_f = 60) \Rightarrow \dot{n}_f = 1.25R_f$

$\quad\quad \dot{n}_a = bR_a, \; (\dot{n}_a = 550 \text{ kmol / h}, \; R_a = 25) \Rightarrow \dot{n}_a = 22.0R_a$

$$x_i = kA_i \implies \sum_i x_i = k\sum_i A_i = 1 \implies k = \frac{1}{\displaystyle\sum_i A_i}$$

$$\implies x_i = \frac{A_i}{\displaystyle\sum_i A_i}, \; i = \text{CH}_4, \text{C}_2\text{H}_4, \text{C}_3\text{H}_8, \text{C}_4\text{H}_{10}$$

Run	P_{xs}	R_f	A_1	A_2	A_3	A_4
1	15%	62	248.7	19.74	6.35	1.48
2	15%	83	305.3	14.57	2.56	0.70
3	15%	108	294.2	16.61	4.78	2.11

Run	n_f	x_1	x_2	x_3	x_4	n_a	R_a
1	77.5	0.900	0.0715	0.0230	0.0054	934	42.4
2	103.8	0.945	0.0451	0.0079	0.0022	1194	54.3
3	135.0	0.926	0.0523	0.0150	0.0066	1592	72.4

d. Either of the flowmeters could be in error, the fuel gas analyzer could be in error, the flowmeter calibration formulas might not be linear, or the stack gas analysis could be incorrect.

4.68 a. $\text{C}_4\text{H}_{10} + 13/2 \text{ O}_2 \rightarrow 4 \text{ CO}_2 + 5 \text{ H}_2\text{O}$

Basis: 100 mol C_4H_{10} → [unit] → n_{CO2} (mol CO_2)

n_{H2O} (mol H_2O)

n_{C4H10} (mol C_4H_{10})

P_{xs} (% excess air)

n_{air} (mol air)

0.21 O_2

0.79 N_2

n_{O2} (mol O_2)

n_{N2} (mol N_2)
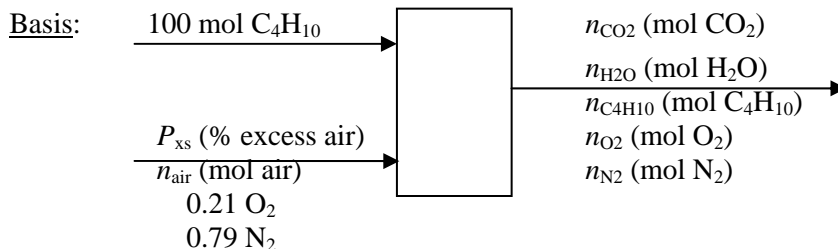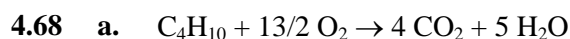
D.F. analysis

6 unknowns (n, n_1, n_2, n_3, n_4, n_5)

-3 atomic balances (C, H, O)

-1 N_2 balance

-1 % excess air

-1 % conversion

0 D.F.

4.68 (cont'd)

b. i) <u>Theoretical oxygen</u> = $(100 \text{ mol } C_4H_{10})(6.5 \text{ mol } O_2/\text{mol } C_4H_{10}) = 650 \text{ mol } O_2$

$n_{air} = (650 \text{ mol } O_2)(1 \text{ mol air } / 0.21 \text{ mol } O_2) = 3095 \text{ mol air}$

<u>100% conversion</u> $\Rightarrow n_{C4H10} = 0$, $n_{O_2} = 0$

$\left.\begin{array}{l} n_{N2} = (0.79)(3095 \text{ mol}) = 2445 \text{ mol} \\ n_{CO2} = (100 \text{ mol } C_4H_{10} \text{ react})(4 \text{ mol } CO_2/\text{mol } C_4H_{10}) = 400 \text{ mol } CO_2 \\ n_{H2O} = (100 \text{ mol } C_4H_{10} \text{ react})(5 \text{ mol } H_2O/\text{mol } C_4H_{10}) = 500 \text{ mol } H_2O \end{array}\right\}$ $\begin{array}{l} \underline{\underline{73.1\% \text{ N}_2}} \\ \underline{\underline{12.0\% \text{ CO}_2}} \\ \underline{\underline{14.9\% \text{ H}_2\text{O}}} \end{array}$

ii) <u>100% conversion</u> $\Rightarrow n_{C4H10} = 0$

<u>20% excess</u> $\Rightarrow n_{air} = 1.2(3095) = 3714 \text{ mol}$ (780 mol O₂, 2934 mol N₂)

<u>Exit gas</u>:

$\left.\begin{array}{l} 400 \text{ mol } CO_2 \\ 500 \text{ mol } H_2O \\ 130 \text{ mol } O_2 \\ 2934 \text{ mol } N_2 \end{array}\right\}$ $\begin{array}{l} 10.1\% \text{ CO}_2 \\ 12.6\% \text{ H}_2\text{O} \\ 3.3\% \text{ O}_2 \\ \underline{\underline{74.0\% \text{ N}_2}} \end{array}$

iii) <u>90% conversion</u> $\Rightarrow n_{C4H10} = 10 \text{ mol } C_4H_{10}$ (90 mol C₄H₁₀ react, 585 mol O₂ consumed)

<u>20% excess</u>: $n_{air} = 1.2(3095) = 3714 \text{ mol}$ (780 mol O₂, 2483 mol N₂)

<u>Exit gas</u>:

$\left.\begin{array}{l} 10 \text{ mol } C_4H_{10} \\ 360 \text{ mol } CO_2 \\ 450 \text{ mol } H_2O \text{ (v)} \\ 195 \text{ mol } O_2 \\ 2934 \text{ mol } N_2 \end{array}\right\}$ $\begin{array}{l} 0.3\% \text{ C}_4\text{H}_{10} \\ 9.1\% \text{ CO}_2 \\ 11.4\% \text{ H}_2\text{O} \\ 4.9\% \text{ O}_2 \\ \underline{\underline{74.3\% \text{ N}_2}} \end{array}$

4.69 a. $C_3H_8 + 5 O_2 \rightarrow 3 CO_2 + 4 H_2O$ $\qquad\qquad\qquad$ $H_2 + 1/2 O_2 \rightarrow H_2O$

$C_3H_8 + 7/2 O_2 \rightarrow 3 CO + 4 H_2O$

<u>Basis:</u> 100 mol feed gas

100 mol
0.75 mol C₃H₈
0.25 mol H₂

n_0 (mol air)
0.21 mol O₂/mol
0.79 mol N₂/mol

n_1 (mol C₃H₈)
n_2 (mol H₂)
n_3 (mol CO₂)
n_4 (mol CO)
n_5 (mol H₂O)
n_6 (mol O₂)
n_7 (mol N₂)

<u>Theoretical oxygen:</u> $\dfrac{75 \text{ mol } C_3H_8}{} \left|\dfrac{5 \text{ mol } O_2}{\text{mol } C_3H_8}\right. + \dfrac{25 \text{ mol } H_2}{} \left|\dfrac{0.50 \text{ mol } O_2}{\text{mol } H_2}\right. = 387.5 \text{ mol } O_2$
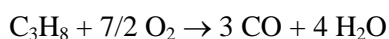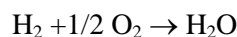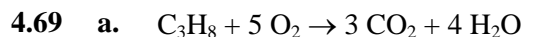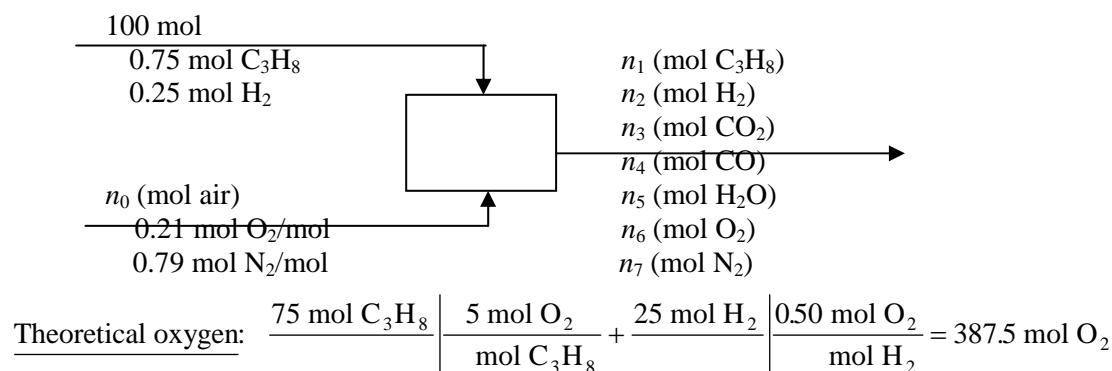
4.69 (cont'd)

Air feed rate: $n_0 = \dfrac{387.5 \text{ mol O}_2}{\text{h}} \left| \dfrac{1 \text{ kmol air}}{0.21 \text{ kmol O}_2} \right| \dfrac{1.25 \text{ kmol air fed}}{1 \text{ kmol air req'd.}} = 2306.5 \text{ mol air}$

90% propane conversion $\Rightarrow n_1 = 0.100(75 \text{ mol C}_3\text{H}_8) = 7.5 \text{ mol C}_3\text{H}_8$

    (67.5 mol C_3H_8 reacts)

85% hydrogen conversion $\Rightarrow n_2 = 0.150(25 \text{ mol C}_3\text{H}_8) = 3.75 \text{ mol H}_2$

95% CO$_2$ selectivity $\Rightarrow n_3 = \dfrac{0.95(67.5 \text{ mol C}_3\text{H}_8 \text{ react})}{} \left| \dfrac{3 \text{ mol CO}_2 \text{ generated}}{\text{mol C}_3\text{H}_8 \text{ react}} \right.$

    $= 192.4 \text{ mol CO}_2$

5% CO selectivity $\Rightarrow n_3 = \dfrac{0.05(67.5 \text{ mol C}_3\text{H}_8 \text{ react})}{} \left| \dfrac{3 \text{ mol CO generated}}{\text{mol C}_3\text{H}_8 \text{ react}} \right. = 10.1 \text{ mol CO}$

H balance: $(75 \text{ mol C}_3\text{H}_8)\left(8 \dfrac{\text{mol H}}{\text{mol C}_3\text{H}_8}\right) + (25 \text{ mol H}_2)(2)$

    $= (7.5 \text{ mol C}_3\text{H}_8)(8) + (3.75 \text{ mol H}_2)(2) + n_5(\text{mol H}_2\text{O})(2) \Rightarrow n_5 = 291.2 \text{ mol H}_2\text{O}$

O balance: $(0.21 \times 2306.5 \text{ mol O}_2)(2 \dfrac{\text{mol O}}{\text{mol O}_2}) = (192.4 \text{ mol CO}_2)(2)$

    $+ (10.1 \text{ mol CO})(1) + (291.2 \text{ mol H}_2\text{O})(1) + 2n_6(\text{mol O}_2) \Rightarrow n_6 = 141.3 \text{ mol O}_2$

N$_2$ balance: $n_7 = 0.79(2306.5) \text{ mol N}_2 = 1822 \text{ mol N}_2$

Total moles of exit gas $= (7.5 + 3.75 + 192.4 + 10.1 + 291.2 + 141.3 + 1822) \text{ mol}$

    $= 2468 \text{ mol}$

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

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.

4.70 **a.** $C_5H_{12} + 8\,O_2 \rightarrow 5\,CO_2 + 6\,H_2O$
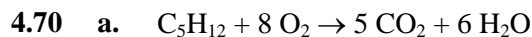
Basis: 100 moles dry product gas
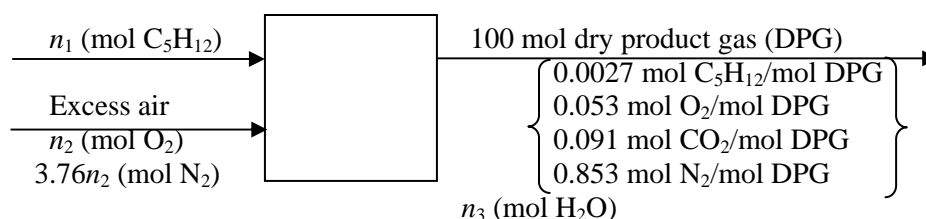
3 unknowns (n_1, n_2, n_3)

-3 atomic balances (O, C, H)

-1 N2 balance

-1 D.F. $\Rightarrow$ Problem is overspecified

b. N₂ balance: 3.76 n_2 = 0.8533 (100) $\Rightarrow$ n_2 = 22.69 mol O_2

C balance: 5 n_1 = 5(0.0027)(100) + (0.091)(100) $\Rightarrow$ n_1 = 2.09 mol C_5H_{12}

H balance: 12 n_1 = 12(0.0027)(100) + 2n_3 $\Rightarrow$ n_3 = 10.92 mol H_2O

O balance: 2n_2 = 100[(0.053)(2) + (0.091)(2)] + n_3 $\Rightarrow$ 45.38 mol O = 39.72 mol O

Since the 4th balance does not close, the given data cannot be correct.

c.
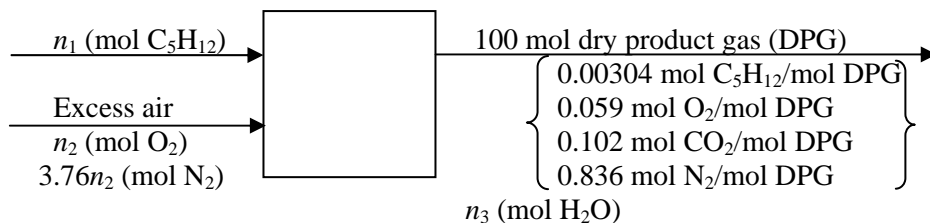
N₂ balance: 3.76 n_2 = 0.836 (100) $\Rightarrow$ n_2 = 22.2 mol O_2

C balance: 5 n_1 = 100 (5*0.00304 + 0.102) $\Rightarrow$ n_1 = 2.34 mol C_5H_{12}

H balance: 12 n_1 = 12(0.00304)(100) + 2n_3 $\Rightarrow$ n_3 = 12.2 mol H_2O

O balance: 2n_2 = 100[(0.0590)(2) + (0.102)(2)] + n_3 $\Rightarrow$ 44.4 mol O = 44.4 mol O √

Fractional conversion of C_5H_{12}: $\dfrac{2.344 - 100 \times 0.00304}{2.344} = 0.870$ mol react/mol fed

Theoretical O_2 required: 2.344 mol C_5H_{12} (8 mol O_2/mol C_5H_{12}) = 18.75 mol O_2

% excess air: $\dfrac{22.23\,\text{mol}\,O_2\ \text{fed} - 18.75\,\text{mol}\,O_2\ \text{required}}{18.75\,\text{mol}\,O_2\ \text{required}} \times 100\% = 18.6\%\ \text{excess air}$

4.71 **a.**

$$\frac{12\,\text{L CH}_3\text{OH}}{\text{h}}\left|\frac{1000\,\text{ml}}{\text{L}}\right|\frac{0.792\,\text{g}}{\text{ml}}\left|\frac{\text{mol}}{32.04\,\text{g}}\right. = 296.6\,\text{mol CH}_3\text{OH}\,/\,\text{h}$$

$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O,\ CH_3OH + O_2 \rightarrow CO + 2\ H_2O$

296.6 mol CH₃OH(l)/h → [box] → $\dot{n}_2$ (mol dry gas / h)

0.0045 mol CH₃OH(v)/mol DG
0.0903 mol CO₂/mol DG
0.0181 mol CO/mol DG
x (mol N₂/mol DG)
(0.8871–x) (mol O₂/mol DG)

$\dot{n}_1$ (mol O₂ / h)
3.76$\dot{n}_1$ (mol N₂ / h)

$\dot{n}_3$ (mol H₂O(v) / h)
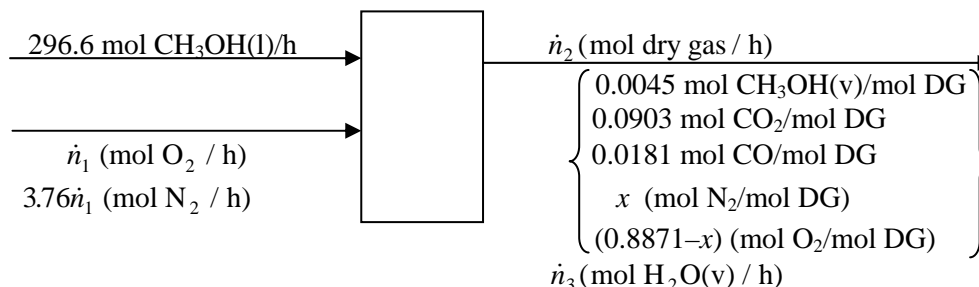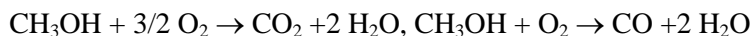
4 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_3, x)$ – 4 balances (C, H, O, N₂) = 0 D.F.

b. Theoretical O₂: 296.6 (1.5) = 444.9 mol O₂ / h

C balance: 296.6 = $\dot{n}_2$ (0.0045 + 0.0903 + 0.0181) $\Rightarrow \dot{n}_2$ = 2627 mol/h

H balance: 4 (296.6) = $\dot{n}_2$ (4*0.0045) + 2 $\dot{n}_3 \Rightarrow \dot{n}_3$ = 569.6 mol H₂O / h

O balance: 296.6 + 2n₁ = 2627[0.0045 + 2(0.0903) + 0.0181 + 2(0.8871 - x)] + 569.6

N₂ balance: 3.76 $\dot{n}_1$ = x (2627)

Solving simultaneously $\Rightarrow \dot{n}_1$ = 574.3 mol O₂ / h, x = 0.822 mol N₂ / mol DG

Fractional conversion: $\dfrac{296.6 - 2627(0.0045)}{296.6} = 0.960$ mol CH₃OH react/mol fed

% excess air: $\dfrac{574.3 - 444.9}{444.9} \times 100\% = 29.1\%$

Mole fraction of water: $\dfrac{569.6\,\text{mol H}_2\text{O}}{(2627 + 569.6)\,\text{mol}} = 0.178$ mol H₂O/mol

c. Fire, CO toxicity. Vent gas to outside, install CO or hydrocarbon detector in room, trigger alarm if concentrations are too high

4.72 **a.** G.C. Say n_s mols fuel gas constitute the sample injected into the G.C. If x_{CH_4} and $x_{C_2H_6}$ are the mole fractions of methane and ethane in the fuel, then

$$\frac{n_s(\text{mol})x_{C_2H_6}(\text{mol C}_2\text{H}_2/\text{mol})(2\ \text{mol C}/1\ \text{mol C}_2\text{H}_6)}{n_s(\text{mol})x_{CH_4}(\text{mol CH}_4/\text{mol})(1\ \text{mol C}/1\ \text{mol CH}_4)} = \frac{20}{85}$$

$\Downarrow$

$$\frac{x_{C_2H_6}(\text{mol C}_2\text{H}_6/\text{mol fuel})}{x_{CH_4}(\text{mol CH}_4/\text{mol fuel})} = 0.1176\ \text{mole C}_2\text{H}_6/\text{mole CH}_4\ \text{in fuel gas}$$

4.72 (cont'd)

<u>Condensation measurement:</u> $\dfrac{(1.134 \text{ g H}_2\text{O})(1 \text{ mol}/18.02 \text{ g})}{0.50 \text{ mol product gas}} = 0.126 \dfrac{\text{mole H}_2\text{O}}{\text{mole product gas}}$

<u>Basis: 100 mol product gas.</u> Since we have the most information about the product stream composition, we choose this basis now, and would subsequently scale to the given fuel and air flow rates if it were necessary (which it is not).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

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

n$_1$ (mol CH$_4$)
0.1176 n$_1$ (mol C$_2$H$_6$)
n$_2$ (mol CO$_2$)

100 mol dry gas / h

0.126 mol H$_2$O / mol
0..874 mol dry gas / mol
0.119 mol CO$_2$ / mol D.G.
x (mol N$_2$ / mol)
(0.881-x) (mol O$_2$ / mol D.G.)

n$_3$ (mol O$_2$ / h)
376 n$_3$ (mol N$_2$ / h)
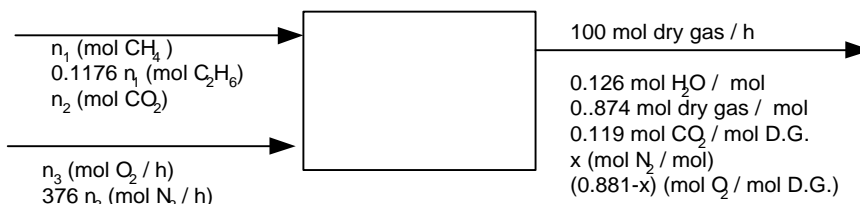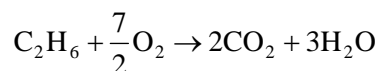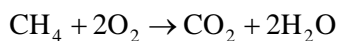
<u>Strategy:</u> H balance $\Rightarrow$ n$_1$; C balance $\Rightarrow$ n$_2$; $\left.\begin{array}{l} \text{N}_2 \text{ balance} \\ \text{O balance} \end{array}\right\} \Rightarrow n_3, x$

<u>H balance:</u> $4n_1 + (6)(0.1176n_1) = (100)(0.126)(2) \Rightarrow n_1 = 5.356$ mol CH$_4$ in fuel

$\Rightarrow 0.1176(5.356) = 0.630$ mol C$_2$H$_6$ in fuel

<u>C balance:</u> $5.356 + (2)(0.630) + n_2 = (100)(0.874)(0.119) \Rightarrow n_2 = 3.784$ mol CO$_2$ in fuel

<u>Composition of fuel:</u> 5.356 mol CH$_4$, 0.630 mol C$_2$H$_6$, 3.784 mols CO$_2$

$\Rightarrow$ <u><u>0.548 CH$_4$, 0.064 C$_2$H$_6$, 0.388 CO$_2$</u></u>

<u>N$_2$ balance:</u> $3.76n_3 = (100)(0.874)x$

<u>O balance:</u> $(2)(3.784) + 2n_3 = (100)(0.126) + (100)(0.874)(2)[0.119 + (0.881 - x)]$

Solve simultaneously: $n_3 = 18.86$ mols O$_2$ fed, $x = 0.813$

<u>Theoretical O$_2$:</u> $\dfrac{5.356 \text{ mol CH}_4}{} \left| \dfrac{2 \text{ mol O}_2}{1 \text{ mol CH}_4} + \dfrac{0.630 \text{ mol C}_2\text{H}_6}{} \right| \dfrac{3.5 \text{ mol O}_2}{1 \text{ mol CH}_4}$

$= 12.92$ mol O$_2$ required

<u>Desired O$_2$ fed:</u> $\dfrac{(5.356 + 0.630 + 3.784) \text{ mol fuel}}{} \left| \dfrac{7 \text{ mol air}}{1 \text{ mol fuel}} \right| \dfrac{0.21 \text{ mol O}_2}{\text{mol air}} = \underline{14.36 \text{ mol O}_2}$

<u>Desired % excess air:</u> $\dfrac{14.36 - 12.92}{12.92} \times 100\% = \underline{\underline{11\%}}$

b.

<u>Actual % excess air:</u> $\dfrac{18.86 - 12.92}{12.92} \times 100\% = \underline{\underline{46\%}}$

<u>Actual molar feed ratio of air to fuel:</u> $\dfrac{(18.86/0.21) \text{ mol air}}{9.77 \text{ mol feed}} = \underline{\underline{9:1}}$

4.73 **a.** $C_3H_8 + 5 O_2 \rightarrow 3 CO_2 + 4 H_2O$, $C_4H_{10} + 13/2 O_2 \rightarrow 4 CO_2 + 5 H_2O$

<u>Basis 100</u>: mol product gas

n_1 (mol C_3H_8)
n_2 (mol C_4H_{10})

n_3 (mol O_2)

100 mol
0.474 mol H_2O/mol
x (mol CO_2/mol)
(0.526–x) (mol O_2/mol)
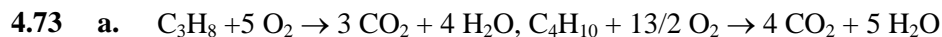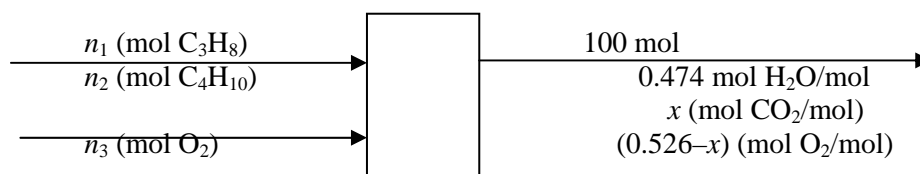
<u>Dry product gas contains 69.4% CO_2</u> $\Rightarrow \dfrac{x}{0.526 - x} = \dfrac{69.4}{30.6} \Rightarrow x = 0.365$ mol CO_2/mol

3 unknowns (n_1, n_2, n_3) – 3 balances (C, H, O) = 0 D.F.

<u>O balance</u>: $2\,n_3 = 152.6 \Rightarrow n_3 = 76.3$ mol O_2

$\left. \begin{array}{l} \underline{\text{C balance}}: 3\,n_1 + 4\,n_2 = 36.5 \\ \underline{\text{H balance}}: 8\,n_1 + 10\,n_2 = 94.8 \end{array} \right\} \Rightarrow \begin{array}{l} n_1 = 7.1 \text{ mol } C_3H_8 \\ n_2 = 3.8 \text{ mol } C_4H_{10} \end{array} \Rightarrow \underline{\underline{65.1\% \ C_3H_8, 34.9\% \ C_4H_{10}}}$

b. n_c=100 mol (0.365 mol CO_2/mol)(1mol C/mol CO_2) = 365 mol C

n_h = 100 mol (0.474 mol H_2O/mol)(2mol H/mol H_2O)=94.8 mol H

$\Rightarrow$ <u>27.8%C, 72.2% H</u>

From a:

$$\frac{\dfrac{7.10\,\text{mol}\,C_3H_8}{} \left| \dfrac{3\,\text{mol}\,C}{\text{mol}\,C_3H_8} + \dfrac{3.80\ \text{mol}\,C_4H_{10}}{} \right| \dfrac{4\,\text{mol}\,C}{\text{mol}\,C_4H_{10}}}{\dfrac{7.10\,\text{mol}\,C_3H_8}{} \left| \dfrac{11\,\text{mol}\,(C+H)}{\text{mol}\,C_3H_8} + \dfrac{3.80\ \text{mol}\,C_4H_{10}}{} \right| \dfrac{14\,\text{mol}\,(C+H)}{\text{mol}\,C_4H_{10}}} \times 100\% = \underline{\underline{27.8\%\ C}}$$

4.74 <u>Basis:</u> 100 kg fuel oil

<u>Moles of C in fuel:</u> $\dfrac{100\,\text{kg}}{} \left| \dfrac{0.85\,\text{kg C}}{\text{kg}} \right| \dfrac{1\,\text{kmol C}}{12.01\,\text{kg C}} = 7.08\,\text{kmol C}$

<u>Moles of H in fuel:</u> $\dfrac{100\,\text{kg}}{} \left| \dfrac{0.12\,\text{kg H}}{\text{kg}} \right| \dfrac{1\,\text{kmol H}}{1\,\text{kg H}} = 12.0\,\text{kmol H}$

<u>Moles of S in fuel:</u> $\dfrac{100\,\text{kg}}{} \left| \dfrac{0.017\,\text{kg S}}{\text{kg}} \right| \dfrac{1\,\text{kmol S}}{32.064\,\text{kg S}} = 0.053\,\text{kmol S}$

1.3 kg non-combustible materials (NC)

4.74 (cont'd)
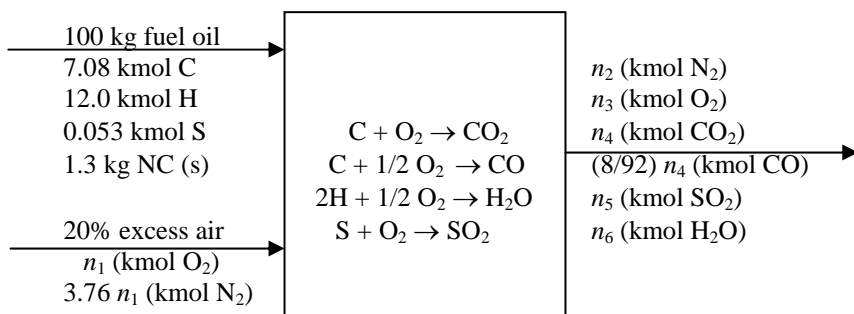
Theoretical O_2:

$$\frac{7.08 \, \text{kmol C}}{} \left| \frac{1 \, \text{kmol O}_2}{1 \, \text{kmol C}} + \frac{12 \, \text{kmol H}}{} \right| \frac{.5 \, \text{kmol O}_2}{2 \, \text{kmol H}} + \frac{0.053 \, \text{kmol S}}{} \left| \frac{1 \, \text{kmol O}_2}{1 \, \text{kmol S}} \right. = 10.133 \, \text{kmol O}_2$$

<u>20 % excess air</u>: $n_1 = 1.2(10.133) = 12.16 \, \text{kmol O}_2$ fed

<u>O balance</u>: $2 \, (12.16) = 2 \, (6.5136) + 0.5664 + 2 \, (0.053) + 6 + 2 \, n_3 \Rightarrow n_3 = 2.3102 \, \text{kmol O}_2$

<u>C balance</u>: $7.08 = n_4 + 8n_4/92 \Rightarrow n_4 = 6.514 \, \text{mol CO}_2$

$$\Rightarrow 8 \, (6.514)/92 = 0.566 \, \text{mol CO}$$

<u>S balance</u>: $n_5 = 0.53 \, \text{kmol SO}_2$

<u>H balance</u>: $12 = 2n_6 \Rightarrow n_6 = 6.00 \, \text{kmol H}_2\text{O}$

<u>N$_2$ balance</u>: $n2 = 3.76(12.16) = 45.72 \, \text{kmol N}_2$

<u>Total moles of stack gas</u> $= (6.514 + 0.566 + 0.053 + 6.00 + 2.310 + 45.72) \, \text{kmol}$

$$= 61.16 \, \text{kmol}$$

$\Rightarrow$ <u>10.7% CO, 0.92% CO, 0.087% SO_2, 9.8% H_2O, 3.8% O_2, 74.8% N_2</u>

4.75 a. <u>Basis</u>: 5000 kg coal/h; 50 kmol air/min = 3000 kmol air/h
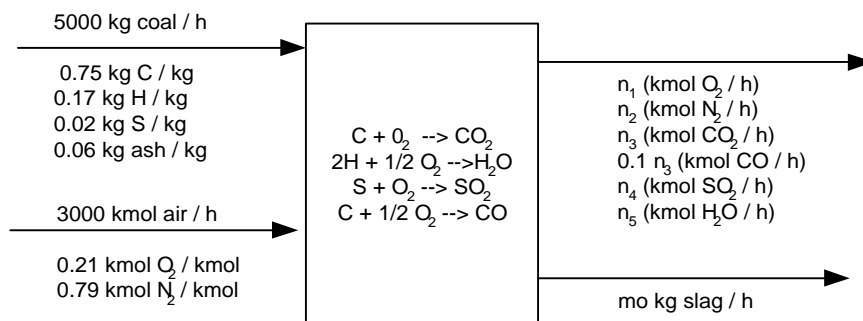
Theoretical O_2:

$$\underline{C}: \quad \frac{0.75(5000) \, \text{kg C}}{h} \left| \frac{1 \, \text{kmol C}}{12.01 \, \text{kg C}} \right| \frac{1 \, \text{kmol O}_2}{1 \, \text{kmol C}} = 312.2 \, \text{kmol O}_2/h$$

4-66

4.75 (cont'd)

$$\underline{H:} \quad \frac{0.17(5000) \text{ kg H}}{h} \left| \frac{1 \text{ kmol H}}{1.01 \text{ kg H}} \right| \frac{1 \text{ kmol H}_2\text{O}}{2 \text{ kmol H}} \left| \frac{1 \text{ kmol O}_2}{2 \text{ kmol H}_2\text{O}} \right. = 210.4 \text{ kmol O}_2/h$$

$$\underline{S:} \quad \frac{0.02(5000) \text{ kg S}}{h} \left| \frac{1 \text{ kmol S}}{32.06 \text{ kg S}} \right| \frac{1 \text{ kmol O}_2}{1 \text{ kmol S}} = 3.1 \text{ kmol O}_2/h$$

Total $= (312.2 + 210.4 + 3.1) \text{ kmol O}_2/h = 525.7 \text{ kmol O}_2/h$

$\underline{O_2 \text{ fed}} = 0.21(3000) = 630 \text{ kmol O}_2/h$

$\underline{\text{Excess air:}} \quad \dfrac{630 - 525.7}{525.7} \times 100\% = \underline{19.8\% \text{ excess air}}$

b. Balances:

$$\underline{C:} \quad \frac{(0.94)(0.75)(5000) \text{ kg C react}}{h} \left| \frac{1 \text{ kmol C}}{12.01 \text{ kg C}} \right. = \dot{n}_3 + 0.1\dot{n}_3$$

$$\Rightarrow \dot{n}_3 = 266.8 \text{ kmol CO}_2/h, \quad 0.1\dot{n}_3 = 26.7 \text{ kmol CO}/h$$

$$\underline{H:} \quad \frac{(0.17)(5000) \text{ kg H}}{h} \left| \frac{1 \text{ kmol H}}{1.01 \text{ kg H}} \right| \frac{1 \text{ kmol H}_2\text{O}}{2 \text{ kmol H}} = n_5 \Rightarrow n_5 = 420.8 \text{ kmol H}_2\text{O}/h$$

$$\underline{S:} \quad \text{(from part a)} \quad \frac{3.1 \text{ kmol O}_2 \text{ (for SO}_2)}{h} \left| \frac{1 \text{ kmol SO}_2}{1 \text{ kmol O}_2} \right. = \dot{n}_4 \Rightarrow \dot{n}_4 = 3.1 \text{ kmol SO}_2/h$$

$\underline{N_2:} \quad (0.79)(3000) \text{ kmol N}_2/h = \dot{n}_2 \Rightarrow \dot{n}_2 = 2370 \text{ kmol N}_2/h$

$\underline{O:} \quad (0.21)(3000)(2) = 2\dot{n}_1 + 2(266.8) + 1(26.68) + 2(3.1) + (1)(420.8)$

$\Rightarrow \dot{n}_1 = 136.4 \text{ kmol O}_2/h$

Stack gas total $= 3223 \text{ kmol}/h$

Mole fractions:

$$x_{CO} = 26.7/3224 = \underline{8.3 \times 10^{-3} \text{ mol CO}/\text{mol}}$$

$$x_{SO_2} = 3.1/3224 = \underline{9.6 \times 10^{-4} \text{ mol SO}_2/\text{mol}}$$

c. $SO_2 + \dfrac{1}{2}O_2 \rightarrow SO_3$

$SO_3 + H_2O \rightarrow H_2SO_4$
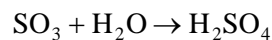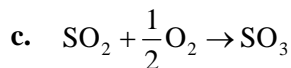
$$\frac{3.1 \text{ kmol SO}_2}{h} \left| \frac{1 \text{ kmol SO}_3}{1 \text{ kmol SO}_2} \right| \frac{1 \text{ kmol H}_2\text{SO}_4}{1 \text{ kmol SO}_3} \left| \frac{98.08 \text{ kg H}_2\text{SO}_4}{\text{kmol H}_2\text{SO}_4} \right. = \underline{304 \text{ kg H}_2\text{SO}_4/h}$$

4.76 a. <u>Basis:</u> 100 g coal as received (c.a.r.). Let a.d.c. denote air-dried coal; v.m. denote volatile matter

$$\frac{100 \text{ g c.a.r.} \mid 1.147 \text{ g a.d.c.}}{1.207 \text{ g c.a.r.}} = 95.03 \text{ g air - dried coal; } 4.97 \text{ g } H_2O \text{ lost by air drying}$$

$$\frac{95.03 \text{ g a.d.c} \mid (1.234 - 1.204) \text{ g } H_2O}{1.234 \text{ g a.d.c.}} = 2.31 \text{ g } H_2O \text{ lost in second drying step}$$

Total $H_2O = 4.97 \text{ g} + 2.31 \text{ g} = \underline{7.28 \text{ g moisture}}$

$$\frac{95.03 \text{ g a.d.c} \mid (1.347 - 0.811) \text{ g } (v.m.+H_2O)}{1.347 \text{ g a.d.c.}} - 2.31 \text{ g } H_2O = \underline{35.50 \text{ g volatile matter}}$$

$$\frac{95.03 \text{ g a.d.c} \mid 0.111 \text{ g ash}}{1.175 \text{ g a.d.c.}} = \underline{8.98 \text{ g ash}}$$

Fixed carbon $= (100 - 7.28 - 35.50 - 8.98)g = \underline{48.24 \text{ g fixed carbon}}$

$$\begin{array}{l} 7.28 \text{ g moisture} \\ 48.24 \text{ g fixed carbon} \\ 35.50 \text{ g volatile matter} \\ 8.98 \text{ g ash} \\ \hline 100 \text{ g coal as received} \end{array} \Rightarrow \begin{array}{l} \underline{\underline{7.3\% \text{ moisture}}} \\ \underline{\underline{48.2\% \text{ fixed carbon}}} \\ \underline{\underline{35.5\% \text{ volatile matter}}} \\ \underline{\underline{9.0\% \text{ ash}}} \end{array}$$

b. Assume volatile matter is all carbon and hydrogen.

$$C + CO_2 \rightarrow CO_2 : \frac{1 \text{ mol } O_2 \mid 1 \text{ mol C} \mid 10^3 \text{ g} \mid 1 \text{ mol air}}{1 \text{ mol C} \mid 12.01 \text{ g C} \mid 1 \text{ kg} \mid 0.21 \text{ mol } O_2} = 396.5 \text{ mol air/kg C}$$

$$2H + \frac{1}{2}O_2 \rightarrow H_2O : \frac{0.5 \text{ mol } O_2 \mid 1 \text{ mol H} \mid 10^3 \text{ g} \mid 1 \text{ mol air}}{2 \text{ mol H} \mid 1.01 \text{ g H} \mid 1 \text{ kg} \mid 0.21 \text{ mol } O_2} = 1179 \text{ mol air/kg H}$$

<u>Air required:</u>
$$\frac{1000 \text{ kg coal} \mid 0.482 \text{ kg C} \mid 396.5 \text{ mol air}}{\mid \text{kg coal} \mid \text{kg C}}$$

$$+ \frac{1000 \text{ kg} \mid 0.355 \text{ kg v.m.} \mid 6 \text{ kg C} \mid 396.5 \text{ mol air}}{\mid \text{kg} \mid 7 \text{ kg v.m.} \mid \text{kg C}}$$

$$+ \frac{1000 \text{ kg} \mid 0.355 \text{ kg v.m.} \mid 1 \text{ kg H} \mid 1179 \text{ mol air}}{\mid \text{kg} \mid 7 \text{ kg v.m.} \mid \text{kg H}} = \underline{\underline{3.72 \times 10^5 \text{ mol air}}}$$

4.77 **a.** Basis 100 mol dry fuel gas.   <u>Assume no solid or liquid products!</u>
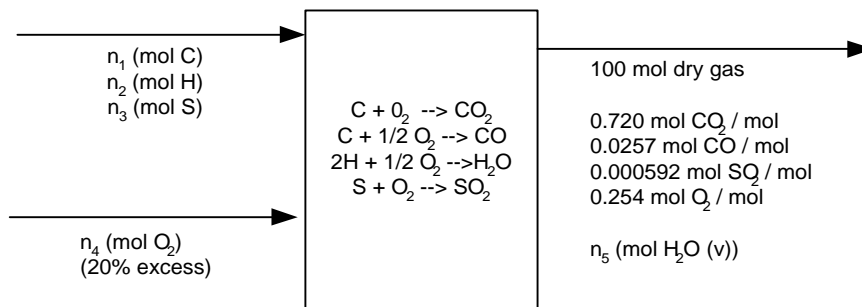
<u>H balance</u>: $n_2 = 2n_5$

<u>O balance</u>: $2n_4 = 100[2(0.720) + 0.0257 + 2(0.000592) + 2(0.254)] + n_5$

<u>20% excess O_2</u>: $(1.20)(74.57 + 0.0592 + 0.25 n_2] = n_4$

$\Rightarrow$ $n_2 = 183.6$ mol H, $n_4 = 144.6$ mol O_2, $n_5 = 91.8$ mol H_2O

Total moles in feed: 258.4 mol (C+H+S) $\Rightarrow$ <u>28.9% C, 71.1% H, 0.023% S</u>

4.78   <u>Basis: 100 g oil</u>
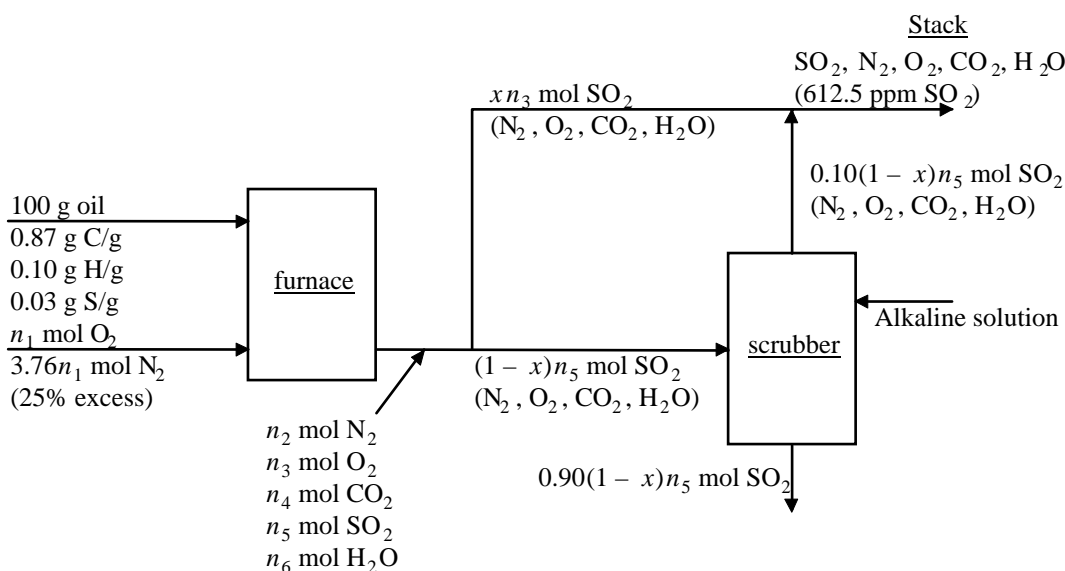
<u>CO_2</u>: $\dfrac{0.87(100)\text{g C}}{} \left| \dfrac{1\text{ mol C}}{12.01\text{ g C}} \right| \dfrac{1\text{ mol } CO_2}{1\text{ mol C}} \Rightarrow n_4 = 7.244$ mol $CO_2 \left(\dfrac{7.244\text{ mol } O_2}{\text{consumed}} \right)$

<u>H_2O</u>: $\dfrac{0.10(100)\text{g H}}{} \left| \dfrac{1\text{ mol H}}{1.01\text{ g H}} \right| \dfrac{1\text{ mol } H_2O}{2\text{ mol H}} \Rightarrow n_6 = 4.95$ mol $H_2O \left(\dfrac{2.475\text{ mol } O_2}{\text{consumed}} \right)$

4.78 (cont'd)

$\underline{SO_2}$: $\dfrac{0.03(100)\text{g S}}{} \dfrac{1 \text{ mol S}}{32.06 \text{ g S}} \dfrac{1 \text{ mol } SO_2}{1 \text{ mol S}} \Rightarrow n_5 = 0.0936 \text{ mol } SO_2 \left(\dfrac{0.0956 \text{ mol } O_2}{\text{consumed}}\right)$

$\underline{25\% \text{ excess } O_2}$: $n_1 = 1.25(7.244 + 2.475 + 0.0936) \Rightarrow 12.27 \text{ mol } O_2$

$\underline{O_2 \text{ balance}}$: $n_3 = 12.27 \text{ mol } O_2 \text{ fed} - (7.244 + 2.475 + 0.0936) \text{ mol } O_2 \text{ consumed}$

$= 2.46 \text{ mol } O_2$

$\underline{N_2 \text{ balance}}$: $n_2 = 3.76(12.27 \text{ mol}) = 46.14 \text{ mol } N_2$

$\underline{SO_2 \text{ in stack } (SO_2 \text{ balance around mixing point})}$:

$$x\underbrace{\left(0.0936\right)}_{n_5} + 0.10(1-x)(0.0936) = 0.00936 + 0.0842x(\text{mol } SO_2)$$

$\underline{\text{Total dry gas in stack}}$ (Assume no CO_2, O_2, or N_2 is absorbed in the scrubber)

$$\underset{(CO_2)}{7.244} + \underset{(O_2)}{2.46} + \underset{(N_2)}{46.14} + \underset{(SO_2)}{(0.00936 + 0.0842x)} = 55.85 + 0.0842x(\text{mol dry gas})$$

$\underline{612.5 \text{ ppm } SO_2 (\text{dry basis}) \text{ in stack gas}}$

$$\dfrac{0.00936 + 0.0842x}{55.85 + 0.0842x} = \dfrac{612.5}{1.0 \times 10^6} \Rightarrow x = 0.295 \Rightarrow \underline{\underline{30\% \text{ bypassed}}}$$

4.79 $\underline{\text{Basis: 100 mol stack gas}}$

n_1 (mol C)
n_2 (mol H)
n_3 (mol S)

$C + O_2 \rightarrow CO_2$
$2H + \frac{1}{2}O_2 \rightarrow H_2O$
$S + O_2 \rightarrow SO_2$

n_4 (mol O_2)
$3.76n_4$ (mol O_2)

100 mol
0.7566 N_2
0.1024 CO_2
0.0827 H_2O
0.0575 O_2
0.000825 SO_2
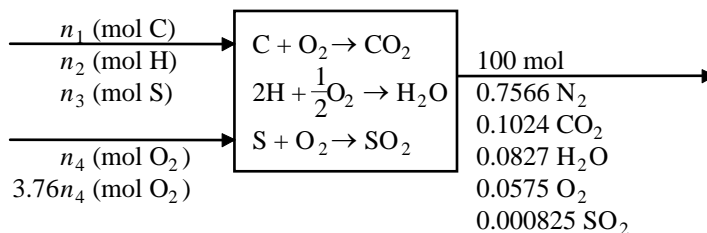
a. $\underline{\text{C balance}}$: $n_1 = (100)(0.1024) = 10.24 \text{ mol C}$
$\underline{\text{H balance}}$: $n_2 = (100)(0.0827)(2) = 16.54 \text{ mol H}$ $\Rightarrow \dfrac{10.24 \text{ mol C}}{16.54 \text{ mol H}} = \underline{\underline{0.62 \dfrac{\text{mol C}}{\text{mol H}}}}$

The C/H mole ratio of CH_4 is 0.25, and that of C_2H_6 is 0.333; no mixture of the two could have a C/H ratio of 0.62, so the fuel could not be the natural gas.

b. $\underline{\text{S balance}}$: $n_3 = (100)(0.000825) = 0.0825 \text{ mol S}$

$(10.24 \text{ mol C})(12.0 \text{ g}/1 \text{ mol}) = 122.88 \text{ g C}$
$(16.54 \text{ mol H})(1.01 \text{ g}/1 \text{ mol}) = 16.71 \text{ g H}$
$(0.0825 \text{ mol S})(32.07 \text{ g}/1 \text{ mol}) = 2.65 \text{ g S}$
$\Rightarrow$
$\dfrac{122.88}{16.71} = \underline{\underline{7.35 \text{ g C/g H}}}$
$\dfrac{2.65}{142.24} \times 100\% = \underline{\underline{1.9\% \text{ S}}}$
$\Rightarrow \underline{\underline{\text{No. 4 fuel oil}}}$

4.80 **a.** Basis: 1 mol $C_pH_qO_r$
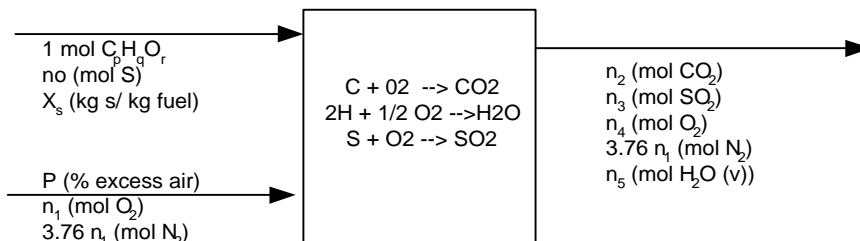
Hydrocarbon mass: p (mol C) (12 g / mol) = 12 p (g C)

q (mol H) (1 g / mol) =   q (g H) $\Rightarrow$ (12 p + q + 16 r) g fuel

r (mol O) (16 g / mol) = 16 r (g O)

S in feed:

$$n_o = \frac{(12\,p + q + 16r)\,\text{g fuel}}{}\left|\frac{X_s\,(\text{g S})}{(1 - X_s)\,(\text{g fuel})}\right|\frac{1\,\text{mol S}}{32.07\,\text{g S}} = \frac{X_s\,(12\,p + q + 16\,r)}{32.07(1 - X_s)}\,(\text{mol S}) \quad (1)$$

Theoretical O_2: $\dfrac{p\,(\text{mol C})}{}\left|\dfrac{1\,\text{mol }O_2}{1\,\text{mol C}} + \dfrac{q\,(\text{mol H})}{}\right|\dfrac{0.5\,\text{mol }O_2}{2\,\text{mol H}} - \dfrac{(r\,\text{mol O})}{}\left|\dfrac{1\,\text{mol }O_2}{2\,\text{mol O}}\right.$

$$= (p + 1/4\,q - 1/2\,r)\,\text{mol }O_2$$

% excess $\Rightarrow n_1 = (1 + P/100)\,(p + 1/4\,q - \tfrac{1}{2}\,r)$ mol O_2 fed   (2)

C balance: $n_2 = p$ (3)
H balance: $n_5 = q/2$ (4)
S balance: $n_3 = n_0$ (5)
O balance: $r + 2n_1 = 2n_2 + 2n_3 + 2n_4 + n_5 \Rightarrow n_4 = \tfrac{1}{2}\,(r + 2n_1 - 2n_2 - 2n_3 - n_5)$ (6)

Given: $p = 0.71$, $q = 1.1$, $r = 0.003$, $X_s = 0.02$ $P = 18\%$ excess air

  (1) $\Rightarrow n_0 = 0.00616$ mol S   (5) $\Rightarrow n_3 = 0.00616$ mol SO_2

  (2) $\Rightarrow n_1 = 1.16$ mol O_2 fed   (6) $\Rightarrow n_4 = 0.170$ mol O_2

  (3) $\Rightarrow n_2 = 0.71$ mol CO_2 (4) $\Rightarrow n_5 = 0.55$ mol H_2O

  (3.76*1.16) mol N_2 = 4.36 mol N_2

Total moles of dry product gas = $n_2 + n_3 + n_4 + 3.76\,n_1 = 5.246$ mol dry product gas
Dry basis composition

  y_{CO2} = (0.710 mol CO_2/ 5.246 mol dry gas) * 100% = 13.5% CO_2

  y_{O2} = (0.170 / 5.246) * 100% = 3.2% O_2

  y_{N2} = (4.36 / 5.246) * 100% = 83.1% N_2

  y_{SO2} = (0.00616 / 5.246) * 10^6 = 1174 ppm SO_2

CHAPTER FIVE

5.1 Assume volume additivity

Av. density (Eq. 5.1-1): $\dfrac{1}{\overline{\rho}} = \dfrac{0.400}{0.703 \ \text{kg/L}} + \dfrac{0.600}{0.730 \ \text{kg/L}} \Rightarrow \overline{\rho} = 0.719 \ \text{kg/L}$

$\uparrow \qquad\qquad\qquad \uparrow$

$\rho_O \qquad\qquad\quad \rho_D$

a. $\underset{\substack{\uparrow \\ \text{mass of tank} \\ \text{at time } t}}{m} = \dot{m}t + \underset{\substack{\uparrow \\ \text{mass of} \\ \text{empty tank}}}{m_0} \Rightarrow \dot{m} = \dfrac{(250 - 150)\text{kg}}{(10 - 3)\text{min}} = 14.28 \ \text{kg/min} \quad (\dot{m} = \text{mass flow rate of liquid})$

$\Rightarrow \dot{V}(\text{L / min}) = \dfrac{\dot{m}(\text{kg / min})}{\overline{\rho}(\text{kg / L})} \Rightarrow \dot{V} = \dfrac{14.28 \ \text{kg}}{\text{min}} \bigg| \dfrac{1 \ \text{L}}{0.719 \ \text{kg}} = \underline{\underline{19.9 \ \text{L/min}}}$

b. $m_0 = m(t) - \dot{m}t = 150 - 14.28(3) = \underline{\underline{107 \ \text{kg}}}$

5.2 void volume of bed: $100 \ \text{cm}^3 - (233.5 - 184)\text{cm}^3 = 50.5 \ \text{cm}^3$

porosity: $50.5 \ \text{cm}^3 \ \text{void}/184 \ \text{cm}^3 \ \text{total} = \underline{\underline{0.274 \ \text{cm}^3 \ \text{void}/\text{cm}^3 \ \text{total}}}$

bulk density: $600 \ \text{g}/184 \ \text{cm}^3 = \underline{\underline{3.26 \ \text{g}/\text{cm}^3}}$

absolute density: $600 \ \text{g}/(184 - 50.5)\text{cm}^3 = \underline{\underline{4.49 \ \text{g}/\text{cm}^3}}$

5.3

$C_6H_6(l)$
$\dot{m}_B \ (\text{kg / min})$
$\dot{V}_B = 20.0 \ \text{L / min}$

$C_7H_8(l)$
$\dot{m}_T \ (\text{kg / min})$
$\dot{V}_T \ (\text{L / min})$
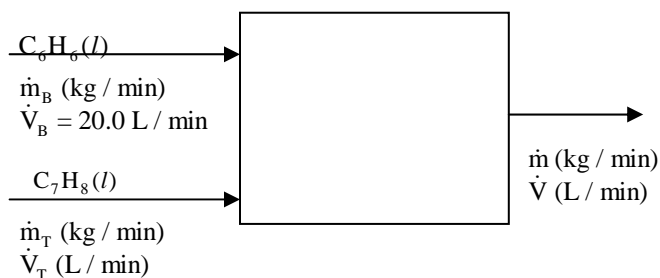
$\dot{m} \ (\text{kg / min})$
$\dot{V} \ (\text{L / min})$

$\dot{V} = \dfrac{\Delta V}{\Delta t} = \dfrac{\pi D^2}{4} \dfrac{\Delta h}{\Delta t} = \dfrac{\pi (5.5 \ \text{m})^2}{4} \bigg| \dfrac{0.15 \ \text{m}}{60 \ \text{min}} = 0.0594 \ \text{m}^3 \text{ / min}$

Assume additive volumes

$\dot{V}_T = \dot{V} - \dot{V}_B = (59.4 - 20.0) \ \text{L / min} = \underline{39.4 \ \text{L / min}}$

$\dot{m} = \rho_B \cdot \dot{V}_B + \rho_T \cdot \dot{V}_T = \dfrac{0.879 \ \text{kg}}{\text{L}} \bigg| \dfrac{20.0 \ \text{L}}{\text{min}} + \dfrac{0.866 \ \text{kg}}{\text{L}} \bigg| \dfrac{39.4 \ \text{L}}{\text{min}} = 51.7 \ \text{kg / min}$

$x_B = \dfrac{\dot{m}_B}{\dot{m}} = \dfrac{(0.879 \ \text{kg / L})(20.0 \ \text{L / min})}{(51.7 \ \text{kg / min})} = \underline{\underline{0.34 \ \text{kg B / kg}}}$

5.4 **a.** $\left.\begin{array}{l} P_1 = P_0 + \rho_{sl}gh_1 \\ P_2 = P_0 + \rho_{sl}gh_2 \\ h = h_1 - h_2 \end{array}\right\} \Rightarrow \Delta P = P_1 - P_2 = \rho_{sl}\left(\frac{kg}{m^3}\right)g\left(\frac{m}{s^2}\right)h(m)\left(\frac{1\,N}{1\frac{kg\cdot m}{s^2}}\right)\left(\frac{1\,Pa}{1\frac{N}{m^2}}\right) = \underline{\underline{\rho_{sl}gh}}$

b. $\dfrac{1}{\rho_{sl}} = \dfrac{x_c}{\rho_c} + \dfrac{(1-x_c)}{\rho_l} \Rightarrow$ check units!

$$\frac{1}{kg\ slurry\,/\,L\ slurry} = \frac{kg\ crystals\,/\,kg\ slurry}{kg\ crystals\,/\,L\ crystals} + \frac{kg\ liquid\,/\,kg\ slurry}{kg\ liquid\,/\,L\ liquid}$$

$$\frac{L\ slurry}{kg\ slurry} = \frac{L\ crystals}{kg\ slurry} + \frac{L\ liquid}{kg\ slurry} = \frac{L\ slurry}{kg\ slurry}$$

c. **i.)** $\rho_{sl} = \dfrac{\Delta P}{gh} = \dfrac{2775}{(9.8066)(0.200)} = \underline{\underline{1415\ kg\,/\,m^3}}$

ii.) $\dfrac{1}{\rho_{sl}} = \dfrac{x_c}{\rho_c} + \dfrac{(1 - x_c)}{\rho_l} \Rightarrow x_c\left(\dfrac{1}{\rho_c} - \dfrac{1}{\rho_l}\right) = \left(\dfrac{1}{\rho_{sl}} - \dfrac{1}{\rho_l}\right)$

$$x_c = \frac{\left(\dfrac{1}{1415\ kg\,/\,m^3} - \dfrac{1}{1.2\left(1000\ kg\,/\,m^3\right)}\right)}{\left(\dfrac{1}{2.3\left(1000\ kg\,/\,m^3\right)} - \dfrac{1}{1.2\left(1000\ kg\,/\,m^3\right)}\right)} = \underline{\underline{0.316\ kg\ crystals\,/\,kg\ slurry}}$$

iii.) $V_{sl} = \dfrac{m_{sl}}{\rho_{sl}} = \dfrac{175\ kg}{1415\ kg\,/\,m^3}\left|\dfrac{1000\ L}{m^3}\right. = \underline{\underline{123.8\ L}}$

iv.) $m_c = x_c m_{sl} = (0.316\ kg\ crystals\,/\,kg\ slurry)(175\ kg\ slurry) = \underline{\underline{55.3\ kg\ crystals}}$

v.) $m_{CuSO_4} = \dfrac{55.3\ kg\ CuSO_4 \cdot 5H_2O}{}\left|\dfrac{1\ kmol}{249\ kg}\right|\dfrac{1\ kmol\ CuSO_4}{1\ kmol\ CuSO_4 \cdot 5H_2O}\left|\dfrac{159.6\ kg}{1\ kmol}\right. = \underline{\underline{35.4\ kg\ CuSO_4}}$

vi.) $m_l = (1 - x_c)m_{sl} = (0.684\ kg\ liquid\,/\,kg\ slurry)(175\ kg\ slurry) = \underline{\underline{120\ kg\ liquid\ solution}}$

vii.) $V_l = \dfrac{m_l}{\rho_l} = \dfrac{120\ kg}{(1.2)\left(1000\ kg\,/\,m^3\right)}\left|\dfrac{1000\ L}{m^3}\right. = \underline{\underline{100\ L}}$

d.

h(m)	0.2							
$\rho l(kg/m^3)$	1200							
$\rho c(kg/m^3)$	2300							
$\Delta P(Pa)$	2353.58	2411.24	2471.80	2602.52	2747.84	2772.61	2910.35	3093.28
xc	0	0.05	0.1	0.2	0.3	0.316	0.4	0.5
$\rho sl(kg/m^3)$	1200.00	1229.40	1260.27	1326.92	1401.02	1413.64	1483.87	1577.14

Effect of Slurry Density on Pressure Measurement

Solids Fraction (y-axis: 0 to 0.6)

Pressure Difference (Pa) (x-axis: 2300.00 to 3100.00)
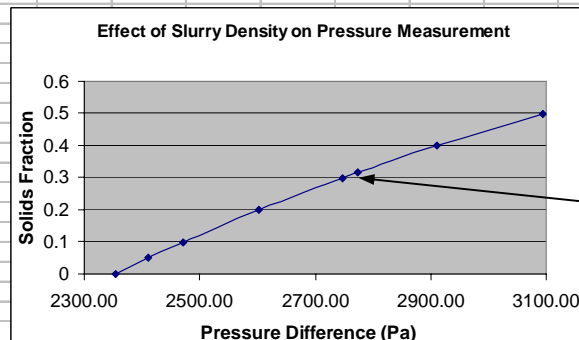
$\Delta P = 2775,\ \rho = 0.316$

5.4 (cont'd)

e. Basis: 1 kg slurry $\Rightarrow x_c$ (kg crystals), V_c (m^3 crystals) $= \dfrac{x_c(\text{kg crystals})}{\rho_c(\text{kg / m}^3)}$

$(1 - x_c)$ (kg liquid), V_l (m^3 liquid) $= \dfrac{(1 - x_c)(\text{kg liquid})}{\rho_l(\text{kg / m}^3)}$

$$\rho_{sl} = \frac{1 \text{ kg}}{(V_c + V_l)(\text{m}^3)} = \frac{1}{\dfrac{x_c}{\rho_c} + \dfrac{(1 - x_c)}{\rho_l}}$$

5.5 Assume $P_{atm} = 1$ atm

$$P\hat{V} = RT \Rightarrow \hat{V} = \frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \bigg| \frac{313.2 \text{ K}}{4.0 \text{ atm}} \bigg| \frac{1 \text{ kmol}}{10^3 \text{ mol}} = \underline{\underline{0.0064 \text{ m}^3/\text{mol}}}$$

$$\rho = \frac{1 \text{ mol}}{0.0064 \text{ m}^3 \text{ air}} \bigg| \frac{29.0 \text{ g}}{\text{mol}} \bigg| \frac{1 \text{ kg}}{10^3 \text{ g}} = \underline{\underline{4.5 \text{ kg}/\text{m}^3}}$$

5.6 a. $V = \dfrac{nRT}{P} = \dfrac{1.00 \text{ mol}}{} \bigg| \dfrac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \bigg| \dfrac{373.2 \text{ K}}{10 \text{ atm}} = \underline{\underline{3.06 \text{ L}}}$

b. % error $= \dfrac{(3.06\text{L} - 2.8\text{L})}{2.8\text{L}} \times 100\% = \underline{\underline{9.3\%}}$

5.7 Assume $P_{atm} = 1.013$ bar

a.
$$PV = nRT \Rightarrow n = \frac{(10 + 1.013)\text{bar}}{(25 + 273.2)\text{K}} \bigg| \frac{20.0 \text{ m}^3}{0.08314 \text{ m}^3 \cdot \text{bar}} \bigg| \frac{\text{kmol} \cdot \text{K}}{} \bigg| \frac{28.02 \text{ kg N}_2}{\text{kmol}} = \underline{\underline{249 \text{ kg N}_2}}$$

b. $\dfrac{PV}{P_s V_s} = \dfrac{nRT}{n_s RT_s} \Rightarrow n = V \cdot \dfrac{T_s}{T} \cdot \dfrac{P}{P_s} \cdot \dfrac{n_s}{V_s}$

$$n = \frac{20.0 \text{ m}^3}{298.2\text{K}} \bigg| \frac{273\text{K}}{1.013 \text{ bar}} \bigg| \frac{(10 + 1.013)\text{bar}}{22.415 \text{ m}^3(\text{STP})} \bigg| \frac{1 \text{ kmol}}{} \bigg| \frac{28.02 \text{ kg N}_2}{\text{kmol}} = \underline{\underline{249 \text{ kg N}_2}}$$

5.8 a. $R = \dfrac{P_s V_s}{n_s T_s} = \dfrac{1 \text{ atm}}{1 \text{ kmol}} \bigg| \dfrac{22.415 \text{ m}^3}{273 \text{ K}} = \underline{\underline{8.21 \times 10^{-2} \dfrac{\text{atm} \cdot \text{m}^3}{\text{kmol} \cdot \text{K}}}}$

b. $R = \dfrac{P_s V_s}{n_s T_s} = \dfrac{1 \text{ atm}}{1 \text{ lb - mole}} \bigg| \dfrac{760 \text{ torr}}{1 \text{ atm}} \bigg| \dfrac{359.05 \text{ ft}^3}{492 \text{ }^\circ\text{R}} = \underline{\underline{555 \dfrac{\text{torr} \cdot \text{ft}^3}{\text{lb - mole} \cdot ^\circ \text{R}}}}$

5.9 $P = 1 \text{ atm} + \dfrac{10 \text{ cm H}_2\text{O}}{} \left|\dfrac{1 \text{ m}}{10^2 \text{ cm}}\right|\dfrac{1 \text{ atm}}{10.333 \text{ m H}_2\text{O}} = 1.01 \text{ atm}$

$T = 25°C = 298.2 \text{ K}, \quad \dot{V} = \dfrac{2.0 \text{ m}^3}{5 \text{ min}} = 0.40 \text{ m}^3/\text{min} = 400 \text{ L}/\text{min}$

$\dot{m} = \dot{n}(\text{mol / min}) \cdot MW(\text{g / mol})$

a. $\dot{m} = \dfrac{P\dot{V}}{RT} \cdot MW = \dfrac{1.01 \text{ atm}}{0.08206 \frac{\text{L·atm}}{\text{mol·K}}} \left|\dfrac{400 \frac{\text{L}}{\text{min}}}{298.2 \text{ K}}\right|\dfrac{28.02 \frac{\text{g}}{\text{mol}}}{} = \underline{\underline{458 \text{ g}/\text{min}}}$

b. $\dot{m} = \dfrac{400 \frac{\text{L}}{\text{min}}}{} \left|\dfrac{273 \text{ K}}{298.2 \text{ K}}\right|\dfrac{1 \text{ mol}}{22.4 \text{ L(STP)}}\left|\dfrac{28.02 \frac{\text{g}}{\text{mol}}}{}\right. = \underline{\underline{458 \text{ g}/\text{min}}}$

5.10 <u>Assume ideal gas behavior:</u> $u\left(\dfrac{\text{m}}{\text{s}}\right) = \dfrac{\dot{V}(\text{m}^3/\text{s})}{A(\text{m}^2)} = \dfrac{\dot{n}RT/P}{\pi D^2/4} \Rightarrow \dfrac{u_2}{u_1} = \dfrac{\dot{n}R}{\dot{n}R} \cdot \dfrac{T_2}{T_1} \cdot \dfrac{P_1}{P_2} \cdot \dfrac{D_1^2}{D_2^2}$

$u_2 = u_1 \dfrac{T_2 P_1 D_1^2}{T_1 P_2 D_2^2} = \dfrac{60.0 \text{ m}}{\text{sec}} \left|\dfrac{333.2\text{K}}{300.2\text{K}}\right|\dfrac{(1.80+1.013)\text{bar}}{(1.53+1.013)\text{bar}}\left|\dfrac{(7.50 \text{ cm})^2}{(5.00 \text{ cm})^2}\right. = \underline{\underline{165 \text{ m}/\text{sec}}}$

5.11 <u>Assume ideal gas behavior:</u> $n = \dfrac{PV}{RT} = \dfrac{(1.00+1.00) \text{ atm}}{0.08206 \frac{\text{L·atm}}{\text{mol·K}}} \left|\dfrac{5 \text{ L}}{300 \text{ K}}\right. = 0.406 \text{ mol}$

$MW = 13.0 \text{ g}/0.406 \text{ mol} = 32.0 \text{ g}/\text{mol} \Rightarrow \underline{\underline{\text{Oxygen}}}$

5.12 <u>Assume ideal gas behavior:</u> Say $m_t = $ mass of tank, $n_g = $ mol of gas in tank

$\left.\begin{array}{l} N_2: \quad 37.289 \text{ g} = m_t + n_g(28.02 \text{ g}/\text{mol}) \\ CO_2: \quad 37.440 \text{ g} = m_t + n_g(44.1 \text{ g}/\text{mol}) \end{array}\right\} \Rightarrow \begin{array}{l} n_g = 0.009391 \text{ mol} \\ m_t = 37.0256 \text{ g} \end{array}$

unknown: $MW = \dfrac{(37.062 - 37.0256)\text{g}}{0.009391 \text{ mol}} = \underline{\underline{3.9 \text{ g}/\text{mol}}} \Rightarrow \text{Helium}$

5.13 a. $\dot{V}_{std}\left[\text{cm}^3(\text{STP})/\text{min}\right] = \dfrac{\Delta V \text{ liters}}{\Delta t \text{ min}} \left|\dfrac{273\text{K}}{296.2\text{K}}\right|\dfrac{763 \text{ mm Hg}}{760 \text{ mm Hg}}\left|\dfrac{10^3 \text{cm}^3}{1 \text{ L}}\right. = 925.3\dfrac{\Delta V}{\Delta t}$

$\left.\begin{array}{cc} \underline{\phi} & \underline{\dot{V}_{std}\left[\text{cm}^3(\text{STP})/\text{min}\right]} \\ 5.0 & 139 \\ 9.0 & 268 \\ 12.0 & 370 \end{array}\right\}$ straight line plot

$\Downarrow$

$\underline{\underline{\phi = 0.031\dot{V}_{std} + 0.93}}$

b. $\dot{V}_{std} = \dfrac{0.010 \text{ mol N}_2}{\text{min}} \left|\dfrac{22.4 \text{ liters(STP)}}{1 \text{ mole}}\right|\dfrac{10^3 \text{ cm}^3}{1 \text{ L}} = 224 \text{ cm}^3 / \text{min}$

$\phi = 0.031(224 \text{ cm}^3 / \text{min}) + 0.93 = \underline{7.9}$

5.14 Assume ideal gas behavior $\rho(kg/L) = \dfrac{n(kmol)M(kg/mol)}{V(L)} \overset{\frac{n}{V}=\frac{P}{RT}}{=\!=\!=\!=\!=\!>} \dfrac{PM}{RT}$

$$V_2\left(cm^3/s\right) = V_1\left(cm^3/s\right)\cdot\left(\frac{\rho_1}{\rho_2}\right)^{1/2} = V_1\left[P_1M_1T_2/P_2M_2T_1\right]^{1/2}$$

a. $V_{H_2} = 350\dfrac{cm^3}{s}\left[\dfrac{758 \text{ mm Hg}}{1800 \text{ mm Hg}}\,\middle|\,\dfrac{28.02 \text{ g/mol}}{2.02 \text{ g/mol}}\,\middle|\,\dfrac{323.2K}{298.2K}\right]^{1/2} = \underline{\underline{881 \text{ cm}^3/s}}$

b. $\overline{M} = 0.25M_{CH_4} + 0.75M_{C_3H_8} = (0.25)(16.05) + (0.75)(44.11) = 37.10 \text{ g/mol}$

$$V_g = 350\dfrac{cm^3}{s}\left[\dfrac{(758)(28.02)(323.2)}{(1800)(37.10)(298.2)}\right]^{1/2} = \underline{\underline{205 \text{ cm}^3/s}}$$

5.15 a.
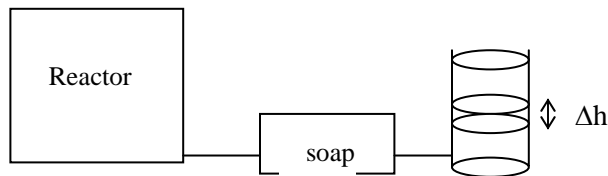
b. $\dot{n}_{CO_2} = \dfrac{P\dot{V}}{RT} \Rightarrow \dot{V} = \dfrac{\pi R^2\Delta h}{\Delta t} = \dfrac{\pi}{4}\dfrac{\left(0.012 \text{ m}^2\right)^2}{}\,\middle|\,\dfrac{1.2 \text{ m}}{7.4 \text{ s}}\,\middle|\,\dfrac{60 \text{ s}}{\text{min}} = 1.1\times10^{-3} \text{ m}^3/\text{min}$

$$\dot{n}_{CO_2} = \dfrac{755 \text{ mm Hg}}{0.08206\,\frac{m^3\cdot atm}{kmol\cdot K}}\,\middle|\,\dfrac{1 \text{ atm}}{760 \text{ mm Hg}}\,\middle|\,\dfrac{1.1\times10^{-3} \text{ m}^3/\text{min}}{300 \text{ K}}\,\middle|\,\dfrac{1000 \text{ mol}}{1 \text{ kmol}} = \underline{\underline{0.044 \text{ mol/min}}}$$

5.16
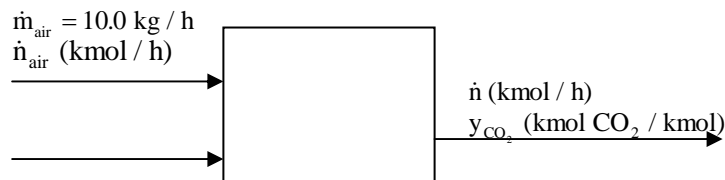
Assume ideal gas behavior

$$\dot{n}_{air} = \dfrac{10.0 \text{ kg}}{h}\,\middle|\,\dfrac{1 \text{ kmol}}{29.0 \text{ kg air}} = 0.345 \text{ kmol air} / h$$

$$\dot{n}_{CO_2} = \dfrac{P\dot{V}}{RT} = \dfrac{1.5 \text{ bar}}{8.314\,\frac{m^3\cdot kPa}{kmol\cdot K}}\,\middle|\,\dfrac{100 \text{ kPa}}{1 \text{ bar}}\,\middle|\,\dfrac{20.0 \text{ m}^3/h}{423.2 \text{ K}} = 0.853 \text{ kmol CO}_2 / h$$

$$y_{CO_2}\times100\% = \dfrac{0.853 \text{ kmol CO}_2/h}{\left(0.853 \text{ kmol CO}_2/h + 0.345 \text{ kmol air}/h\right)}\times100\% = \underline{\underline{71.2\%}}$$

5.17 Basis: Given flow rates of outlet gas. Assume ideal gas behavior

$\dot{m}_1$ (kg / min)
0.70 kg H_2O / kg
0.30 kg S / kg

311 m^3 / min, $83°C$, 1 atm
$\dot{n}_3$ (kmol / min)
0.12 kmol H_2O / kmol
0.88 kmol dry air / kmol

$\dot{n}_2$ (kmol air / min)
$\dot{V}_2$ (m^3 / min)
$167°C$, - 40 cm H_2O gauge
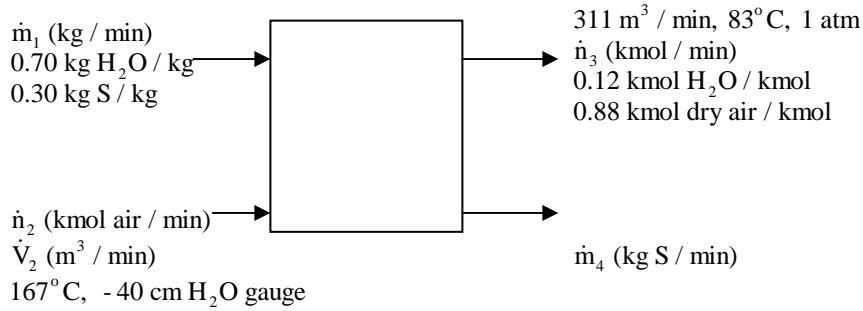
$\dot{m}_4$ (kg S / min)

a. $\dot{n}_3 = \dfrac{1 \text{ atm}}{356.2K} \left| \dfrac{311 \text{ m}^3}{\text{min}} \right| \dfrac{\text{kmol} \cdot \text{K}}{0.08206 \text{ m}^3 \cdot \text{atm}} = 10.64 \text{ kmol/min}$

$\underline{\text{H}_2\text{O balance}:}$ $0.70 \, m_1 = \dfrac{10.64 \text{ kmol}}{\text{min}} \left| \dfrac{0.12 \text{ kmol H}_2\text{O}}{\text{kmol}} \right| \dfrac{18.02 \text{ kg}}{\text{kmol}}$

$\Rightarrow \dot{m}_1 = 32.9 \text{ kg/min milk}$

$\underline{\text{S(olids) balance:}}$ $0.30(32.2 \text{ kg/min}) = \dot{m}_4 \Rightarrow \underline{\underline{\dot{m}_4 = 9.6 \text{ kg S/min}}}$

$\underline{\text{Dry air balance}:}$ $\dot{n}_2 = 0.88(10.64 \text{ kmol/min}) \Rightarrow \dot{n}_2 = 9.36 \text{ kmol/min air}$

$\dot{V}_2 = \dfrac{9.36 \text{ kmol}}{\text{min}} \left| \dfrac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \dfrac{440K}{(1033-40)\text{cm H}_2\text{O}} \left| \dfrac{1033 \text{ cm H}_2\text{O}}{1 \text{ atm}} \right.$

$= \underline{\underline{352 \text{ m}^3 \text{ air/min}}}$

$u_{\text{air}} (\text{m/min}) = \dfrac{\dot{V}_{\text{air}} \text{ (m}^3 / \text{s)}}{A \text{ (m}^2)} = \dfrac{352 \text{ m}^3}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} \right| \dfrac{1}{\text{π}/4 \cdot (6 \text{ m})^2} = \underline{\underline{0.21 \text{ m/s}}}$

b. If the velocity of the air is too high, the powdered milk would be blown out of the reactor by the air instead of falling to the conveyor belt.

5.18 $SG_{CO_2} = \dfrac{\rho_{CO_2}}{\rho_{\text{air}}} = \dfrac{\frac{PM_{CO_2}}{RT}}{\frac{PM_{\text{air}}}{RT}} = \dfrac{M_{CO_2}}{M_{\text{air}}} = \dfrac{44 \text{ kg / kmol}}{29 \text{ kg / kmol}} = \underline{\underline{1.52}}$

5.19 a. $x_{CO_2} = 0.75$ $x_{\text{air}} = 1 - 0.75 = 0.25$

Since air is 21% O_2, $x_{O_2} = (0.25)(0.21) = 0.0525 = \underline{\underline{5.25 \text{ mole% O}_2}}$

b. $m_{CO_2} = n \cdot x_{CO_2} \cdot M_{CO_2} = \dfrac{1 \text{ atm}}{0.08206 \frac{\text{m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}}} \left| \dfrac{(2 \times 1.5 \times 3)\text{m}^3}{298.2 \text{ K}} \right| \dfrac{0.75 \text{ kmol CO}_2}{\text{kmol}} \left| \dfrac{44.01 \text{ kg CO}_2}{\text{kmol CO}_2} = \underline{\underline{12 \text{ kg}}}\right.$

More needs to escape from the cylinder since the room is not sealed.

5.19 (cont'd)

    c. With the room closed off all weekend and the valve to the liquid cylinder leaking, if a person entered the room and closed the door, over a period of time the person could die of asphyxiation. Measures that would reduce hazards are:

      1. Change the lock so the door can always be opened from the inside without a key.

      2. Provide ventilation that keeps air flowing through the room.

      3. Install a gas monitor that sets off an alarm once the mole% reaches a certain amount.

      4. Install safety valves on the cylinder in case of leaks.

5.20 $n_{CO_2} = \dfrac{15.7 \text{ kg}}{} \left|\dfrac{1 \text{ kmol}}{44.01 \text{ kg}}\right. = 0.357 \text{ kmol CO}_2$

Assume ideal gas behavior, negligible temperature change $(T = 19°C = 292.2K)$

    a. $\dfrac{P_1 V}{P_2 V} = \dfrac{n_1 RT}{(n_1 + 0.357)RT} \Rightarrow \dfrac{n_1}{n_1 + 0.357} = \dfrac{P_1}{P_2} = \dfrac{102 \text{kPa}}{3.27 \times 10^3 \text{kPa}}$

        $\Rightarrow n_1 = \underline{0.0115 \text{ kmol air in tank}}$

    b. $V_{tank} = \dfrac{n_1 RT}{P_1} = \dfrac{0.0115 \text{ kmol}}{}\left|\dfrac{292.2 \text{ K}}{102 \text{kPa}}\right|\dfrac{8.314 \text{ m}^3 \cdot \text{kPa}}{\text{kmol} \cdot \text{K}}\left|\dfrac{10^3 \text{L}}{\text{m}^3}\right. = 274 \text{ L}$

      $\rho_f = \dfrac{15700 \text{ g CO}_2 + 11.5 \text{ mol air} \cdot (29.0 \text{ g air / mol})}{274 \text{ L}} = \underline{\underline{58.5 \text{ g / L}}}$

    c. CO_2 sublimates $\Rightarrow$ large volume change due to phase change $\Rightarrow$ rapid pressure rise. Sublimation causes temperature drop; afterwards, T gradually rises back to room temperature, increase in T at constant V $\Rightarrow$ slow pressure rise.

5.21 At point of entry, $P_1 = (10 \text{ ft H}_2\text{O})(29.9 \text{ in. Hg}/33.9 \text{ ft H}_2\text{O}) + 28.3 \text{ in. Hg} = 37.1 \text{ in. Hg}$.

At surface, $P_2 = 28.3 \text{ in. Hg}$, $V_2 = $ bubble volume at entry

Mean Slurry Density: $\dfrac{1}{\rho_{sl}} = \dfrac{x_{solid}}{\rho_{solid}} + \dfrac{x_{solution}}{\rho_{solution}} = \dfrac{0.20}{(1.2)(1.00 \text{ g / cm}^3)} + \dfrac{0.80}{(1.00 \text{ g / cm}^3)}$

$= 0.967 \dfrac{\text{cm}^3}{\text{g}} \Rightarrow \rho_{sl} = \dfrac{1.03 \text{ g}}{\text{cm}^3}\left|\dfrac{2.20 \text{ lb}}{1000 \text{ g}}\right|\dfrac{5 \times 10^{-4} \text{ ton}}{1 \text{ lb}}\left|\dfrac{10^6 \text{ cm}^3}{264.17 \text{ gal}}\right. = 4.3 \times 10^{-3} \text{ ton / gal}$

    a. $\dfrac{300 \text{ ton}}{\text{hr}}\left|\dfrac{\text{gal}}{4.3 \times 10^{-3} \text{ ton}}\right|\dfrac{40.0 \text{ ft}^3 (\text{STP})}{1000 \text{ gal}}\left|\dfrac{534.7° \text{R}}{492° \text{R}}\right|\dfrac{29.9 \text{ in Hg}}{37.1 \text{ in Hg}} = \underline{\underline{2440 \text{ ft}^3 \text{ / hr}}}$

    b. $\dfrac{P_2 V_2}{P_1 V_1} = \dfrac{nRT}{nRT} \Rightarrow \dfrac{V_2}{V_1} = \dfrac{P_1}{P_2} \Rightarrow \dfrac{\frac{4}{3}\pi\left(\frac{D_2}{2}\right)^3}{\frac{4}{3}\pi\left(\frac{D_1}{2}\right)^3} = \dfrac{37.1}{28.3} \Rightarrow D_2^3 = 1.31 D_1^3 \overset{D_1 = 2 \text{ mm}}{=\!=\!=\!>} D_2 = 2.2 \text{ mm}$

      % change $= \dfrac{(2.2 \text{ - } 2.0) \text{ mm}}{2.0 \text{ mm}} \times 100 = \underline{\underline{10\%}}$

5.22 Let $B = $ benzene

$n_1, n_2, n_3 = $ moles in the container when the sample is collected, after the helium is added, and after the gas is fed to the GC.

$n_{inj} = $ moles of gas injected

$n_B, n_{air}, n_{He} = $ moles of benzene and air in the container and moles of helium added

$n_{BGC}, m_{BGC} = $ moles, g of benzene in the GC

$y_B = $ mole fraction of benzene in room air

a. $P_1 V_1 = n_1 R T_1$ ($1 \equiv $ condition when sample was taken): $P_1 = 99$ kPa, $T_1 = 306$K

$$n_1 = \frac{99 \text{ kPa}}{101.3 \frac{\text{kPa}}{\text{atm}}} \left| \frac{2 \text{ L}}{306 \text{ K}} \right| \frac{\text{mol} \cdot \text{K}}{.08206 \text{ L} \cdot \text{atm}} = 0.078 \text{ mol} = n_{air} + n_B$$

$P_2 V_2 = n_2 R T_2$ ($2 \equiv $ condition when charged with He): $P_2 = 500$ kPa, $T_2 = 306$K

$$n_2 = \frac{500 \text{ kPa}}{101.3 \frac{\text{kPa}}{\text{atm}}} \left| \frac{2 \text{ L}}{306 \text{ K}} \right| \frac{\text{mol} \cdot \text{K}}{.08206 \text{ L} \cdot \text{atm}} = 0.393 \text{ mol} = n_{air} + n_B + n_{He}$$

$P_3 V_3 = n_3 R T_3$ ($3 \equiv $ final condition in lab): $P_3 = 400$ kPa, $T_3 = 296$K

$$n_3 = \frac{400 \text{ kPa}}{101.3 \frac{\text{kPa}}{\text{atm}}} \left| \frac{2 \text{ L}}{296 \text{ K}} \right| \frac{\text{mol} \cdot \text{K}}{.08206 \text{ L} \cdot \text{atm}} = 0.325 \text{ mol} = (n_{air} + n_B + n_{He}) - n_{inj}$$

$n_{inj} = n_2 - n_3 = 0.068$ mol

$$n_B = n_{BGC} \times \frac{n_2}{n_{inj}} = \frac{0.393 \text{ mol}}{0.068 \text{ mol}} \left| \frac{m_{BGC} (\text{g B})}{} \right| \frac{1 \text{ mol}}{78.0 \text{ g}} = 0.0741 \cdot m_{BGC}$$

$$y_B (\text{ppm}) = \frac{n_B}{n_1} \times 10^6 = \frac{0.0741 \cdot m_{BGC}}{0.078} \times 10^6 = 0.950 \times 10^6 \cdot m_{BGC}$$

9 am: $y_B = (0.950 \times 10^6)(0.656 \times 10^{-6}) = \underline{\underline{0.623 \text{ ppm}}}$

1 pm: $y_B = (0.950 \times 10^6)(0.788 \times 10^{-6}) = \underline{\underline{0.749 \text{ ppm}}}$ The avg. is below the PEL

5 pm: $y_B = (0.950 \times 10^6)(0.910 \times 10^{-6}) = \underline{\underline{0.864 \text{ ppm}}}$

b. Helium is used as a carrier gas for the gas chromatograph, and to pressurize the container so gas will flow into the GC sample chamber. Waiting a day allows the gases to mix sufficiently and to reach thermal equilibrium.

c. (*i*) It is very difficult to have a completely evacuated sample cylinder; the sample may be dilute to begin with. (*ii*) The sample was taken on Monday after 2 days of inactivity at the plant. A reading should be taken on Friday. (*iii*) Helium used for the carrier gas is less dense than the benzene and air; therefore, the sample injected in the GC may be He-rich depending on where the sample was taken from the cylinder. (*iv*) The benzene may not be uniformly distributed in the laboratory. In some areas the benzene concentration could be well above the PEL.

5.23 Volume of balloon $= \dfrac{4}{3}\pi(10\ \text{m})^3 = 4189\ \text{m}^3$
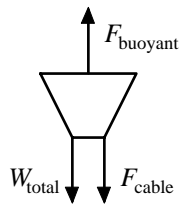
Moles of gas in balloon

$$n(\text{kmol}) = \frac{4189\ \text{m}^3}{}\left|\frac{492°\text{R}}{535°\text{R}}\right|\frac{3\ \text{atm}}{1\ \text{atm}}\left|\frac{1\ \text{kmol}}{22.4\ \text{m}^3(\text{STP})}\right. = 515.9\ \text{kmol}$$

a. He in balloon:

$$m = (515.9\ \text{kmol})\cdot(4.003\ \text{kg/kmol}) = \underline{\underline{2065\ \text{kg He}}}$$

$$m_g = \frac{2065\ \text{kg}}{}\left|\frac{9.807\ \text{m}}{\text{s}^2}\right|\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m}/\text{s}^2} = \underline{\underline{20{,}250\ \text{N}}}$$

b. $\begin{pmatrix}P_{\text{gas in balloon}}\end{pmatrix}V = n_{\text{gas}}RT \\ \begin{pmatrix}P_{\text{air displaced}}\end{pmatrix}V = n_{\text{air}}RT \Rightarrow n_{\text{air}} = \dfrac{P_{\text{air}}}{P_{\text{gas}}}\cdot n_{\text{gas}} = \dfrac{1\ \text{atm}}{3\ \text{atm}}\cdot 515.9\ \text{kmol} = 172.0\ \text{kmol}$

$$F_{\text{buoyant}} = W_{\text{air displaced}} = \frac{172.0\ \text{kmol}}{}\left|\frac{29.0\ \text{kg}}{1\ \text{kmol}}\right|\frac{9.807\ \text{m}}{\text{s}^2}\left|\frac{1\ \text{N}}{1\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2}}\right. = 48{,}920\ \text{N}$$

Since balloon is stationary, $\sum F_i = 0$

$$F_{\text{cable}} = F_{\text{buoyant}} - W_{\text{total}} = 48920\ \text{N} - \frac{(2065+150)\text{kg}}{}\left|\frac{9.807\ \text{m}}{\text{s}^2}\right|\frac{1\ \text{N}}{1\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2}} = \underline{\underline{27{,}20}}$$

c. When cable is released, $F_{\text{net}}(\uparrow) = 27200\ \text{N} = M_{\text{tot}}a$

$$\Rightarrow a = \frac{27200\ \text{N}}{(2065+150)\text{kg}}\left|\frac{1\ \text{kg}\cdot\text{m}/\text{s}^2}{\text{N}}\right. = \underline{\underline{12.3\ \text{m}/\text{s}^2}}$$

d. When mass of displaced air equals mass of balloon + helium the balloon stops rising. Need to know how density of air varies with altitude.

e. The balloon expands, displacing more air $\Rightarrow$ buoyant force increases $\Rightarrow$ balloon rises until decrease in air density at higher altitudes compensates for added volume.

5.24 Assume ideal gas behavior, $P_{\text{atm}} = 1\ \text{atm}$

a. $P_N V_N = P_c V_c \Rightarrow V_c = \dfrac{P_N V_N}{P_c} = \dfrac{5.7\ \text{atm}}{9.5\ \text{atm}}\left|\dfrac{400\ \text{m}^3/\text{h}}{}\right. = \underline{\underline{240\ \text{m}^3/\text{h}}}$

b. Mass flow rate before diversion:

$$\frac{400\ \text{m}^3}{\text{h}}\left|\frac{273\ \text{K}}{303\ \text{K}}\right|\frac{5.7\ \text{atm}}{1\ \text{atm}}\left|\frac{1\ \text{kmol}}{22.4\ \text{m}^3(\text{STP})}\right|\frac{44.09\ \text{kg}}{\text{kmol}} = 4043\frac{\text{kg}\ C_3H_6}{\text{h}}$$

5.24 (cont'd)

Monthly revenue:

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

c. Mass flow rate at Noxious plant after diversion:

$$\frac{400 \text{ m}^3}{\text{hr}} \left| \frac{273 \text{ K}}{303 \text{ K}} \right| \frac{2.8 \text{ atm}}{1 \text{ atm}} \left| \frac{1 \text{ kmol}}{22.4 \text{ m}^3} \right| \frac{44.09 \text{ kg}}{\text{kmol}} = 1986 \text{ kg/hr}$$

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

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

$P_{\text{CH}_4} = y_{\text{CH}_4} \cdot P = 0.20 \cdot (2.00 \text{ atm}) = \underline{0.40 \text{ atm}}$

$P_{\text{N}_2} = y_{\text{N}_2} \cdot P = 0.45 \cdot (2.00 \text{ atm}) = \underline{0.90 \text{ atm}}$

b. Assume 1.00 mole gas

$$\left.\begin{array}{l} 0.35 \text{ mol He} \left(\dfrac{4.004 \text{ g}}{\text{mol}}\right) = 1.40 \text{ g He} \\[3mm] 0.20 \text{ mol CH}_4 \left(\dfrac{16.05 \text{ g}}{\text{mol}}\right) = 3.21 \text{ g CH}_4 \\[3mm] 0.45 \text{ mol N}_2 \left(\dfrac{28.02 \text{ g}}{\text{mol}}\right) = 12.61 \text{ g N}_2 \end{array}\right\} 17.22 \text{ g} \Rightarrow \text{mass fraction CH}_4 = \dfrac{3.21 \text{ g}}{17.22 \text{ g}} = \underline{0.186}$$
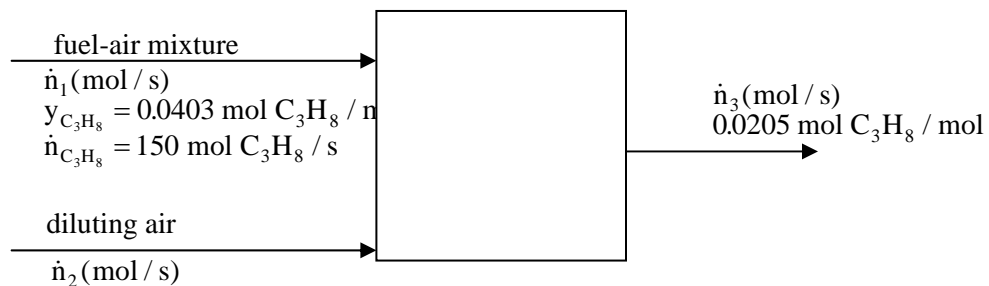
c. $\overline{\text{MW}} = \dfrac{\text{g of gas}}{\text{mol}} = \underline{17.2 \text{ g / mol}}$

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

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.

$$\dot{n}_1 = \frac{150 \text{ mol C}_3\text{H}_8}{\text{s}} \left| \frac{\text{mol}}{0.0403 \text{ mol C}_3\text{H}_8} \right. = 3722 \text{ mol / s}$$

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

5.26 (cont'd)

Total mole balance: $\dot{n}_1 + \dot{n}_2 = \dot{n}_3 \Rightarrow \dot{n}_2 = 7317 - 3722 = 3595$ mol air / s

**c.** $\dot{n}_2 = 1.3(\dot{n}_2)_{min} = 4674$ mol / s

$$\dot{V}_2 = \frac{4674 \text{ mol / s}}{} \left|\frac{8.314 \text{ m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}}\right| \frac{398.2 \text{ K}}{131,000 \text{ Pa}} = 118 \text{ m}^3 / \text{s}$$

$$\dot{V}_1 = \frac{3722 \text{ mol}}{\text{s}} \left|\frac{8.314 \text{ m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}}\right| \frac{298.2 \text{ K}}{110000 \text{ Pa}} = 83.9 \text{ m}^3 / \text{s}$$

$$\left.\right\} \quad \frac{\dot{V}_2}{\dot{V}_1} = 1.41 \frac{\text{m}^3 \text{ diluting air}}{\text{m}^3 \text{ fuel gas}}$$

$$y_2 = \frac{150 \text{ mol / s}}{\dot{n}_1 + \dot{n}_2} = \frac{150 \text{ mol / s}}{(3722 \text{ mol / s} + 4674 \text{ mol / s})} \times 100\% = \underline{\underline{1.8\%}}$$

d. The incoming propane mixture could be higher than 4.03%.
If $\dot{n}_2 = (\dot{n}_2)_{min}$, fluctuations in the air flow rate would lead to temporary explosive conditions.

5.27 Basis: $(12 \text{ breaths/min})(500 \text{ mL air inhaled/breath}) = 6000 \text{ mL inhaled/min}$
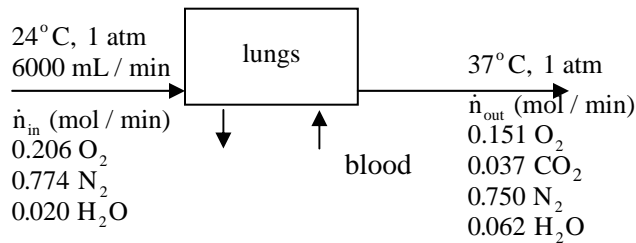
a. $\dot{n}_{in} = \frac{6000 \text{ mL}}{\text{min}} \left|\frac{1 \text{ L}}{10^3 \text{ mL}}\right| \frac{273\text{K}}{297\text{K}} \left|\frac{1 \text{ mol}}{22.4 \text{ L (STP)}}\right| = 0.246 \text{ mol/min}$

N_2 balance: $(0.774)(0.246) = 0.750\dot{n}_{out} \Rightarrow \dot{n}_{out} = 0.254 \text{ mol exhaled/min}$

O_2 transferred to blood: $[(0.246)(0.206) - (0.254)(0.151)](\text{mol } O_2/\text{min})[32.0 \text{ g/mol}]$
$$= \underline{\underline{0.394 \text{ g } O_2/\text{min}}}$$

CO_2 transferred from blood: $[(0.254)(0.037)](\text{mol } CO_2/\text{min})[44.01 \text{ g/mol}]$
$$= \underline{\underline{0.414 \text{ g } CO_2/\text{min}}}$$

H_2O transferred from blood:
$$[(0.254)(0.062) - (0.246)(0.020)](\text{mol } H_2O/\text{min})[18.02 \text{ g/mol}]$$
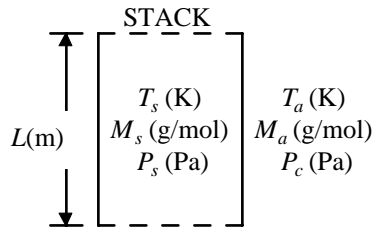$$= \underline{\underline{0.195 \text{ g } H_2O/\text{min}}}$$

5.27 (cont'd)

$$\frac{PV_{in}}{PV_{out}} = \frac{n_{in}RT_{in}}{n_{out}RT_{out}}$$

$$\Rightarrow \frac{V_{out}}{V_{in}} = \left(\frac{n_{out}}{n_{in}}\right)\left(\frac{T_{out}}{T_{in}}\right) = \left(\frac{0.254 \text{ mol/min}}{0.246 \text{ mol/min}}\right)\left(\frac{310K}{297K}\right) = \underline{\underline{1.078 \text{ mL exhaled/ml inhaled}}}$$

b. $\left(0.414 \text{ g } CO_2 \text{ lost/min}\right) + \left(0.195 \text{ g } H_2O \text{ lost/min}\right) - \left(0.394 \text{ g } O_2 \text{ gained/min}\right) = \underline{\underline{0.215 \text{ g/min}}}$

5.28

$$\underline{\text{Ideal gas: } \rho = \frac{PM}{RT}}$$

a. $D = \left(\rho gL\right)_{combust.} - \left(\rho gL\right)_{stack} = \frac{P_a M_a}{RT_a}gL - \frac{P_a M_s}{RT_s}gL = \frac{P_a gL}{R}\left[\frac{M_a}{T_a} - \frac{M_a}{T_s}\right]$

b. $M_s = (0.18)(44.1) + (0.02)(32.0) + (0.80)(28.0) = 31.0 \text{ g/mol}$, $T_s = 655K$,
$P_a = 755 \text{ mm Hg}$

$M_a = 29.0 \text{ g/mol}$, $T_a = 294K$, $L = 53 \text{ m}$

$$D = \frac{755 \text{ mm Hg}}{} \left|\frac{1 \text{ atm}}{760 \text{ mm Hg}}\right| \frac{53.0 \text{ m}}{} \left|\frac{9.807 \text{ m}}{s^2}\right| \frac{kmol\text{-}K}{0.08206 \text{ m}^3 - atm}$$

$$\times \left[\frac{29.0 \text{ kg/kmol}}{294K} - \frac{31.0 \text{ kg/kmol}}{655K}\right] \times \left(\frac{1 \text{ N}}{1 \text{ kg}\cdot m/s^2}\right) = \frac{323 \text{ N}}{m^2}\left|\frac{1033 \text{ cm } H_2O}{1.013\times10^5 \text{ N/m}^2}\right|$$

$$= \underline{\underline{3.3 \text{ cm } H_2O}}$$

5.29 a. $\rho = \frac{P(MW)}{RT} \xmapsto{MW_{CCl_2O} = 98.91 \text{ g/mol}} \frac{\rho_{CCl_2O}}{\rho_{air}} = \frac{98.91}{29.0} = 3.41$

Phosgene, which is 3.41 times more dense than air, will displace air near the ground.

b. $V_{tube} = \frac{\pi(D_{in})^2 L}{4} = \frac{\pi}{4}[0.635 \text{ cm} - 2(0.0559 \text{ cm})]^2 (15.0 \text{ cm}) = 3.22 \text{ cm}^3$

$$m_{CCl_2O} = V_{tube} \cdot \rho_{CCl_2O} = \frac{3.22 \text{ cm}^3}{} \left|\frac{1 \text{ L}}{10^3 \text{ cm}^3}\right| \frac{1 \text{ atm}}{0.08206 \frac{L\cdot atm}{mol\cdot K}} \left|\frac{98.91 \text{ g / mol}}{296.2 \text{ K}}\right| = \underline{\underline{0.0131 \text{ g}}}$$

c. $n_{CCl_2O(l)} = \frac{3.22 \text{ cm}^3}{} \left|\frac{1.37 \times 1.000 \text{ g}}{cm^3}\right| \frac{mol}{98.91 \text{ g}} = 0.0446 \text{ mol } CCl_2O$
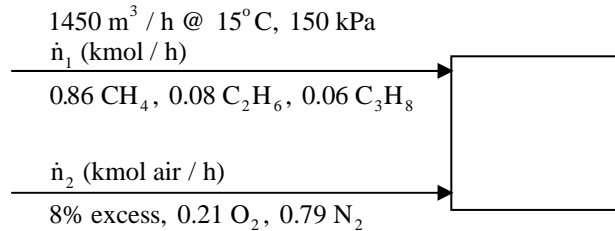
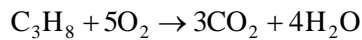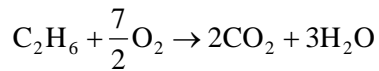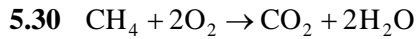**5.29 (cont'd)**

$$n_{air} = \frac{PV}{RT} = \frac{1\text{ atm}}{296.2\text{K}} \left| \frac{2200\text{ ft}^3}{} \right| \frac{28.317\text{ L}}{\text{ft}^3} \left| \frac{\text{mol} \cdot \text{K}}{.08206\text{ L} \cdot \text{atm}} \right. = 2563\text{ mol air}$$

$$\frac{n_{CCl_2O}}{n_{air}} = \frac{0.0446}{2563} = \underline{\underline{17.4 \times 10^{-6}}} = \underline{\underline{17.4\text{ ppm}}}$$

The level of phosgene in the room exceeded the safe level by a factor of more than 100. Even if the phosgene were below the safe level, there would be an unsafe level near the floor since phosgene is denser than air, and the concentration would be much higher in the vicinity of the leak.

d. Pete's biggest mistake was working with a highly toxic substance with no supervision or guidance from an experienced safety officer. He also should have been working under a hood and should have worn a gas mask.

5.30 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

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

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

1450 m³ / h @ 15°C, 150 kPa
$\dot{n}_1$ (kmol / h)
0.86 CH_4, 0.08 C_2H_6, 0.06 C_3H_8

$\dot{n}_2$ (kmol air / h)
8% excess, 0.21 O_2, 0.79 N_2

$$\dot{n}_1 = \frac{1450\text{ m}^3}{\text{h}} \left| \frac{273.2\text{K}}{288.2\text{K}} \right| \frac{(101.3 + 150)\text{kPa}}{101.3\text{ kPa}} \left| \frac{1\text{ kmol}}{22.4\text{ m}^3\text{(STP)}} \right. = 152\text{ kmol/h}$$

Theoretical O_2:

$$\frac{152\text{kmol}}{\text{h}} \left[0.86 \left(\frac{2\text{ kmol }O_2}{\text{kmol }CH_4} \right) + 0.08 \left(\frac{3.5\text{ kmol }O_2}{\text{kmol }C_2H_6} \right) + 0.06 \left(\frac{5\text{ kmol }O_2}{\text{kmol }C_3H_8} \right) \right] = 349.6\text{ kmol/h }O_2$$

Air flow: $\dot{V}_{air} = \frac{1.08(349.6)\text{ kmol }O_2}{\text{h}} \left| \frac{1\text{ kmol Air}}{0.21\text{ kmol }O_2} \right| \frac{22.4\text{ m}^3\text{(STP)}}{\text{kmol}} = \underline{\underline{4.0 \times 10^4\text{ m}^3\text{(STP)}/\text{h}}}$

5.31 Calibration formulas
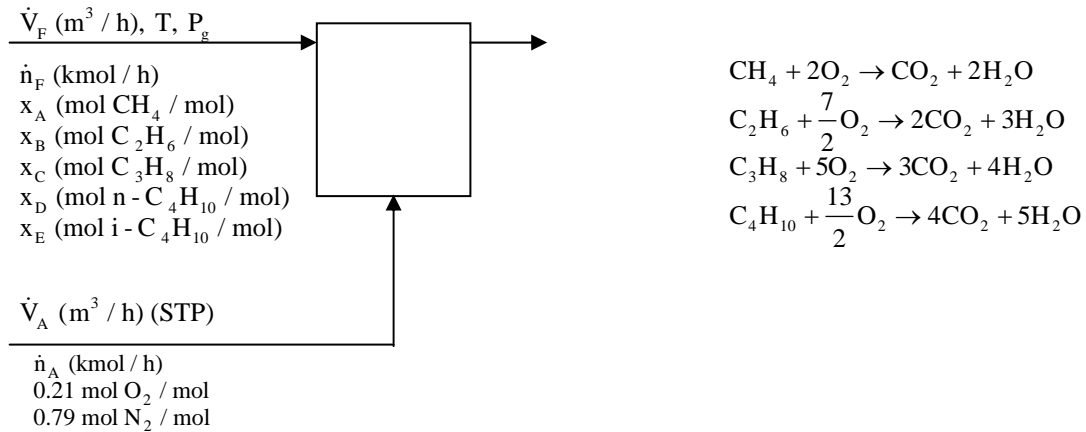
$$\left(T = 25.0; \ R_T = 14\right), \ \left(T = 35.0, \ R_T = 27\right) \Rightarrow T(^\circ C) = 0.77R_T + 14.2$$

$$\left(P_g = 0; \ R_p = 0\right), \ \left(P_g = 20.0, \ R_r = 6\right) \Rightarrow P_{gauge}(kPa) = 3.33R_p$$

$$\left(\dot{V}_F = 0; \ R_p = 0\right), \ \left(\dot{V}_F = 2.0 \times 10^3, \ R_F = 10\right) \Rightarrow \dot{V}_F\left(m^3/h\right) = 200R_F$$

$$\left(\dot{V}_A = 0; \ R_A = 0\right), \ \left(\dot{V}_A = 1.0 \times 10^5, \ R_A = 25\right) \Rightarrow \dot{V}_A\left(m^3/h\right) = 4000R_A$$

$\dot{V}_F \ (m^3/h), \ T, \ P_g$

$\dot{n}_F$ (kmol / h)
x_A (mol CH_4 / mol)
x_B (mol C_2H_6 / mol)
x_C (mol C_3H_8 / mol)
x_D (mol n-C_4H_{10} / mol)
x_E (mol i-C_4H_{10} / mol)

$\dot{V}_A \ (m^3/h)$ (STP)

$\dot{n}_A$ (kmol / h)
0.21 mol O_2 / mol
0.79 mol N_2 / mol

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

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

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

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

$$\dot{n}_F = \frac{\dot{V}_F\left(m^3/h\right)}{} \left| \frac{273.2K}{(T+273.2)K} \right| \left| \frac{(P_g + 101.3)kPa}{101.3 \ kPa} \right| \frac{1 \ kmol}{22.4 \ m^3(STP)}$$

$$= \frac{0.12031\dot{V}_F\left(P_g + 101.3\right)}{(T+273)}\left(\frac{kmol}{h}\right)$$

Theoretical O_2:

$$\left(\dot{n}_{O_2}\right)_{Th} = \dot{n}_F\left(2x_A + 3.5x_B + 5x_C + 6.5(x_D + x_E)\right)kmol \ O_2 \ req./h$$

Air feed: $\dot{n}_A = \dfrac{\left(\dot{n}_{O_2}\right)_{Th} kmol \ O_2 \ req.}{h} \left| \dfrac{1 \ kmol \ air}{0.21 \ kmol \ O_2} \right| \dfrac{(1 + P_x/100)kmol \ feed}{1 \ kmol \ req.}$

$$= 4.762\left(1 + \frac{P_x}{100}\right)\left(n_{O_2}\right)_{Th}$$

$$\dot{V}_A = \left[\dot{n}_a \ (kmol \ air/h)\right]\left(22.4 \ m^3(STP)/kmol\right) = 22.4\dot{n}_A\left[m^3(STP)/h\right]$$

RT	T(C)	Rp	Pg(kPa)	Rf	xa	xb	xc	xd	xe	PX(%)	nF	nO2, th	nA	Vf (m3/h)	Va(m3/h)	Ra
23.1	32.0	7.5	25.0	7.25	0.81	0.08	0.05	0.04	0.02	15	72.2	183.47	1004.74	1450	22506.2	5.63
7.5	20.0	19.3	64.3	5.8	0.58	0.31	0.06	0.05	0.00	23	78.9	226.4	1325.8	1160	29697.8	7.42
46.5	50.0	15.8	52.6	2.45	0.00	0.00	0.65	0.25	0.10	33	28.1	155.2	983.1	490	22022.3	5.51
21	30.4	3	10.0	6	0.02	0.4	0.35	0.1	0.13	15	53.0	248.1	1358.9	1200	30439.2	7.6
23	31.9	4	13.3	7	0.45	0.12	0.23	0.16	0.04	15	63.3	238.7	1307.3	1400	29283.4	7.3
25	33.5	5	16.7	9	0.5	0.3	0.1	0.04	0.06	15	83.4	266.7	1460.8	1800	32721.2	8.2
27	35.0	6	20.0	10	0.5	0.3	0.1	0.04	0.06	15	94.8	303.2	1660.6	2000	37196.7	9.3

5.32 $NO + \frac{1}{2}O_2 \Leftrightarrow NO_2$

1 mol
0.20 mol NO / mol
$\begin{cases} 0.80 \text{ mol air / mol} \\ \quad 0.21 \; O_2 \\ \quad 0.79 \; N_2 \end{cases}$
$P_0 = 380$ kPa

n_1 (mol NO)
n_2 (mol O_2)
n_3 (mol N_2)
n_4 (mol NO_2)
P_f (kPa)
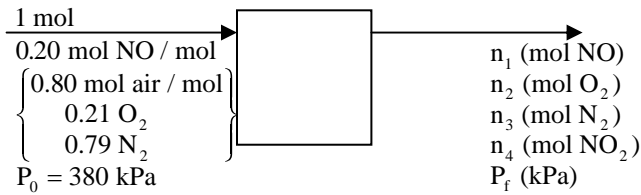
a. <u>Basis: 1.0 mol feed</u>

90% NO conversion: $n_1 = 0.10(0.20) = 0.020$ mol NO $\Rightarrow$ NO reacted $= 0.18$ mol

<u>O_2 balance:</u> $n_2 = 0.80(0.21) - \dfrac{0.18 \text{ mol NO}}{} \bigg| \dfrac{0.5 \text{ mol } O_2}{\text{mol NO}} = 0.0780$ mol O_2

<u>N_2 balance:</u> $n_3 = 0.80(0.79) = 0.632$ mol N_2

$n_4 = \dfrac{0.18 \text{ mol NO}}{} \bigg| \dfrac{1 \text{ mol } NO_2}{1 \text{ mol NO}} = 0.18$ mol $NO_2 \Rightarrow n_f = n_1 + n_2 + n_3 + n_4 = 0.91$ mol

$y_{NO} = \dfrac{0.020 \text{ mol NO}}{0.91 \text{ mol}} = \underline{\underline{0.022 \dfrac{\text{mol NO}}{\text{mol}}}}$

$y_{O_2} = \underline{\underline{0.086 \dfrac{\text{mol } O_2}{\text{mol}}}}$ $y_{N_2} = \underline{\underline{0.695 \dfrac{\text{mol } N_2}{\text{mol}}}}$ $y_{NO_2} = \underline{\underline{0.198 \dfrac{\text{mol } NO_2}{\text{mol}}}}$

$\dfrac{P_f V}{P_0 V} = \dfrac{n_f RT}{n_0 RT} \Rightarrow P_f = P_0 \dfrac{n_f}{n_0} = 380 \text{ kPa} \left(\dfrac{0.91 \text{ mol}}{1 \text{ mol}} \right) = \underline{\underline{346 \text{ kPa}}}$

b. $n_f = n_0 \dfrac{P_f}{P_0} = (1 \text{ mol}) \dfrac{360 \text{ kPa}}{380 \text{ kPa}} = 0.95$ mol

$n_i = n_{i0} + \upsilon_i \xi$

$\Downarrow$

n_1 (mol NO) $= 0.20 - \xi$

n_2 (mol O_2) $= (0.21)(0.80) - 0.5\xi$

n_3 (mol N_2) $= (0.79)(0.80)$

$\underline{n_4 \text{ (mol } NO_2) = \xi}$

$n_f = 1 - 0.5\xi = 0.95 \Rightarrow \xi = \underline{\underline{0.10}}$

$\Rightarrow n_1 = 0.10$ mol NO, $n_2 = 0.118$ mol O_2, $n_3 = 0.632$ mol N_2,

$n_4 = 0.10$ mol $NO_2 \Rightarrow y_{NO} = 0.105$, $y_{O_2} = 0.124$, $y_{N_2} = 0.665$, $y_{NO_2} = 0.105$

<u>NO conversion</u> $= \dfrac{(0.20 - n_1)}{0.20} \times 100\% = \underline{\underline{50\%}}$

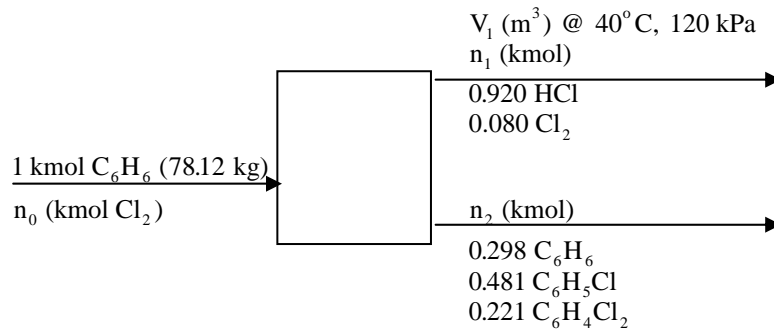$P \text{ (atm)} = \dfrac{360 \text{ kPa}}{101.3 \; \frac{\text{kPa}}{\text{atm}}} = 3.55$ atm

$K_p = \dfrac{(y_{NO_2} P)}{(y_{NO} P)(y_{O_2} P)^{0.5}} = \dfrac{(y_{NO_2})}{(y_{NO})(y_{O_2})^{0.5} P^{0.5}} = \dfrac{0.105}{(0.105)(0.124)^{0.5}(3.55)^{0.5}} = \underline{\underline{1.51 \text{ atm}^{\frac{1}{2}}}}$

5.33

Liquid composition:

$$100 \text{ kg liquid} \Rightarrow \left.\begin{array}{l} \dfrac{49.2 \text{ kg M}}{} \left| \dfrac{1 \text{ kmol}}{112.6 \text{ kg}} = 0.437 \text{ kmol M} \\[2mm] \dfrac{29.6 \text{ kg D}}{} \left| \dfrac{1 \text{ kmol}}{147.0 \text{ kg}} = 0.201 \text{ kmol D} \\[2mm] \dfrac{21.2 \text{ kg B}}{} \left| \dfrac{1 \text{ kmol}}{78.12 \text{ kg}} = 0.271 \text{ kmol B} \end{array}\right\} \Rightarrow \begin{array}{l} 0.481 \text{ kmol M / kmol} \\[2mm] 0.221 \text{ kmol D / kmol} \\[2mm] 0.298 \text{ kmol B / kmol} \end{array}$$

$$0.909 \text{ kmol}$$

a. Basis: 1 kmol C_6H_6 fed

$$V_1 \text{ (m}^3) \text{ @ } 40^\circ C, \ 120 \text{ kPa}$$
$$n_1 \text{ (kmol)}$$
$$0.920 \text{ HCl}$$
$$0.080 \text{ Cl}_2$$

$$1 \text{ kmol } C_6H_6 \text{ (78.12 kg)}$$
$$n_0 \text{ (kmol Cl}_2)$$

$$n_2 \text{ (kmol)}$$
$$0.298 \ C_6H_6$$
$$0.481 \ C_6H_5Cl$$
$$0.221 \ C_6H_4Cl_2$$

$$C_6H_6 + Cl_2 \rightarrow C_6H_5Cl + HCl \qquad C_6H_5Cl + Cl_2 \rightarrow C_6H_5Cl_2 + HCl$$

C balance: $\dfrac{1 \text{ kmol } C_6H_6}{} \left| \dfrac{6 \text{ kmol C}}{1 \text{ kmol } C_6H_6} = n_2 \left[0.298 \times 6 + 0.481 \times 6 + 0.221 \times 6 \right]$

$$\Rightarrow n_2 = 1.00 \text{ kmol}$$

H balance: $\dfrac{1 \text{ kmol } C_6H_6}{} \left| \dfrac{6 \text{ kmol H}}{1 \text{ kmol } C_6H_6} = n_1 (0.920)(1)$

$$+ \, n_2 \left[0.298 \times 6 + 0.481 \times 5 + 0.221 \times 4 \right] \Rightarrow n_1 = 1.00 \text{ kmol}$$

$$V_1 = \frac{n_1 RT}{P} = \frac{1.00 \text{ kmol}}{120 \text{ kPa}} \left| \frac{101.3 \text{ kPa}}{1 \text{ atm}} \right| \frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \left| 313.2 \text{K} \right. = 21.7 \text{ m}^3$$

$$\Rightarrow \frac{V_1}{m_B} = \frac{21.7 \text{ m}^3}{78.12 \text{ kg B}} = \underline{\underline{0.278 \text{ m}^3 / \text{kg B}}}$$

b. $\dot{V}_{gas} (\text{m}^3 / \text{s}) = u(\text{m/s}) \cdot A(\text{m}^2) = u \cdot \dfrac{\pi d^2}{4} \Rightarrow d^2 = \dfrac{4 \cdot \dot{V}_{gas}}{\pi \cdot u}$

$$d^2 = \frac{4\dot{m}_{B0}(\text{kg B})}{\text{min}} \left| \frac{0.278 \text{ m}^3}{\text{kg B}} \right| \frac{\text{s}}{\pi(10)\text{m}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{10^4 \text{ cm}^2}{\text{m}^2} = 5.90 \dot{m}_{B0} \ (\text{cm}^2)$$

$$\Rightarrow \underline{\underline{d(\text{cm}) = 2.43 \cdot (\dot{m}_{B0})^{\frac{1}{2}}}}$$

c. Decreased use of chlorinated products, especially solvents.

5.34

3.74 SCMM → [box] → $V_b \, (m^3 / min) \, @900°C, \, 604 \, mtorr$

$\dot{n}_a \, (mol / min)$
0.220 DCS
0.780 N$_2$O

60% DCS conversion
$\dot{n}_1 \, (mol \, DCS / min)$
$\dot{n}_2 \, (mol \, N_2O / min)$
$\dot{n}_3 \, (mol \, N_2 / min)$
$\dot{n}_4 \, (mol \, HCl(g) / min)$
$\Big\} \dot{n}_b \, (mol / min)$

$$SiH_2Cl_{2(g)} + 2N_2O_{(g)} \rightarrow SiO_{2(s)} + 2N_{2(g)} + 2HCl_{(g)}$$
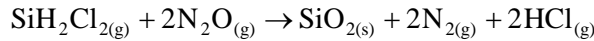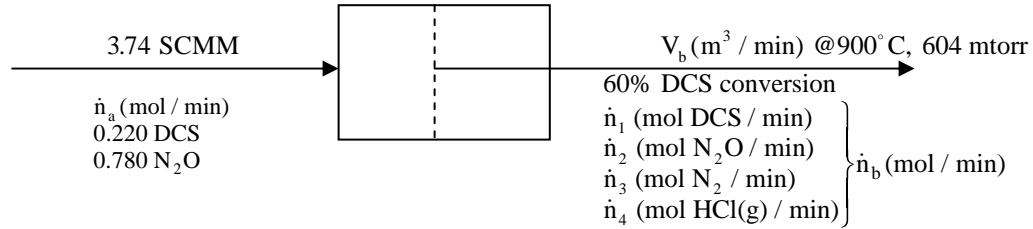
a. $\dot{n}_a = \dfrac{3.74 \, m^3 \, (STP)}{min} \left| \dfrac{10^3 \, mol}{22.4 \, m^3 \, (STP)} \right. = 167 \, mol / min$

60% conversion: $\dot{n}_1 = (1 - 0.60) \left(\dfrac{0.220 \, mol \, DCS}{mol} \right) (167 \, mol / min) = 14.7 \, mol \, DCS / min$

<u>DCS reacted:</u> $(0.60)(0.220)(167) \dfrac{mol \, DCS}{min} = 22.04 \, mol \, DCS \, reacted / min$

<u>N$_2$O balance:</u> $\dot{n}_2 = 0.780(167) \dfrac{mol \, N_2O}{min}$

$- \dfrac{22.04 \, mol \, DCS}{min} \left| \dfrac{2 \, mol \, N_2O}{mol \, DCS} \right. = 86.18 \, mol \, N_2O / min$

<u>N$_2$ balance:</u> $\dot{n}_3 = \dfrac{22.04 \, mol \, DCS}{min} \left| \dfrac{2 \, mol \, N_2}{mol \, DCS} \right. = 44.08 \, mol \, N_2 / min$

<u>HCl balance:</u> $\dot{n}_4 = \dfrac{22.04 \, mol \, DCS}{min} \left| \dfrac{2 \, mol \, HCl}{mol \, DCS} \right. = 44.08 \, mol \, HCl / min$

$\dot{n}_B = \dot{n}_1 + \dot{n}_2 + \dot{n}_3 + \dot{n}_4 = 189 \, mol / min$

$\Rightarrow \dot{V}_B = \dfrac{\dot{n}_B RT}{P} = \dfrac{189 \, mol}{min} \left| \dfrac{62.36 \, L \cdot torr}{mol \cdot K} \right| \dfrac{0.001 \, m^3}{L} \left| \dfrac{1173 \, K}{0.604 \, torr} \right. = \underline{\underline{2.29 \times 10^4 \, m^3 / min}}$

b. $p_{DCS} = x_{DCS} \cdot P = \dfrac{\dot{n}_1}{\dot{n}_B} P = \dfrac{14.7 \, mol \, DCS/min}{189 \, mol/min} \cdot 604 \, mtorr = 47.0 \, mtorr$

$p_{N_2O} = x_{N_2O} \cdot P = \dfrac{\dot{n}_2}{\dot{n}_B} P = \dfrac{86.2 \, mol \, N_2O/min}{189 \, mol/min} \cdot 604 \, mtorr = 275.5 \, mtorr$

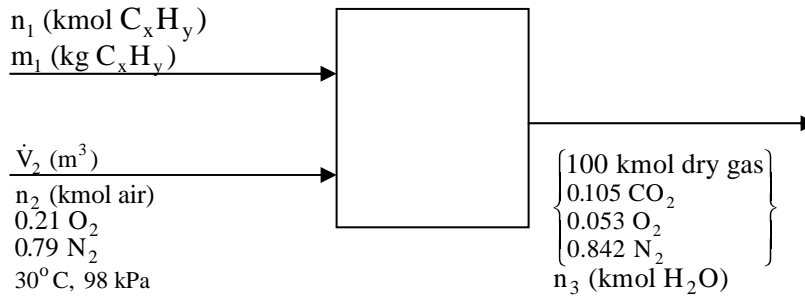$r = 3.16 \times 10^{-8} \cdot p_{DCS} \cdot p_{N_2O}^{0.65} = 3.16 \times 10^{-8} (47.0)(275.5)^{0.65} = \underline{\underline{5.7 \times 10^{-5} \, \dfrac{mol \, SiO_2}{m^2 \cdot s}}}$

c. $h(\mathring{A}) = r \cdot t \cdot \dfrac{MW}{\rho_{SiO_2}} = \dfrac{5.7 \times 10^{-5} \, mol \, SiO_2}{m^2 \cdot s} \left| \dfrac{60 \, s}{min} \right| \dfrac{120 \, min}{} \left| \dfrac{60.09 \, g/mol}{2.25 \times 10^6 \, g/m^3} \right| \dfrac{10^{10} \, \mathring{A}}{1 \, m}$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (Table B.1)

$= \underline{\underline{1.1 \times 10^5 \, \mathring{A}}}$

The films will be thicker closer to the entrance where the lower conversion yields higher p_{DCS} and p_{N_2O} values, which in turn yields a higher deposition rate.

5.35

Basis: 100 kmol dry product gas

n_1 (kmol C_xH_y)
m_1 (kg C_xH_y)

$\dot{V}_2$ (m³)
n_2 (kmol air)
0.21 O_2
0.79 N_2
30°C, 98 kPa

{100 kmol dry gas
0.105 CO_2
0.053 O_2
0.842 N_2}
n_3 (kmol H_2O)

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

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

C balance: $\dfrac{n_1\ (\text{kmol } C_xH_y)}{}\left|\dfrac{x\ (\text{kmol C})}{(\text{kmol } C_xH_y)}\right. = 100(0.105) \Rightarrow n_1x = 10.5$ \qquad (1)

H balance: $n_1y = 2n_3 \overset{n_3=13.17}{=\!=\!=\!=\!=\!>} n_1y = 26.34$ \qquad (2)

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

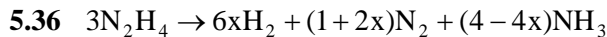O_2 fed: $0.21(106.6$ kmol air$) = 22.4$ kmol

O_2 in excess $= 5.3$ kmol $\Rightarrow$ Theoretical $O_2 = (22.4 - 5.3)$ kmol $= 17.1$ kmol

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

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

$m_1 = \dfrac{n_1x\ (\text{kmol C})}{}\left|\dfrac{12.0\ \text{kg}}{\text{kmol}}\right. + \dfrac{n_1y\ (\text{kmol H})}{}\left|\dfrac{1.01\ \text{kg}}{\text{kmol}}\right. \overset{n_1x=10.5}{\underset{n_1y=26.34}{=\!=\!=\!=\!=\!>}} m_1 = 152.6\ \text{kg}$

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

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

a. $0 \le x \le 1$

b. $n_{N_2H_4} = \dfrac{50\ \text{L}}{}\left|\dfrac{0.82\ \text{kg}}{\text{L}}\right|\dfrac{1\ \text{kmol}}{32.06\ \text{kg}} = 1.28$ kmol

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

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

5.36 (cont'd)

x	nproduct	Vp (L)
0	2.13	15447.92
0.1	2.30	16685.93
0.2	2.47	17923.94
0.3	2.64	19161.95
0.4	2.81	20399.96
0.5	2.98	21637.97
0.6	3.15	22875.98
0.7	3.32	24113.99
0.8	3.50	25352.00
0.9	3.67	26590.01
1	3.84	27828.02

Volume of Product Gas
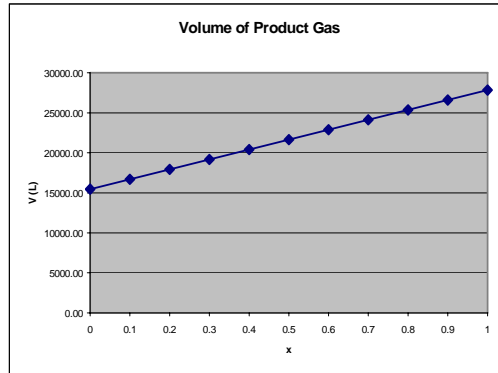
    c. Hydrazine is a good propellant because as it decomposes generates a large number of moles and hence a large volume of gas.

5.37

$$\dot{m}_A \,(g\,A\,/\,h)$$

$$\dot{V}_{air}\left(m^3\,/\,h\right) \qquad C_A\,(g\,A\,/\,m^3)$$
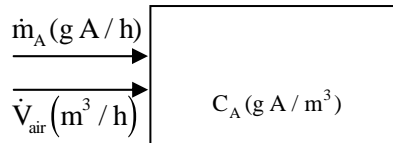
    a. (i) Cap left off container of liquid A and it evaporates into room, (ii) valve leak in cylinder with A in it, (iii) pill of liquid A which evaporates into room, (iv) waste containing A poured into sink, A used as cleaning solvent.

    b. $\dot{m}_A\left(\dfrac{kg\,A}{h}\right)_{in} = \dot{m}_A\left(\dfrac{kg\,A}{h}\right)_{out} = \underline{\underline{\dot{V}_{air}\left(\dfrac{m^3}{h}\right)C_A\left(\dfrac{kg\,A}{m^3}\right)}}$

    c. $y_A = \dfrac{mol\,A}{mol\,air} = \dfrac{C_A\left(\frac{g\,A}{m^3}\right)\cdot V}{M_A\left(\frac{g\,A}{mol}\right)\cdot n_{air}} \quad\xrightarrow[C_A=\frac{\dot{m}_A}{k\cdot V_{air}};\ n_{air}=\frac{PV}{RT}]{}\quad \underline{\underline{y_A = \dfrac{\dot{m}_A}{k\cdot V_{air}}\dfrac{RT}{M_A P}}}$

    d. $y_A = 50\times10^{-6} \qquad \dot{m}_A = 9.0\,g/h$

$$\left(\dot{V}_{air}\right)_{min} = \dfrac{\dot{m}_A}{ky_A}\dfrac{RT}{M_A P} = \dfrac{9.0\,g/h}{0.5\!\left(50\times10^{-6}\right)}\left|\dfrac{8.314\frac{m^3\cdot Pa}{mol\cdot K}}{}\right|\dfrac{293\,K}{101.3\times10^3\,Pa}\left|\dfrac{}{104.14\,g/mol}\right. = \underline{\underline{83\,m^3/h}}$$

Concentration of styrene could be higher in some areas due to incomplete mixing (high concentrations of A near source); 9.0 g/h may be an underestimate; some individuals might be sensitive to concentrations < PEL.

    e. Increase in the room temperature could increase the volatility of A and hence the rate of evaporation from the tank. T in the numerator of expression for $\dot{V}_{air}$: At higher T, need a greater air volume throughput for y to be < PEL.

5.38 Basis: 2 mol feed gas $C_3H_6 + H_2 \Leftrightarrow C_3H_8$

```
                ┌──────────────┐
  ───────────►  │              │  ──────────────►
                │              │
  1 mol C₃H₆    │              │
  1 mol H₂      │              │
  25°C, 32 atm  │              │
                └──────────────┘
```

n_p (mol C_3H_8)
(1 - n_p)(mol C_3H_6) $\Big\}$ $n_2 = n_p + 2(1 - n_p) = 2 - n_p$
(1 - n_p)(mol H_2)
235°C, P_2
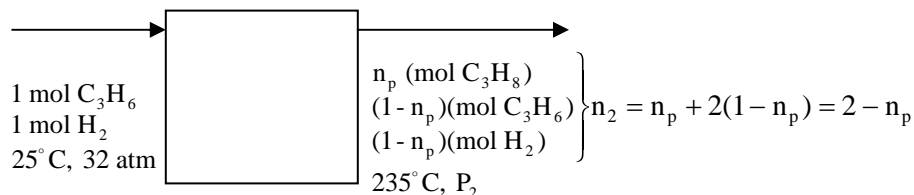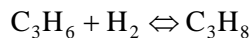
a. At completion, $n_p = 1$ mol , $n_2 = 2 - 1 = 1$ mol

$$\frac{P_2 V}{P_1 V} = \frac{n_2 R T_2}{n_1 R T_1} \Rightarrow P_2 = \frac{n_2}{n_1}\frac{T_2}{T_1} P_1 = \frac{1 \text{ mol}}{2 \text{ mol}}\left|\frac{508K}{298K}\right|\frac{32.0 \text{ atm}}{} = 27.3 \text{ atm}$$

b. $P_2 = 35.1$ atm

$$n_2 = \frac{P_2}{P_1}\frac{T_1}{T_2} n_1 = \frac{35.1 \text{ atm}}{32.0 \text{ atm}}\left|\frac{298K}{508K}\right|\frac{2 \text{ mol}}{} = 1.29 \text{ mol}$$

$1.29 = 2 - n_p \Rightarrow n_p = 0.71$ mol C_3H_8 produced

$\Rightarrow (1 - 0.71) = 0.29$ mol C_3H_6 unreacted $\Rightarrow$ 71% conversion of propylene

c.

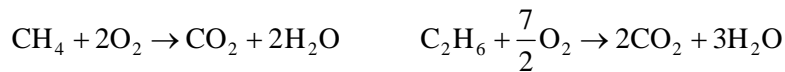| P2 (atm)	n2	C3H8 prod.	%conv.
27.5	1.009	0.99075	99.075
28.0	1.028	0.9724	97.24
29.5	1.083	0.91735	91.735
30.0	1.101	0.899	89.9
31.5	1.156	0.84395	84.395
32.0	1.174	0.8256	82.56
33.0	1.211	0.7889	78.89
33.5	1.229	0.77055	77.055
34.0	1.248	0.7522	75.22
34.5	1.266	0.73385	73.385
35.0	1.285	0.7155	71.55
37.0	1.358	0.6421	64.21
39.0	1.431	0.5687	56.87
40.0	1.468	0.532	53.2

Pressure vs Fraction Conversion
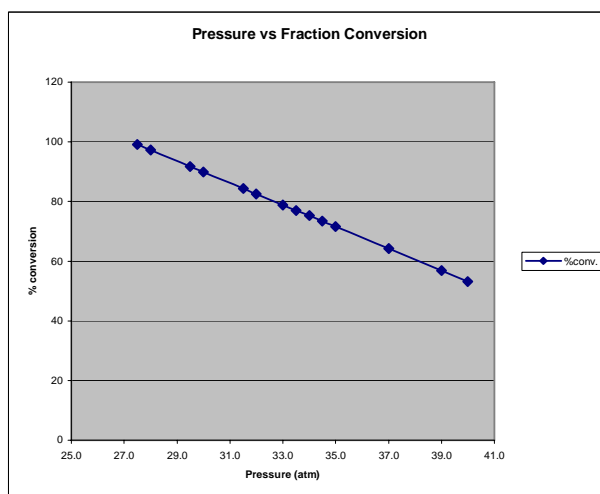
5.39   Convert fuel composition to molar basis

$$\underline{\text{Basis:}\ 100\ \text{g}} \Rightarrow \left.\begin{array}{l} 95\ \text{g CH}_4\left(1\ \text{mol}/16.04\ \text{g}\right) = 5.92\ \text{mol CH}_4 \\ 5\ \text{g C}_2\text{H}_6\left(1\ \text{mol}/30.07\ \text{g}\right) = 0.17\ \text{mol C}_2\text{H}_6 \end{array}\right\} \Rightarrow \begin{array}{l} 97.2\ \text{mol \% CH}_4 \\ 2.8\ \text{mol \% C}_2\text{H}_6 \end{array}$$
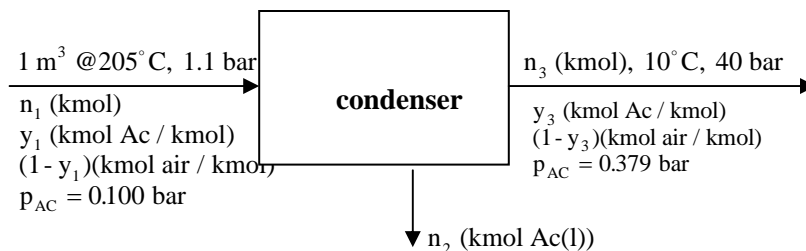
500 m³ / h
$\dot{n}_1$ (mol / h)
0.972 CH₄

0.028 C₂H₆
40°C, 1.1 bar

$\dot{n}_2$ (kmol CO₂ / h)
$\dot{n}_3$ (kmol H₂O / h)
$\dot{n}_4$ (kmol O₂ / h)
$\dot{n}_5$ (kmol N₂ / h)

$\dot{V}_{air}$ (SCMH)
25% excess air
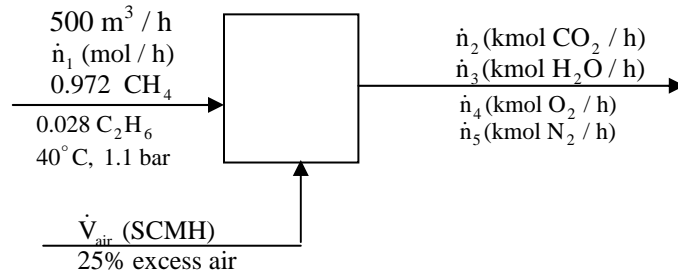
$$\dot{n}_1 = \frac{P_1 \dot{V}_1}{RT_1} = \frac{1.1\ \text{bar}}{313\text{K}} \left| \frac{500\ \text{m}^3}{\text{h}} \right| \frac{\text{kmol} \cdot \text{K}}{0.08314\ \text{m}^3 \cdot \text{bar}} = 21.1\ \text{kmol/h}$$

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

$$\underline{\text{Theoretical O}_2} = \frac{21.1\ \text{kmol}}{\text{h}} \left[\frac{0.972\ \text{kmol CH}_4}{\text{kmol}} \left| \frac{2\ \text{kmol O}_2}{1\ \text{kmol CH}_4} \right.\right.$$

$$\left. + \frac{0.028\ \text{kmol C}_2\text{H}_6}{\text{kmol}} \left| \frac{3.5\ \text{kmol O}_2}{1\ \text{kmol C}_2\text{H}_6} \right] = 43.1 \frac{\text{kmol O}_2}{\text{h}} \right.$$

$$\underline{\text{Air Feed:}} \quad \frac{1.25(43.1\ \text{kmol O}_2)}{\text{h}} \left| \frac{1\ \text{kmol Air}}{0.21\ \text{kmol O}_2} \right| \frac{22.4\ \text{m}^3(\text{STP})}{1\ \text{kmol}} = \underline{\underline{5700\ \text{SCMH}}}$$

5.40   Basis: 1 m³ gas fed @ 205°C, 1.1 bars   Ac = acetone

1 m³ @205°C, 1.1 bar

n_1 (kmol)
y_1 (kmol Ac / kmol)
$(1 - y_1)$(kmol air / kmol)
$p_{AC} = 0.100$ bar

condenser

n_3 (kmol), 10°C, 40 bar

y_3 (kmol Ac / kmol)
$(1 - y_3)$(kmol air / kmol)
$p_{AC} = 0.379$ bar

n_2 (kmol Ac(l))

a. $$n_1 = \frac{1.00\ \text{m}^3}{478\text{K}} \left| \frac{273\text{K}}{1.0132\ \text{bars}} \right| \frac{1.10\ \text{bars}}{22.4\ \text{m}^3(\text{STP})} \left| \frac{1\ \text{kmol}}{} \right. = 0.0277\ \text{kmol}$$

$$y_1 = \frac{0.100\ \text{bar}}{1.1\ \text{bars}} = 0.0909\ \text{kmol Ac/kmol}, \ y_3 = \frac{0.379\ \text{bar}}{40.0\ \text{bars}} = 9.47 \times 10^{-3}\ \text{kmol Ac/kmol}$$

$$\underline{\text{Air balance:}}\ (0.0277)(0.910) = (1 - 9.47 \times 10^{-3})n_3 \Rightarrow n_3 = 0.0254\ \text{kmol}$$

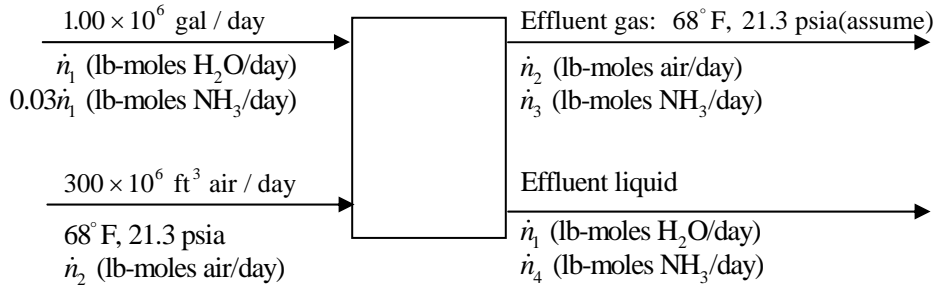$$\underline{\text{Mole balance:}}\ 0.0277 = 0.0254 + n_2 \Rightarrow n_2 = 0.0023\ \text{kmol Ac condensed}$$

$$\underline{\text{Acetone condensed}} = \frac{0.0023\ \text{kmol Ac}}{} \left| \frac{58.08\ \text{kg Ac}}{1\ \text{kmol Ac}} \right. = \underline{\underline{0.133\ \text{kg acetone condensed}}}$$

5.40 (cont'd)

$$\text{Product gas volume} = \frac{0.0254 \text{ kmol}}{} \left| \frac{22.4 \text{ m}^3 (\text{STP})}{} \right| \frac{283\text{K}}{273\text{K}} \left| \frac{1.0132 \text{ bars}}{40.0 \text{ bars}} \right. = \underline{\underline{0.0149 \text{ m}^3}}$$

b. $\dfrac{20.0 \text{ m}^3 \text{ effluent}}{\text{h}} \left| \dfrac{0.0277 \text{ kmol feed}}{0.0149 \text{ m}^3 \text{ effluent}} \right| \dfrac{0.0909 \text{ kmol Ac}}{\text{kmol feed}} \left| \dfrac{58.08 \text{ kg Ac}}{\text{kmol Ac}} \right. = \underline{\underline{196 \text{ kg Ac/h}}}$

5.41 <u>Basis</u>: 1.00×10^6 gal. wastewater/day. Neglect evaporation of water.

1.00×10^6 gal / day
$\dot{n}_1$ (lb-moles H_2O/day)
$0.03\dot{n}_1$ (lb-moles NH_3/day)

Effluent gas: $68°$F, 21.3 psia(assume)
$\dot{n}_2$ (lb-moles air/day)
$\dot{n}_3$ (lb-moles NH_3/day)

300×10^6 ft^3 air / day
$68°$F, 21.3 psia
$\dot{n}_2$ (lb-moles air/day)

Effluent liquid
$\dot{n}_1$ (lb-moles H_2O/day)
$\dot{n}_4$ (lb-moles NH_3/day)

a. <u>Density of wastewater</u>: Assume $\rho = 62.4$ lb$_m$/ft^3

$$\left[\frac{\dot{n}_1 \text{ lb-moles } H_2O}{\text{day}} \left| \frac{18.02 \text{ lb}_m}{1 \text{ lb-mole}} + \frac{0.03\dot{n}_1 \text{ lb}_m \ NH_3}{\text{day}} \right| \frac{17.03 \text{ lb}_m}{1 \text{ lb-mole}} \right] \times \frac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \left| \frac{7.4805 \text{ gal}}{1 \text{ ft}^3} \right.$$

$$= 1.00 \times 10^6 \frac{\text{gal}}{\text{day}}$$

$\Rightarrow \dot{n}_1 = 4.50 \times 10^5$ lb-moles H_2O fed/day , $0.03\dot{n}_1 = 1.35 \times 10^4$ lb-moles NH_3 fed/day

$$\dot{n}_2 = \frac{300 \times 10^6 \text{ ft}^3}{\text{day}} \left| \frac{492°\text{R}}{527.7°\text{R}} \right| \frac{21.3 \text{ psi}}{14.7 \text{ psi}} \left| \frac{1 \text{ lb-mole}}{359 \text{ ft}^3 (\text{STP})} \right. = \underline{\underline{1.13 \times 10^6 \text{ lb-moles air/day}}}$$

<u>93% stripping</u>: $\dot{n}_3 = 0.93 \times 13500$ lb-moles NH_3 fed/day $= 12555$ lb-moles NH_3/day

<u>Volumetric flow rate of effluent gas</u>

$$\frac{P\dot{V}_{\text{out}}}{P\dot{V}_{\text{in}}} = \frac{\dot{n}_{\text{out}}RT}{\dot{n}_{\text{in}}RT} \Rightarrow \dot{V}_{\text{out}} = \dot{V}_{\text{in}} \frac{\dot{n}_{\text{out}}}{\dot{n}_{\text{in}}} = \frac{300 \times 10^6 \text{ ft}^3}{\text{day}} \left| \frac{\left(1.13 \times 10^6 + 12555\right) \text{ lb-moles/day}}{1.13 \times 10^6 \text{ lb-moles/day}} \right.$$
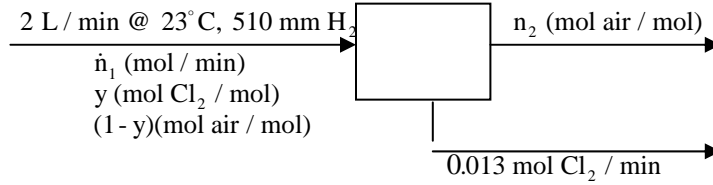
$$= \underline{\underline{303 \times 10^6 \text{ ft}^3/\text{day}}}$$

$$\underline{\text{Partial pressure of } NH_3} = y_{NH_3} P = \frac{12555 \text{ lb - moles } NH_3/\text{day}}{\left(1.129 \times 10^6 + 12555\right) \text{lb - moles/day}} \times 21.3 \text{ psi}$$

$$= \underline{\underline{0.234 \text{ psi}}}$$

5.42 <u>Basis: 2 liters fed / min</u>

$$\text{Cl ads.} = \frac{2.0 \text{ L soln}}{60 \text{ min}} \left| \frac{1130 \text{ g}}{\text{L}} \right| \frac{0.12 \text{ g NaOH}}{\text{g soln}} \left| \frac{1 \text{ mol}}{40.0 \text{ g}} \right| \frac{0.23 \text{ NaOH ads.}}{\text{mol NaOH}} \left| \frac{1 \text{ mol Cl}_2}{2 \text{ mol NaOH}} \right. = 0.013 \frac{\text{mol}}{\text{min}}$$
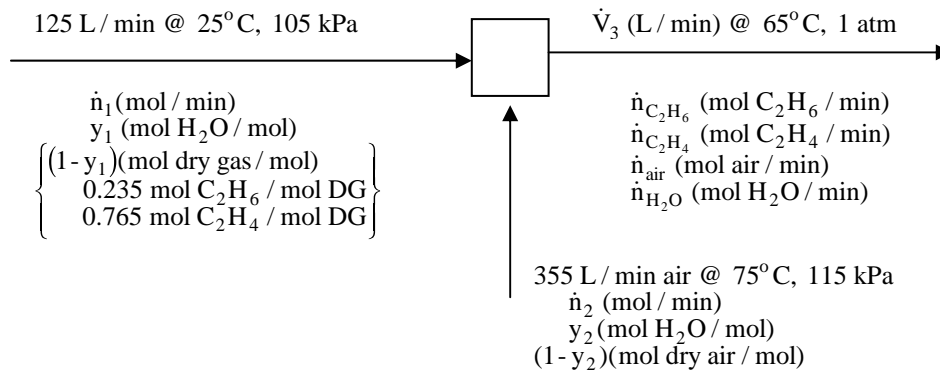
2 L / min @ 23°C, 510 mm H$_2$ ⟶ n_2 (mol air / mol)
$\dot{n}_1$ (mol / min)
y (mol Cl$_2$ / mol)
(1 - y)(mol air / mol)

0.013 mol Cl$_2$ / min

<u>Assume P$_{atm}$ = 10.33 m H$_2$O</u> $\Rightarrow (P_{abs})_{in} = (10.33 + 0.510)$ m H$_2$O = 10.84 m H$_2$O

$$\dot{n}_1 = \frac{2 \text{ L}}{\text{min}} \left| \frac{273K}{296K} \right| \frac{10.84 \text{ m H}_2\text{O}}{10.33 \text{ m H}_2\text{O}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right. = 0.0864 \text{ mol/min}$$

<u>Cl balance:</u> $0.0864y = 0.013 \Rightarrow y = 0.150 \dfrac{\text{mol Cl}_2}{\text{mol}}, \therefore$ specification is wrong

5.43

125 L / min @ 25°C, 105 kPa ⟶ $\dot{V}_3$ (L / min) @ 65°C, 1 atm

$\dot{n}_1$ (mol / min)
y_1 (mol H$_2$O / mol)
$\begin{cases} (1 - y_1)(\text{mol dry gas / mol}) \\ \quad 0.235 \text{ mol C}_2\text{H}_6 \text{ / mol DG} \\ \quad 0.765 \text{ mol C}_2\text{H}_4 \text{ / mol DG} \end{cases}$

$\dot{n}_{C_2H_6}$ (mol C$_2$H$_6$ / min)
$\dot{n}_{C_2H_4}$ (mol C$_2$H$_4$ / min)
$\dot{n}_{air}$ (mol air / min)
$\dot{n}_{H_2O}$ (mol H$_2$O / min)

355 L / min air @ 75°C, 115 kPa
$\dot{n}_2$ (mol / min)
y_2 (mol H$_2$O / mol)
(1 - y_2)(mol dry air / mol)

a. <u>Hygrometer Calibration</u> $\ln y = bR + \ln a \quad (y = ae^{bR})$

$$b = \frac{\ln(y_1/y_2)}{R_2 - R_1} = \frac{\ln(0.2/10^{-4})}{90 - 5} = 0.08942$$

$\ln a = \ln y_1 - bR_1 = \ln 10^{-4} - 0.08942(5) \Rightarrow a = 6.395 \times 10^{-5} \Rightarrow \underline{\underline{y = 6.395 \times 10^{-5} e^{0.08942R}}}$

b. $\dot{n}_1 = \dfrac{125 \text{ L}}{\text{min}} \left| \dfrac{273K}{298K} \right| \dfrac{105 \text{ kPa}}{101 \text{ kPa}} \left| \dfrac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right. = 5.315 \text{ mol/min wet gas}$

$\dot{n}_2 = \dfrac{355 \text{ L}}{\text{min}} \left| \dfrac{273K}{348K} \right| \dfrac{115 \text{ kPa}}{101 \text{ kPa}} \left| \dfrac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right. = 14.156 \text{ mol/min wet air}$

$R_1 = 86.0 \rightarrow y_1 = 0.140$, $R_2 = 12.8 \rightarrow y_2 = 2.00 \times 10^{-4}$ mol H$_2$O/mol

5.43 (cont'd)

$\underline{C_2H_6 \text{ balance:}}$ $\dot{n}_{C_2H_6} = (5.315 \text{ mol/min})\left((1-0.140)\dfrac{\text{mol DG}}{\text{mol}}\right)\left(0.235\dfrac{\text{mol } C_2H_6}{\text{mol DG}}\right)$

$= 1.07 \text{ mol } C_2H_6/\text{min}$

$\underline{C_2H_4 \text{ balance:}}$ $\dot{n}_{C_2H_4} = (5.315)(0.860)(0.765) = 3.50 \text{ mol } C_2H_4/\text{min}$

$\underline{\text{Dry air balance:}}$ $\dot{n}_{air} = (14.156)(1 - 2.00 \times 10^{-4}) = 14.15 \text{ mol DA/min}$

$\underline{\text{Water balance:}}$ $\dot{n}_{H_2O} = (5.315)(0.140) + (14.156)(1.00 \times 10^{-4}) = 0.746 \text{ mol } H_2O/\text{min}$

$\dot{n}_{\text{dry product gas}} = (1.07 + 3.50 + 14.15)\text{mol/min} = 18.72 \text{ mol/min}$,

$\dot{n}_{\text{total}} = (18.72 + 0.746) = 19.47 \text{ mol/min}$

$\dot{V}_3 = \dfrac{19.47 \text{ mol/min}}{} \left|\dfrac{22.4 \text{ L (STP)}}{\text{mol}}\right|\dfrac{338K}{273K} = \underline{\underline{540 \text{ liters/min}}}$

$\underline{\text{Dry basis composition:}}$ $\left(\dfrac{1.07}{18.72}\right) \times 100\% = \underline{\underline{5.7\% \ C_2H_6,\ 18.7\% \ C_2H_4,\ 75\% \text{ dry air}}}$

c. $p_{H_2O} = y_{H_2O_1} \cdot P = \dfrac{0.746 \text{ mol } H_2O}{19.47 \text{ mol}} \times 1 \text{ atm} = \underline{\underline{0.03832 \text{ atm}}}$

$y_{H_2O} = 0.03832 \Rightarrow R = \dfrac{1}{0.08942}\ln\left(\dfrac{0.03832}{6.395 \times 10^{-5}}\right) = \underline{\underline{71.5}}$

5.44 $CaCO_3 \rightarrow CaO + CO_2$

$\dot{n}_{CO_2} = \dfrac{1350 \text{ m}^3}{\text{h}}\left|\dfrac{273K}{1273K}\right|\dfrac{1 \text{ kmol}}{22.4 \text{ m}^3 (\text{STP})} = 12.92 \text{ kmol } CO_2/\text{h}$
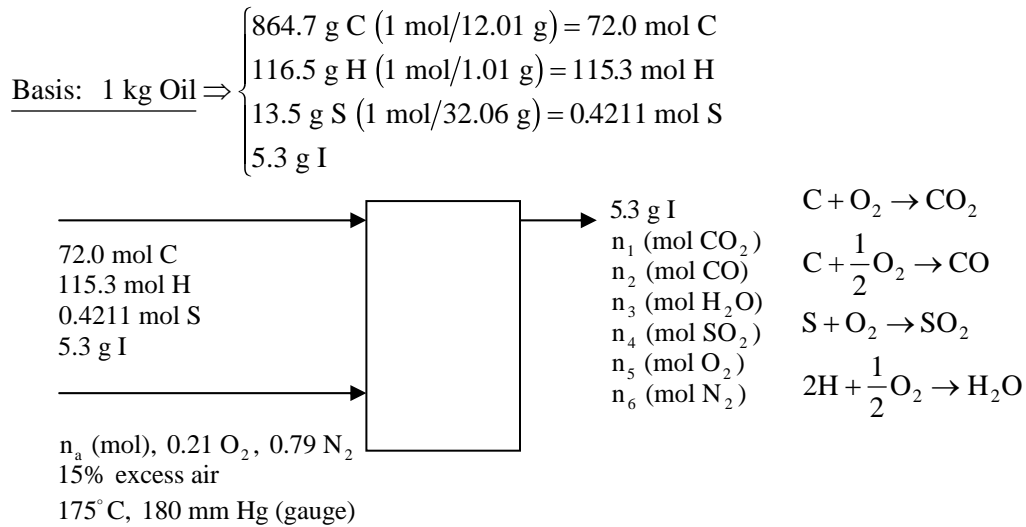
$\dfrac{12.92 \text{ kmol } CO_2}{\text{h}}\left|\dfrac{1 \text{ kmol CaCO}_3}{1 \text{ kmol } CO_2}\right|\dfrac{100.09 \text{ kg CaCO}_3}{1 \text{ kmol CaCO}_3}\left|\dfrac{1 \text{ kg limestone}}{0.95 \text{ kg CaCO}_3}\right. = \underline{\underline{1362 \text{ kg limestone/h}}}$

$\dfrac{1362 \text{ kg limestone}}{\text{h}}\left|\dfrac{0.17 \text{ kg clay}}{0.83 \text{ kg limestone}}\right. = \underline{\underline{279 \text{ kg clay/h}}}$

$\underline{\text{Weight \% Fe}_2O_3}$

$\dfrac{\overset{\text{kg Fe}_2O_3/\text{kg clay}}{279 \quad (0.07)}}{\underset{\substack{\text{kg limestone} \quad \text{kg clay}}}{1362 \ + \ 279} - \underbrace{12.92(44.1)}_{\text{kg CO}_2 \text{ evolved}}} \times 100\% = \underline{\underline{1.8\% \ Fe_2O_3}}$

5.45

Basis: 1 kg Oil $\Rightarrow$ $\begin{cases} 864.7 \text{ g C } (1 \text{ mol}/12.01 \text{ g}) = 72.0 \text{ mol C} \\ 116.5 \text{ g H } (1 \text{ mol}/1.01 \text{ g}) = 115.3 \text{ mol H} \\ 13.5 \text{ g S } (1 \text{ mol}/32.06 \text{ g}) = 0.4211 \text{ mol S} \\ 5.3 \text{ g I} \end{cases}$

72.0 mol C
115.3 mol H
0.4211 mol S
5.3 g I

n_a (mol), 0.21 O_2, 0.79 N_2
15% excess air
175°C, 180 mm Hg (gauge)

5.3 g I
n_1 (mol CO_2)
n_2 (mol CO)
n_3 (mol H_2O)
n_4 (mol SO_2)
n_5 (mol O_2)
n_6 (mol N_2)

$C + O_2 \rightarrow CO_2$

$C + \dfrac{1}{2}O_2 \rightarrow CO$

$S + O_2 \rightarrow SO_2$

$2H + \dfrac{1}{2}O_2 \rightarrow H_2O$

a. Theoretical O_2:

$$\frac{72.0 \text{ mol C}}{} \left| \frac{1 \text{ mol O}_2}{1 \text{ mol C}} + \frac{115.3 \text{ mol H}}{} \right| \frac{0.25 \text{ mol O}_2}{1 \text{ mol H}}$$

$$+ \frac{0.4211 \text{ mol S}}{} \left| \frac{1 \text{ mol O}_2}{1 \text{ mol S}} \right. = 101.2 \text{ mol O}_2$$

Air Fed: $\dfrac{1.15 \left(101.2 \text{ mol O}_2\right)}{} \left| \dfrac{1 \text{ mol Air}}{0.21 \text{ mol O}_2} \right. = 554 \text{ mol Air} = n_a$

$$\frac{554 \text{ mol Air}}{1 \text{ kg oil}} \left| \frac{22.4 \text{ liter (STP)}}{\text{mol}} \right| \frac{1 \text{ m}^3}{10^3 \text{ liter}} \left| \frac{448\text{K}}{273\text{K}} \right| \frac{760 \text{ mm Hg}}{940 \text{ mm Hg}} = \underline{\underline{16.5 \text{ m}^3 \text{ air/kg oil}}}$$

b. S balance: $n_4 = 0.4211 \text{ mol SO}_2$

H balance: $115.3 = 2n_3 \Rightarrow n_3 = 57.6 \text{ mol H}_2\text{O}$

C balance: $0.95(72.0) = n_1 \Rightarrow n_1 = 68.4 \text{ mol CO}_2 \Rightarrow 0.05(72.0) = n_2 = 3.6 \text{ mol CO}$

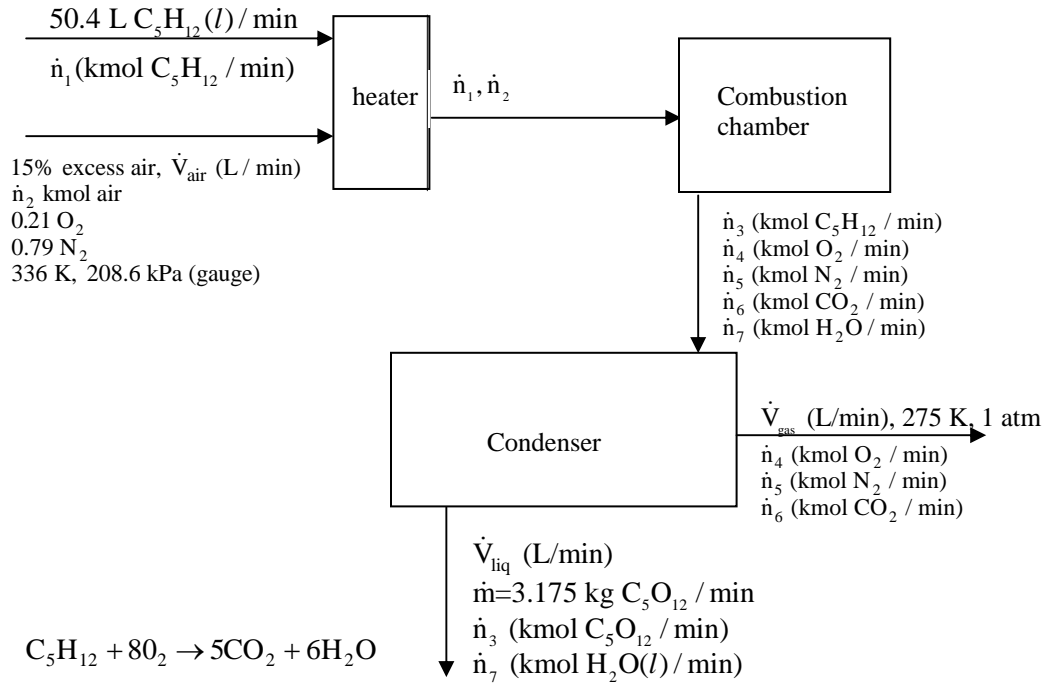N_2 balance: $0.79(554) = n_6 \Rightarrow n_6 = 437.7 \text{ mol N}_2$

O balance: $0.21(554)2 = 57.6 + 3.6 + 2(68.4) + 2(0.4211) + 2n_5 \Rightarrow n_5 = 16.9 \text{ mol O}_2$

Total moles (excluding inerts)   wet: 585 mols   dry: 527 mols

dry basis: $\dfrac{3.6 \text{ mol CO}}{527 \text{ mol}} = \underline{\underline{6.8 \times 10^{-3} \dfrac{\text{mol CO}}{\text{mol}}}}$, $\dfrac{0.4211 \text{ mol SO}_2}{527 \text{ mol}} = \underline{\underline{7.2 \times 10^{-4} \dfrac{\text{mol SO}_2}{\text{mol}}}}$

wet basis: $\dfrac{3.6 \text{ mol CO}}{585 \text{ mol}} \times 10^6 = \underline{\underline{6150 \text{ ppm CO}}}$, $\dfrac{0.4211 \text{ mol SO}_2}{585 \text{ mol}} \times 10^6 = \underline{\underline{720 \text{ ppm SO}_2}}$

5.46 Basis: 50.4 liters $C_5H_{12}(l)/min$

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$$

a. $\dot{n}_1 = \dfrac{50.4\ \text{L}}{\text{min}}\left|\dfrac{0.630\ \text{kg}}{\text{L}}\right|\dfrac{1\ \text{kmol}}{72.15\ \text{kg}} = 0.440\ \text{kmol/min}$

$\dot{n}_3 = \dfrac{3.175\ \text{kg}}{\text{min}}\left|\dfrac{1\ \text{kmol}}{72.15\ \text{kg}}\right. = 0.044\ \text{kmol / min}$

frac. convert $= \dfrac{0.440\text{ - }0.044\ \text{kmol}}{0.440} \times 100 = \underline{\underline{90\%\ C_5H_{12}\ \text{converted}}}$

$\dot{n}_2 = \dfrac{0.440\ \text{kmol }C_5H_{12}}{\text{min}}\left|\dfrac{1.15(8\ \text{kmol }O_2)}{\text{kmol }C_5H_{12}}\right|\dfrac{1\ \text{mol air}}{0.21\ \text{mol }O_2} = 19.28\ \text{kmol air/min}$

$\dot{V}_{air} = \dfrac{19.28\ \text{kmol}}{\text{min}}\left|\dfrac{22.4\ \text{L(STP)}}{\text{mol}}\right|\dfrac{336\text{K}}{273\text{K}}\left|\dfrac{101\ \text{kPa}}{309.6\ \text{kPa}}\right|\dfrac{1000\ \text{mol}}{\text{kmol}} = \underline{\underline{173000\ \text{L/min}}}$

$\dot{n}_4 = [(0.21)(19.28) - (0.90)(0.440)(8)]\dfrac{\text{kmol }O_2}{\text{min}} = \underline{\underline{0.882\ \text{kmol }O_2\ /\ \text{min}}}$

$\dot{n}_5 = \dfrac{19.28\ \text{kmol air}}{\text{min}}\left|\dfrac{0.79\ \text{kmol }N_2}{\text{kmol air}}\right. = 15.23\ \text{kmol }N_2\ /\ \text{min}$

$\dot{n}_6 = \dfrac{0.90(0.440\ \text{kmol }C_5H_{12})}{\text{min}}\left|\dfrac{5\ \text{kmol }CO_2}{\text{kmol }C_5H_{12}}\right. = 1.98\ \text{kmol }CO_2\ /\ \text{min}$

$\dot{V}_{gas} = \dfrac{0.882 + 15.23 + 1.98\ \text{kmol}}{\text{min}}\left|\dfrac{22.4\ \text{L(STP)}}{\text{mol}}\right|\dfrac{275\ \text{K}}{273\ \text{K}}\left|\dfrac{1000\ \text{mol}}{\text{kmol}}\right. = \underline{\underline{4.08 \times 10^5\ \text{L/min}}}$

5.46 (cont'd)

$$\dot{n}_7 = \frac{0.9(0.440 \text{ kmol } C_5H_{12})}{\text{min}} \bigg| \frac{6 \text{ kmol } H_2O}{\text{kmol } C_5H_{12}} = 2.38 \text{ kmol } H_2O(l) \, / \, \text{min}$$

<u>Condensate:</u>

$$\dot{V}_{C_5H_{12}} = \frac{0.044 \text{ kmol}}{\text{min}} \bigg| \frac{72.15 \text{ kg}}{\text{kmol}} \bigg| \frac{L}{0.630 \text{ kg}} = 5.04 \text{ L/min}$$

$$\dot{V}_{H_2O} = \frac{2.38 \text{ kmol}}{\text{min}} \bigg| \frac{18.02 \text{ kg}}{\text{kmol}} \bigg| \frac{L}{1 \text{ kg}} = 42.89 \text{ L/min}$$

Assume volume additivity (liquids are immiscible)

$$\dot{V}_{liq} = 5.04 + 42.89 = \underline{\underline{47.9 \text{ L/min}}}$$

b.
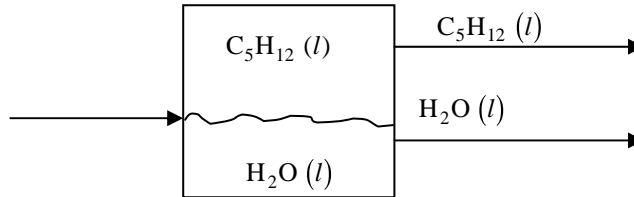
5.47
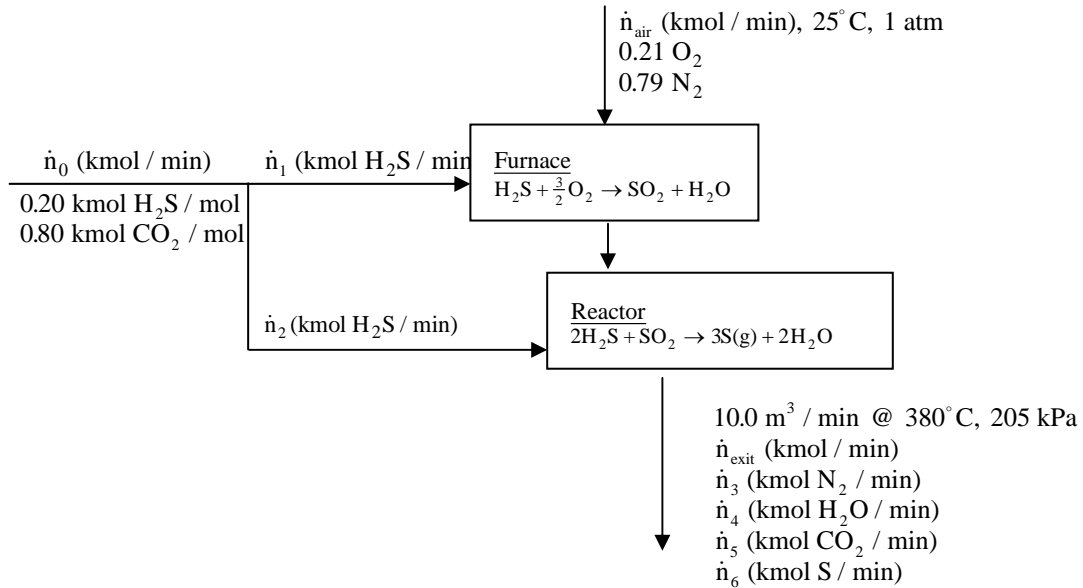
$$\dot{n}_{exit} = \frac{P\dot{V}}{RT} = \frac{205 \text{ kPa}}{8.314 \frac{m^3 \cdot kPa}{kmol \cdot K}} \bigg| \frac{10.0 \text{ m}^3 \, / \, \text{min}}{653 \text{ K}} = 0.377 \text{ kmol } / \text{ min}$$

$$\dot{n}_1 = (0.20)\dot{n}_0 \, / \, 3 = 0.0667\dot{n}_0; \quad \dot{n}_2 = 2\dot{n}_1 = 0.133\dot{n}_0$$

5.47 (cont'd)

Air feed to furnace: $\dot{n}_{air} = \dfrac{0.0667\dot{n}_0 \text{ (kmol } H_2S \text{ fed)}}{(\text{min})} \left|\dfrac{1.5 \text{ kmol } O_2}{1 \text{ kmol } H_2S}\right| \dfrac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2}$

$$= 0.4764\dot{n}_0 \text{ kmol air / min}$$

<u>Overall N_2 balance:</u> $\dot{n}_3 = \dfrac{0.4764\dot{n}_0 \text{ (kmol air)}}{(\text{min})} \left|\dfrac{0.79 \text{ kmol } N_2}{\text{min}}\right. = 0.3764\dot{n}_0 (\text{kmol } N_2 \text{ / min})$

<u>Overall S balance:</u> $\dot{n}_6 = \dfrac{0.200\dot{n}_0 \text{ (kmol } H_2S)}{(\text{min})} \left|\dfrac{1 \text{ kmol S}}{1 \text{ kmol } H_2S}\right. = 0.200\dot{n}_0 \text{ (kmol S / min)}$

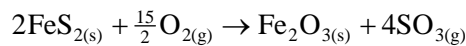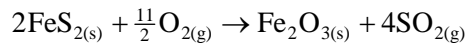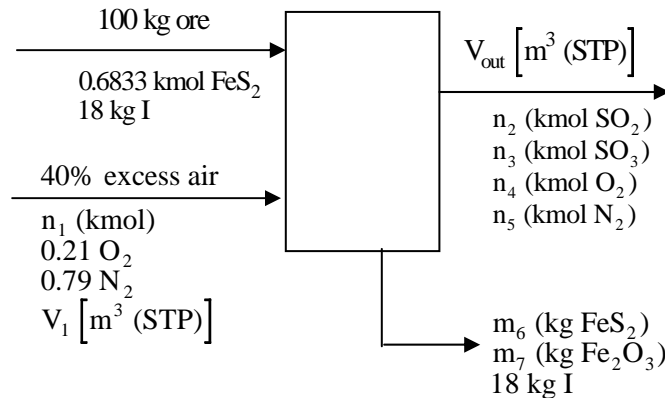<u>Overall CO_2 balance:</u> $\dot{n}_5 = 0.800\dot{n}_0 \text{ (kmol } CO_2 \text{ / min)}$

<u>Overall H balance:</u> $\dfrac{0.200\dot{n}_0 \text{ (kmol } H_2S)}{(\text{min})} \left|\dfrac{2 \text{ kmol H}}{1 \text{ kmol } H_2S}\right| = \dfrac{\dot{n}_4 \text{ kmol } H_2O}{\text{min}} \left|\dfrac{2 \text{ kmol H}}{1 \text{ kmol } H_2O}\right.$

$$\Rightarrow \dot{n}_4 = 0.200\dot{n}_0 \text{ (kmol } H_2O \text{ / min)}$$

$$\dot{n}_{exit} = \dot{n}_0(0.376 + 0.200 + 0.200 + 0.800) = 0.377 \text{ kmol / min} \Rightarrow \dot{n}_0 = \underline{\underline{0.24 \text{ kmol / min}}}$$

$$\dot{n}_{air} = 0.4764(0.24 \text{ kmol air / min}) = \underline{\underline{0.114 \text{ kmol air / min}}}$$

5.48 <u>Basis:</u> 100 kg ore fed $\Rightarrow$ 82.0 kg FeS_2(s), 18.0 kg I.

$$n_{FeS_2} \text{ fed} = (82.0 \text{ kg } FeS_2)(1 \text{ kmol / } 120.0 \text{ kg}) = 0.6833 \text{ kmol } FeS_2$$

$$2FeS_{2(s)} + \tfrac{11}{2}O_{2(g)} \rightarrow Fe_2O_{3(s)} + 4SO_{2(g)}$$

$$2FeS_{2(s)} + \tfrac{15}{2}O_{2(g)} \rightarrow Fe_2O_{3(s)} + 4SO_{3(g)}$$

a. $n_1 = \dfrac{0.6833 \text{ kmol } FeS_2}{} \left|\dfrac{7.5 \text{ kmol } O_2}{2 \text{ kmol } FeS_2}\right| \dfrac{1 \text{ kmol air req'd}}{0.21 \text{ kmol } O_2} \left|\dfrac{1.40 \text{ kmol air fed}}{\text{kmol air req'd}}\right. = 17.08 \text{ kmol air}$

$$V_1 = (17.08 \text{ kmol})(22.4 \text{ SCM / kmol}) = \underline{\underline{382 \text{ SCM / 100 kg ore}}}$$

$$n_2 = \dfrac{(0.85)(0.40)0.6833 \text{ kmol } FeS_2}{} \left|\dfrac{4 \text{ kmol } SO_2}{2 \text{ kmol } FeS_2}\right. = 0.4646 \text{ kmol } SO_2$$

5.48 (cont'd)

$$n_3 = \frac{(0.85)(0.60)0.6833 \text{ kmol FeS}_2}{} \left| \frac{4 \text{ kmol SO}_2}{2 \text{ kmol FeS}_2} \right. = 0.6970 \text{ kmol SO}_3$$

$$n_4 = (0.21 \times 17.08) \text{kmol O}_2 \text{ fed} - \frac{.4646 \text{ kmol SO}_2}{} \left| \frac{5.5 \text{ kmol O}_2}{4 \text{ kmol SO}_2} \right.$$

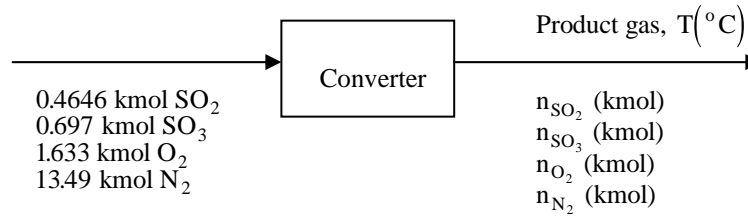$$- \frac{.697 \text{ kmol SO}_3}{} \left| \frac{7.5 \text{ kmol O}_2}{4 \text{ kmol SO}_3} \right. = 1.641 \text{ kmol O}_2$$

$$n_5 = (0.79 \times 17.08) \text{ kmol N}_2 = 13.49 \text{ kmol N}_2$$

$$V_{out} = \left[(0.4646 + 0.6970 + 1.641 + 13.49) \text{ kmol} \right] \left[22.4 \text{ SCM (STP)/kmol} \right]$$
$$= \underline{\underline{365 \text{ SCM/100 kg ore fed}}}$$

$$y_{SO_2} = \frac{0.4646 \text{ kmol SO}_2}{16.285 \text{ kmol}} \times 100\% = \underline{\underline{2.9\%}}; \quad y_{SO_3} = \underline{\underline{4.3\%}}; \quad y_{O_2} = \underline{\underline{10.1\%}}; \quad y_{N_2} = \underline{\underline{82.8\%}}$$

b.

Product gas, $T(^\circ C)$

0.4646 kmol SO_2
0.697 kmol SO_3
1.633 kmol O_2
13.49 kmol N_2

Converter

n_{SO_2} (kmol)
n_{SO_3} (kmol)
n_{O_2} (kmol)
n_{N_2} (kmol)

Let ξ (kmol) = extent of reaction

$$\left. \begin{array}{l} n_{SO_2} = 0.4646 - \xi \\ n_{SO_3} = 0.697 + \xi \\ n_{O_2} = 1.641 - \tfrac{1}{2}\xi \\ n_{N_2} = 13.49 \\ \hline n = 16.29 - \tfrac{1}{2}\xi \end{array} \right\} \Rightarrow \begin{array}{l} y_{SO_2} = \dfrac{0.4646 - \xi}{16.29 - \tfrac{1}{2}\xi}, \quad y_{SO_3} = \dfrac{0.697 + \xi}{16.29 - \tfrac{1}{2}\xi} \\[2mm] y_{O_2} = \dfrac{1.641 - \tfrac{1}{2}\xi}{16.29 - \tfrac{1}{2}\xi}, \quad y_{N_2} = \dfrac{13.49}{16.29 - \tfrac{1}{2}\xi} \end{array}$$

$$K_p(T) = \frac{P \cdot y_{SO_3}}{P \cdot y_{SO_2}(P \cdot y_{O_2})^{\frac{1}{2}}} \Rightarrow \frac{(0.697 + \xi)(16.29 - \tfrac{1}{2}\xi)^{\frac{1}{2}}}{(0.4646 - \xi)(1.641 - \tfrac{1}{2}\xi)^{\frac{1}{2}}} \cdot P^{-\frac{1}{2}} = K_p(T)$$

P=1 atm, T=600°C, $K_p = 9.53 \text{ atm}^{-\frac{1}{2}} \Rightarrow \xi = 0.1707 \text{ kmol}$

$$\Rightarrow n_{SO_2} = 0.2939 \text{ kmol} \Rightarrow f_{SO_2} = \frac{(0.4646 - 0.2939) \text{ kmol SO}_2 \text{ reacted}}{0.4646 \text{ kmol SO}_2 \text{ fed}} = \underline{\underline{0.367}}$$

P=1 atm, T=400°C, $K_p = 397 \text{ atm}^{-\frac{1}{2}} \Rightarrow \xi = 0.4548 \text{ kmol}$

$$\Rightarrow n_{SO_2} = 0.0098 \text{ kmol} \Rightarrow f_{SO_2} = \underline{\underline{0.979}}$$

The gases are initially heated in order to get the reaction going at a reasonable rate. Once the reaction approaches equilibrium the gases are cooled to produce a higher equilibrium conversion of SO_2.

5.48 (cont'd)

c. SO$_3$ leaving converter: $(0.6970 + 0.4687)$ kmol $= 1.156$ kmol

$$\Rightarrow \frac{1.156 \text{ kmol SO}_3}{\text{min}} \left| \frac{1 \text{ kmol H}_2\text{SO}_4}{1 \text{ kmol SO}_3} \right| \frac{98 \text{ kg H}_2\text{SO}_4}{\text{kmol}} = 113.3 \text{ kg H}_2\text{SO}_4$$

Sulfur in ore: $\dfrac{0.683 \text{ kmol FeS}_2}{} \left| \dfrac{2 \text{ kmol S}}{\text{kmol FeS}_2} \right| \dfrac{32.1 \text{ kg S}}{\text{kmol}} = 43.8 \text{ kg S}$

$$\frac{113.3 \text{ kg H}_2\text{SO}_4}{43.8 \text{ kg S}} = 2.59 \frac{\text{kg H}_2\text{SO}_4}{\text{kg S}}$$

100% conv. of S: $\dfrac{0.683 \text{ kmol FeS}_2}{} \left| \dfrac{2 \text{ kmol S}}{\text{kmol FeS}_2} \right| \dfrac{1 \text{ kmol H}_2\text{SO}_4}{1 \text{ kmol S}} \left| \dfrac{98 \text{ kg}}{\text{kmol}} \right. = 133.9 \text{ kg H}_2\text{SO}_4$

$$\Rightarrow \frac{133.9 \text{ kg H}_2\text{SO}_4}{43.8 \text{ kg S}} = 3.06 \frac{\text{kg H}_2\text{SO}_4}{\text{kg S}}$$

The sulfur is not completely converted to H$_2$SO$_4$ because of (i) incomplete oxidation of FeS$_2$ in the roasting furnace, (ii) incomplete conversion of SO$_2$ to SO$_3$ in the converter.

5.49 $N_2O_4 \Leftrightarrow 2NO_2$

a. $n_0 = \dfrac{(P_{gauge} + 1.00)V}{RT_0} = \dfrac{(2.00 \text{ atm})(2.00 \text{ L})}{(473\text{K})(0.08206 \text{ L} \cdot \text{atm/mol - K})} = \underline{\underline{0.103 \text{ mol NO}_2}}$

b. $n_1 = \text{mol NO}_2$, $n_2 = \text{mol N}_2\text{O}_4$

$$p_{NO_2} = y_{NO_2} P = \left(\frac{n_1}{n_1 + n_2} \right) P, \quad p_{N_2O_4} = \left(\frac{n_2}{n_1 + n_2} \right) P \Rightarrow K_p = \frac{n_1^2}{n_2(n_1 + n_2)} P$$

Ideal gas equation of state $\Rightarrow PV = (n_1 + n_2)RT \Rightarrow n_1 + n_2 = PV / RT$ (1)

Stoichiometric equation $\Rightarrow$ each mole of N_2O_4 present at equilibrium represents a loss of two moles of NO_2 from that initially present $\Rightarrow n_1 + 2n_2 = 0.103$ (2)

Solve (1) and (2) $\Rightarrow n_1 = 2(PV / RT) - 0.103$ (3), $\quad n_2 = 0.103 - (PV / RT)$ (4)

Substitute (3) and (4) in the expression for K_p, and replace P with $P_{gauge} + 1$

$$K_p = \frac{(2n_t - 0.103)^2}{n_t(0.103 - n_t)}(P_{gauge} + 1) \text{ where } n_t = \frac{(P_{gauge} + 1)V}{RT} \underset{V = 2 \text{ L}}{\Rightarrow} n_t = \frac{24.37(P_g + 1)}{T}$$

T(K)	Pgauge(atm)	nt	Kp(atm)	(1/T)	ln(Kp)
350	0.272	0.088568	5.46915	0.002857	1.699123
335	0.111	0.080821	2.131425	0.002985	0.756791
315	-0.097	0.069861	0.525954	0.003175	-0.64254
300	-0.224	0.063037	0.164006	0.003333	-1.80785

Variation of Kp with Temperature

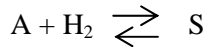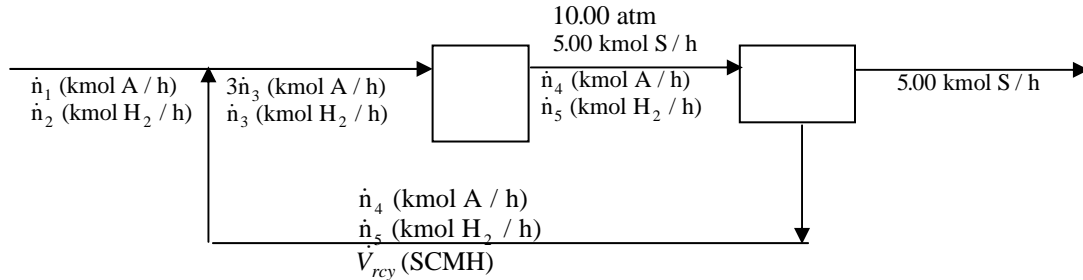$y = -7367x + 22.747$
$R^2 = 1$
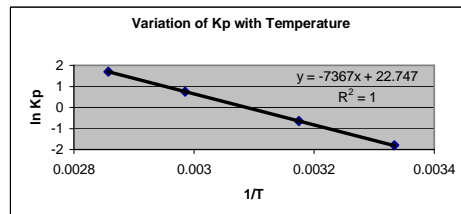
5.49 (cont'd)

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

$$\ln K_p = -\frac{7367}{T} + 22.747 \Rightarrow K_p = 7.567 \times 10^9 \exp\left(\frac{-7367}{T}\right) \Rightarrow \begin{array}{l} a = 7.567 \times 10^9 \text{ atm} \\ \underline{\underline{b = 7367K}} \end{array}$$
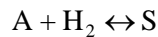
5.50

$$A + H_2 \rightleftarrows S$$

Overall A balance: $n_1 = \dfrac{5.00 \text{ kmol S}}{\text{h}} \dfrac{1 \text{ kmol A react}}{1 \text{ kmol S form}} = \underline{5.00 \text{ kmol A / h}}$

Overall H_2 balance: $n_2 = \dfrac{5.00 \text{ kmol S}}{\text{h}} \dfrac{1 \text{ kmol } H_2 \text{ react}}{1 \text{ kmol S form}} = \underline{5.00 \text{ kmol } H_2 \text{ / h}}$

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

$A + H_2 \leftrightarrow S$

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

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

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

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

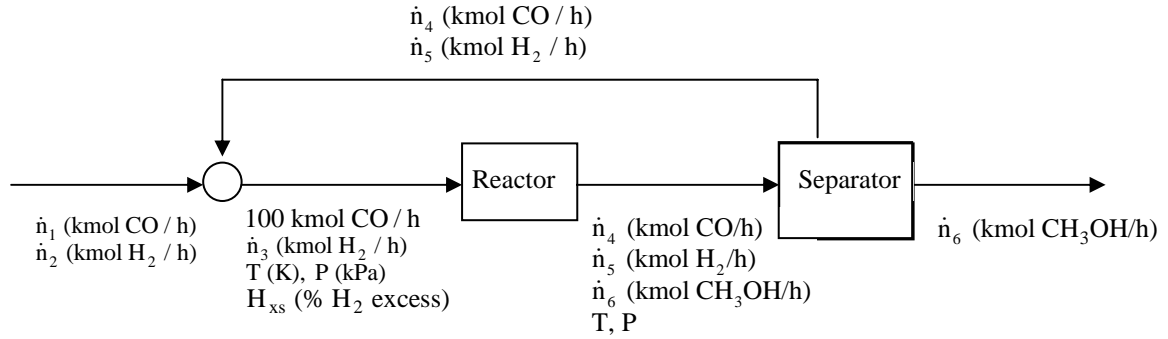$$p_S = y_S P = \frac{5.00}{4\dot{n}_3 - 5.00} 10.0$$

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

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

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

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

5.51

$\dot{n}_4$ (kmol CO / h)
$\dot{n}_5$ (kmol H_2 / h)

$\dot{n}_1$ (kmol CO / h)   100 kmol CO / h   Reactor   Separator $\dot{n}_6$ (kmol CH_3OH/h)
$\dot{n}_2$ (kmol H_2 / h) $\dot{n}_3$ (kmol H_2 / h)
T (K), P (kPa) $\dot{n}_4$ (kmol CO/h)
H_{xs} (% H_2 excess) $\dot{n}_5$ (kmol H_2/h)
$\dot{n}_6$ (kmol CH_3OH/h)
T, P

a. Balances on reactor $\Rightarrow$ 4 equations in $\dot{n}_3$, $\dot{n}_4$, $\dot{n}_5$, and $\dot{n}_6$.

<u>5.0% XS H_2</u>: $\dot{n}_3 = \dfrac{100 \text{ kmol CO fed}}{h} \left| \dfrac{2 \text{ kmol } H_2 \text{ reqd}}{1 \text{ kmol CO fed}} \right| \dfrac{1.05 \text{ kmol } H_2 \text{ fed}}{1 \text{ kmol } H_2 \text{ reqd}} = 210 \dfrac{\text{kmol } H_2}{h}$

<u>C balance</u>: $\dfrac{100 \text{ kmol CO}}{h} \left| \dfrac{1 \text{ kmol C}}{1 \text{ kmol CO}} = \dot{n}_4(1) + \dot{n}_6(1) \Rightarrow 100 = \dot{n}_4 + \dot{n}_6$ (1)

<u>H balance</u>: $210(2) = \dot{n}_5(2) + \dot{n}_6(4) \Rightarrow 210 = \dot{n}_5 + 2\dot{n}_6$ (2)

(<u>O balance</u>: $100 = \dot{n}_4 + \dot{n}_6 \Rightarrow$ identical to C balance $\Rightarrow$ not independent)

$(1) \Rightarrow \dot{n}_4 = 100 - \dot{n}_6$, $(2) \Rightarrow \dot{n}_5 = 210 - 2\dot{n}_6$
$\dot{n}_{tot} = \dot{n}_4 + \dot{n}_5 + \dot{n}_6 = (100 - \dot{n}_6) + (210 - 2\dot{n}_6) + \dot{n}_6 = 310 - 2\dot{n}_6$

$K_p(T=500K) = 1.390 \times 10^{-4} \exp \left(\begin{array}{l} 21.225 + \dfrac{9143.6}{500 \text{ K}} - 7.492\ln(500K) \\ +4.076 \times 10^{-3}(500K) - 1.161 \times 10^{-8}(500K)^2 \end{array} \right) = 9.11 \times 10^{-7} \text{ kPa}^{-2}$

$K_p = \dfrac{y_M P}{y_{CO} P (y_{H_2} P)^2} \Rightarrow K_p P^2 = \dfrac{y_M}{y_{CO}(y_{H_2})^2} \overset{(1)-(3)}{====} \dfrac{\dfrac{\dot{n}_6}{(310 - 2\dot{n}_6)}}{\dfrac{(100 - \dot{n}_6)}{(310 - 2\dot{n}_6)} \dfrac{(210 - 2\dot{n}_6)^2}{(310 - 2\dot{n}_6)^2}}$

$K_p P^2 = 9.11 \times 10^{-7} \text{ kPa}^{-2}(5000 \text{ kPa})^2 = 22.775 = \dfrac{\dot{n}_6(310 - 2\dot{n}_6)^2}{(100 - \dot{n}_6)(210 - 2\dot{n}_6)^2}$

Solving for $\dot{n}_6 \Rightarrow \dot{n}_6 = \underline{\underline{75.7 \text{ kmol } CH_3OH/h}}$, $\dot{n}_4 = 100 - \dot{n}_6 = \underline{\underline{24.3 \text{ kmol CO/h}}}$

$\dot{n}_5 = 210 - 2\dot{n}_6 = \underline{\underline{58.6 \text{ kmol } H_2 / h}}$

<u>Overall C balance</u>: $\dot{n}_1(1) = \dot{n}_6(1) \Rightarrow \dot{n}_1 = \underline{\underline{75.7 \text{ kmol CO/h}}}$

<u>Overall H balance</u>: $\dot{n}_2(2) = \dot{n}_6(4) \Rightarrow \dot{n}_2 = \underline{\underline{151 \text{ kmol } H_2/h}}$

$\dot{V}_{rec} = (\dot{n}_4 + \dot{n}_5) \dfrac{22.4 \text{ m}^3(STP)}{\text{kmol}} = \underline{\underline{1860 \text{ SCMH}}}$
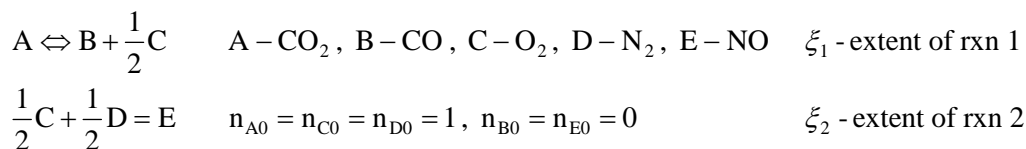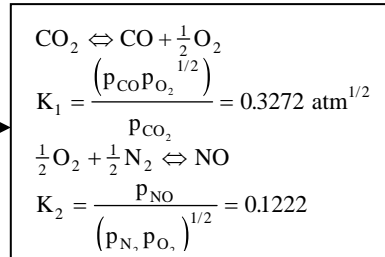
5.51 (cont'd)

b.

P(kPa)	T(K)	Hxs(%)	Kc(T)EB	KcP'2	n3(kmol H2/h)	n4(kmol CO/h)	n5(kmol H2/h)
1000	500	5	9.1E+01	0.91	210	74.45	158.90
5000	500	5	9.1E+01	22.78	210	91.00	192.00
10000	500	5	9.1E+01	91.11	210	13.28	36.56
5000	400	5	3.1E+04	7849.77	210	1.07	12.15
5000	**500**	**5**	**9.1E+01**	**22.78**	**210**	**24.32**	**58.64**
5000	600	5	1.6E+00	0.41	210	85.42	180.84
5000	500	0	9.1E+01	22.78	200	26.65	53.30
5000	500	5	9.1E+01	22.78	210	24.32	58.64
5000	500	10	9.1E+01	22.78	220	22.23	64.45

n6(kmol MeOH/h)	ntot (kmol/h)	KpcEB	KpcP'2	n1 (kmol CO/h)	n2(kmol H2/h)	Vdot (SCMH)
25.55	258.90	9.1E-01	1.3E-05	25.55	51.10	5227
9.00	292.00	2.3E-01	2.3E+01	9.00	18.00	6339
86.72	136.56	9.1E+01	4.9E-03	86.72	173.44	1116
98.93	112.15	7.8E+03	3.2E-08	98.93	197.85	296
75.68	**158.64**	**2.3E+01**	**3.4E-03**	**75.68**	**151.36**	**1858**
14.58	280.84	4.1E-01	-2.9E-04	14.58	29.16	5964
73.35	153.30	2.3E+01	9.8E-03	73.35	146.70	1791
75.68	158.64	2.3E+01	3.4E-03	75.68	151.36	1858
77.77	164.45	2.3E+01	-3.1E-03	77.77	155.55	1942

c. Increase yield by <u>raising pressure, lowering temperature, increasing H_{xs}</u>. Increasing the pressure raises costs because more compression is needed.

d. If the temperature is too low, a low reaction rate may keep the reaction from reaching equilibrium in a reasonable time period.

e. Assumed that reaction reached equilibrium, ideal gas behavior, complete condensation of methanol, not steady-state measurement errors.

5.52

1.0 mol CO_2
1.0 mol O_2
1.0 mol N_2
T = 3000 K, P = 5.0 atm

$$CO_2 \Leftrightarrow CO + \tfrac{1}{2}O_2$$

$$K_1 = \frac{\left(p_{CO}\,p_{O_2}^{1/2}\right)}{p_{CO_2}} = 0.3272 \text{ atm}^{1/2}$$

$$\tfrac{1}{2}O_2 + \tfrac{1}{2}N_2 \Leftrightarrow NO$$

$$K_2 = \frac{p_{NO}}{\left(p_{N_2}\,p_{O_2}\right)^{1/2}} = 0.1222$$

$A \Leftrightarrow B + \dfrac{1}{2}C$ $A - CO_2$, $B - CO$, $C - O_2$, $D - N_2$, $E - NO$ ξ_1 - extent of rxn 1

$\dfrac{1}{2}C + \dfrac{1}{2}D = E$ $n_{A0} = n_{C0} = n_{D0} = 1$, $n_{B0} = n_{E0} = 0$ ξ_2 - extent of rxn 2

5.52 (cont'd)

$$n_A = 1 - \xi_1$$
$$n_B = \xi_1$$
$$n_C = 1 + \frac{1}{2}\xi_1 - \frac{1}{2}\xi_2$$
$$n_D = 1 - \frac{1}{2}\xi_2$$
$$\frac{n_E = \xi_2}{n_{tot} = 3 + \frac{1}{2}\xi_1 = \frac{6 + \xi_1}{2}}$$

$$y_A = n_A/n_{tot} = 2(1 - \xi_1)/(6 + \xi_1)$$
$$y_B = 2\xi_1/(6 + \xi_1)$$
$$y_C = (2 + \xi_1 - \xi_2)/(6 + \xi_1)$$
$$y_D = (2 - \xi_2)/(6 + \xi_1)$$
$$y_E = 2\xi_2/(6 + \xi_1)$$

$$p_i = y_i P$$

$$K_1 = \frac{p_{CO}p_{O_2}^{1/2}}{p_{CO_2}} = \frac{y_B y_C^{1/2}}{y_A}p^{(1+\frac{1}{2}-1)} = \frac{2\xi_1(2 + \xi_1 - \xi_2)^{1/2}}{2(1 - \xi_1)(6 + \xi_1)^{1/2}}(5)^{1/2} = 0.3272$$

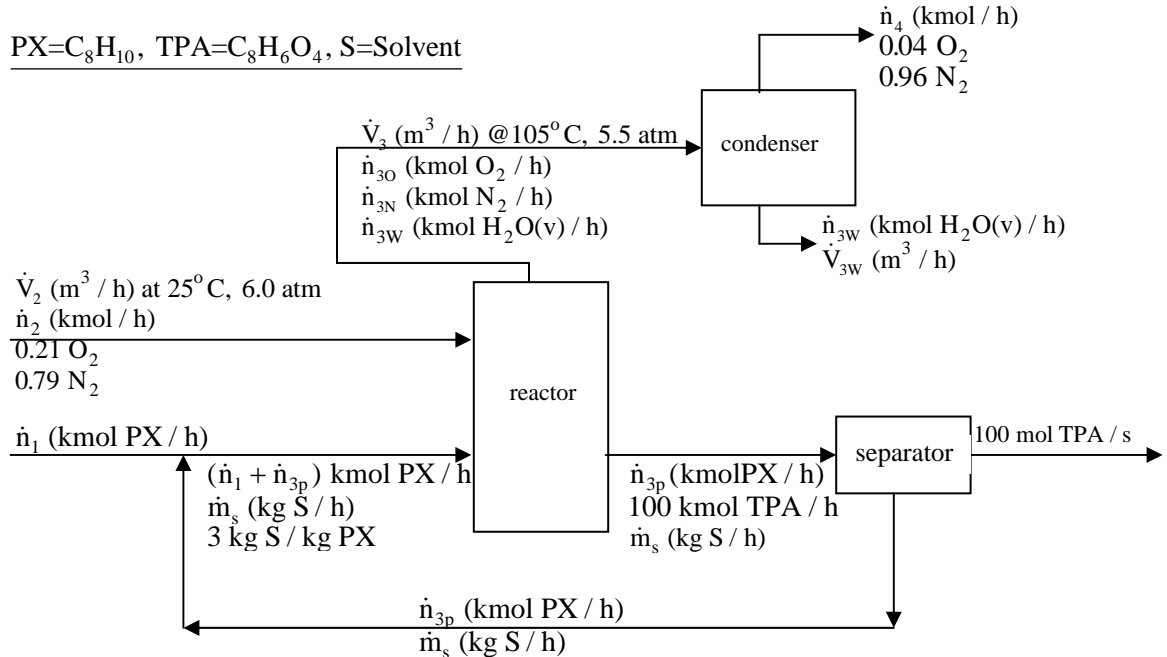$$\Rightarrow 0.3272(1 - \xi_1)(6 + \xi_1)^{1/2} = 2.236\xi_1(2 + \xi_1 - \xi_2)^{1/2} \tag{1}$$

$$K_2 = \frac{p_{NO}}{\left(p_{O_2}p_{N_2}\right)^{1/2}} = \frac{y_E}{y_C^{1/2}y_D^{1/2}}p^{1-1/2-1/2} = \frac{2\xi_2}{(2 + \xi_1 - \xi_2)^{1/2}(2 - \xi_2)^{1/2}} = 0.1222$$

$$\Rightarrow 0.1222(2 + \xi_1 - \xi_2)^{1/2}(2 - \xi_2)^{1/2} = 2\xi_2 \tag{2}$$

Solve (1) and (2) simultaneously with E-Z Solve $\Rightarrow \xi_1 = 0.20167, \ \xi_2 = 0.12081,$

$$y_A = 2(1 - \xi_1)/(6 + \xi_1) = 0.2574 \text{ mol } CO_2/\text{mol} \quad y_D = 0.3030 \text{ mol } N_2/\text{mol}$$
$$y_B = 0.0650 \text{ mol } CO/\text{mol} \quad\quad\quad\quad y_E = 0.0390 \text{ mol } NO/\text{mol}$$
$$y_C = 0.3355 \text{ mol } O_2/\text{mol}$$

5.53 a. $\underline{PX = C_8H_{10}, \ TPA = C_8H_6O_4, \ S = Solvent}$

5.53 (cont'd)

b. Overall C balance:

$$\dot{n}_1\left(\frac{\text{kmol PX}}{\text{h}}\right)\frac{8\text{ kmol C}}{\text{kmol PX}} = \frac{100\text{ kmol TPA}}{\text{h}}\left|\frac{8\text{ kmol C}}{\text{kmol TPA}}\right. \Rightarrow \dot{n}_1 = \underline{\underline{100\text{ kmol PX / h}}}$$

c. $\underline{O_2 \text{ consumed}} = \dfrac{100\text{ kmol TPA}}{\text{h}}\left|\dfrac{3\text{ kmol }O_2}{1\text{ kmol TPA}}\right. = 300\text{ kmol }O_2/\text{h}$

$\underline{\text{Overall }O_2\text{ balance:}}\ 0.21\dot{n}_2 = 300\ \dfrac{\text{kmol }O_2}{\text{h}} + 0.04\dot{n}_4$

$\underline{\text{Overall }N_2\text{ balance:}}\ 0.79\dot{n}_2 = 0.96\dot{n}_4$
$\left.\begin{array}{l}\\[2mm]\\\end{array}\right\} \Rightarrow \begin{array}{l}\dot{n}_2 = 1694\text{ kmol air/h}\\[2mm]\dot{n}_4 = 1394\text{ kmol/h}\end{array}$

$\underline{\text{Overall }H_2O\text{ balance:}}\ \dot{n}_{3W} = \dfrac{100\text{ kmol TPA}}{\text{h}}\left|\dfrac{2\text{ kmol }H_2O}{1\text{ kmol TPA}}\right. = 200\text{ kmol }H_2O / \text{h}$

$\dot{V}_2 = \dfrac{\dot{n}_2 RT}{P} = \dfrac{1694\text{ kmol}}{\text{h}}\left|\dfrac{0.08206\text{ m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\right|\dfrac{298\text{ K}}{6.0\text{ atm}} = \underline{\underline{6.90\times10^3\text{ m}^3\text{ air/h}}}$

$\dot{V}_3 = \dfrac{(\dot{n}_{3W}+\dot{n}_4)RT}{P} = \dfrac{(200+1394)\text{ kmol}}{\text{h}}\left|\dfrac{0.08206\text{ m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\right|\dfrac{378\text{ K}}{5.5\text{ atm}} = \underline{\underline{8990\text{ m}^3/\text{h}}}$

$\dot{V}_{3W} = \dfrac{200\text{ kmol }H_2O\text{ (l)}}{\text{h}}\left|\dfrac{18.0\text{ kg}}{\text{kmol}}\right|\dfrac{1\text{ m}^3}{1000\text{ kg}} = \underline{\underline{3.60\text{ m}^3\ H_2O(l) / \text{h leave condenser}}}$

d. $\underline{90\%\text{ single pass conversion}} \Rightarrow \dot{n}_{3p} = 0.10(\dot{n}_1 + \dot{n}_{3p}) \overset{\dot{n}_1=100}{====>} \dot{n}_{3p} = 11.1\text{ kmol PX / h}$

$\dot{m}_{\text{recycle}} = \dot{m}_S + \dot{m}_{3P} = \dfrac{(100+11.1)\text{ kg PX}}{\text{h}}\left|\dfrac{106\text{ kg PX}}{1\text{ kmol PX}}\right|\dfrac{3\text{ kg S}}{\text{kg PX}} + \dfrac{11.1\text{ kmol PX}}{\text{h}}\left|\dfrac{106\text{ kg PX}}{1\text{ kmol PX}}\right.$

$= \underline{\underline{3.65\times10^4\text{ kg/h}}}$

e. O_2 is used to react with the PX. N_2 does not react with anything but enters with O_2 in the air. The catalyst is used to accelerate the reaction and the solvent is used to disperse the PX.

f. The stream can be allowed to settle and separate into water and PX layers, which may then be separated.

5.54

5.54 (cont'd)

$$CO + 2H_2 \Leftrightarrow CH_3OH(M)$$
$$CO_2 + 3H_2 \Leftrightarrow CH_3OH + H_2O$$
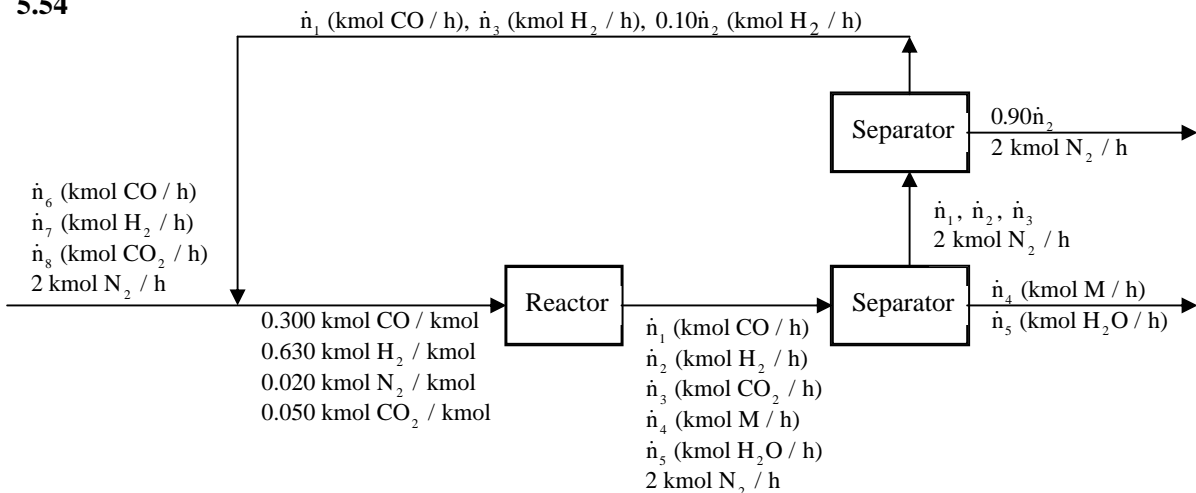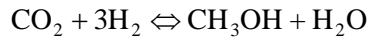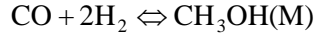
a. Let ξ_1 (kmol / h) = extent of rxn 1, ξ_2 (kmol / h) = extent of rxn 2

$\underline{CO:}$ $\dot{n}_1 = 30 - \xi_1$

$\underline{H_2:}$ $\dot{n}_2 = 63 - 2\xi_1 - 3\xi_2$

$\underline{CO_2:}$ $\dot{n}_3 = 5 - \xi_2$

$\underline{M:}$ $\dot{n}_4 = \xi_1 + \xi_2$

$\underline{H_2O:}$ $\dot{n}_5 = \xi_2$

$\underline{N_2:}$ $\dot{n}_{N_2} = 2$

$\dot{n}_{tot} = 100 - 2\xi_1 - 2\xi_2$

$$\Rightarrow \left(K_p\right)_1 = \frac{P \cdot y_M}{P \cdot y_{CO}\left(P \cdot y_{H_2}\right)^2}, \quad \left(K_p\right)_2 = \frac{\left(P \cdot y_M\right)\left(P \cdot y_{H_2O}\right)}{\left(P \cdot y_{CO_2}\right)\left(P \cdot y_{H_2}\right)^3}$$

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

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

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

$\Rightarrow$

$\dot{n}_1 = 30.0 - 25.27 = \underline{\underline{4.73 \text{ kmol CO / h}}}$ $\qquad$ $\underline{9.98\% \text{ CO}}$

$\dot{n}_2 = 63.0 - 2(25.27) - 3(0.0157) = \underline{\underline{12.4 \text{ kmol } H_2 / h}}$ $\qquad$ $\underline{26.2\% \ H_2}$

$\dot{n}_3 = 5.0 - 0.0157 = \underline{\underline{4.98 \text{ kmol } CO_2 / h}}$ $\qquad$ $\underline{10.5\% \ CO_2}$

$\dot{n}_4 = 25.27 + 0.0157 = \underline{\underline{25.3 \text{ kmol M / h}}}$ $\qquad \Rightarrow \qquad$ $\underline{53.4\% \text{ M}}$

$\dot{n}_5 = 0.0157 = \underline{\underline{0.0157 \text{ kmol } H_2O / h}}$ $\qquad$ $\underline{0.03\% \ H_2O}$

$n_{total} = 49.4$ kmol / h

$\underline{\text{C balance:}}$ $\dot{n}_4 = 25.3$ kmol / h $\qquad \left.\right\}$ $\dot{n}_6 = \underline{25.4 \text{ kmol CO / h}}$

$\underline{\text{O balance:}}$ $\dot{n}_6 + 2\dot{n}_8 = \dot{n}_4 + \dot{n}_5 = 25.44$ mol / s $\qquad \Rightarrow$ $\dot{n}_8 = \underline{0.02 \text{ kmol } CO_2 / h}$

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

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

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

5.54 (cont'd)

Process feed: $(25.4 + 61.8 + 0.02 + 2.0)\left(\dfrac{237 \text{ kmol / h}}{25.3 \text{ kmol / h}}\right)\left(\dfrac{22.4 \text{ m}^3 \text{ (STP)}}{\text{kmol}}\right) = \underline{\underline{18,700 \text{ SCMH}}}$

Reactor effluent flow rate: $\left(49.4 \text{ kmol / h}\right)\left(\dfrac{237 \text{ kmol / h}}{25.3 \text{ kmol / s}}\right) = 444 \text{ kmol / h}$

$$\Rightarrow \dot{V}_{std}\left(444 \ \dfrac{\text{kmol}}{\text{h}}\right)\left(\dfrac{22.4 \text{ m}^3 \text{ (STP)}}{\text{kmol}}\right) = \underline{\underline{9946 \text{ SCMH}}}$$

$$\Rightarrow \dot{V}_{actual} = \dfrac{9950 \text{ m}^3 \text{(STP)}}{\text{h}}\left|\dfrac{473.2 \text{ K}}{273.2 \text{ K}}\right|\dfrac{101.3 \text{ kPa}}{4925 \text{ kPa}} = \underline{\underline{354 \text{ m}^3 \text{ / h}}}$$

c. $\hat{V} = \dfrac{\dot{V}}{\dot{n}} = \dfrac{354 \text{ m}^3 \text{ / h}}{444 \text{ kmol / h}}\left|\dfrac{1000 \text{ L}}{\text{m}^3}\right|\dfrac{1 \text{ kmol}}{1000 \text{ mol}} = \underline{\underline{0.8 \text{ L / mol}}}$

$\hat{V} < 20 \text{ L / mol} \overset{(5.2\text{-}36)}{=\!=\!=\!=\!\Rightarrow} \text{ideal gas approximation is poor}$

Most obviously, the calculation of $\dot{V}$ from $\dot{n}$ using the ideal gas equation of state is likely to lead to error. In addition, the reaction equilibrium expressions are probably strictly valid only for ideal gases, so that every calculated quantity is likely to be in error.

5.55 a. $\dfrac{P\hat{V}}{RT} = 1 + \dfrac{B}{\hat{V}} \Rightarrow B = \dfrac{RT_c}{P_c}\left(B_o + \omega B_1\right)$

From Table B.1 for ethane: $T_c = 305.4 \text{ K}$, $P_c = 48.2 \text{ atm}$

From Table 5.3-1 $\omega = 0.098$

$B_o = 0.083 - \dfrac{0.422}{T_r^{1.6}} = 0.083 - \dfrac{0.422}{\left(\dfrac{308.2 \text{K}}{305.4 \text{K}}\right)^{1.6}} = -0.333$

$B_1 = 0.139 - \dfrac{0.172}{T_r^{4.2}} = 0.139 - \dfrac{0.172}{\left(\dfrac{308.2 \text{K}}{305.4 \text{K}}\right)^{4.2}} = -0.0270$

$B(T) = \dfrac{RT_c}{P_c}\left(B_o + \omega B_1\right) = \dfrac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}\left|\dfrac{305.4 \text{K}}{48.2 \text{ atm}}\right.\left[-0.333 - \left(0.098\right)0.0270\right]$

$\qquad = -0.1745 \text{ L / mol}$

$\dfrac{P\hat{V}^2}{RT} - \hat{V} - B = \left(\dfrac{10.0 \text{ atm}}{308.2 \text{K}}\left|\dfrac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}}\right.\right)\hat{V}^2 - \hat{V} + 0.1745 = 0$

$\Rightarrow \hat{V} = \dfrac{1 \pm \sqrt{1 - 4\left(0.395 \text{ mol / L}\right)\left(0.1745 \text{ L / mol}\right)}}{2\left(0.395 \text{ mol / L}\right)} = \underline{\underline{2.343 \text{ L / mol}, \ \overline{0.188 \text{ L / mol}}}}$

$\hat{V}_{ideal} = RT / P = 0.08206 \times 308.2 / 10.0 = 2.53,$ so the second solution is likely to be a mathematical artifact.

b. $z = \dfrac{P\hat{V}}{RT} = \dfrac{10.0 \text{ atm}}{0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}}\left|\dfrac{2.343 \text{ L / mol}}{308.2 \text{K}}\right. = \underline{\underline{0.926}}$

c. $\dot{m} = \dfrac{\dot{V}}{\hat{V}} MW = \dfrac{1000 \text{ L}}{\text{h}}\left|\dfrac{\text{mol}}{2.343 \text{ L}}\right|\dfrac{30.0 \text{ g}}{\text{mol}}\left|\dfrac{1 \text{ kg}}{1000 \text{ g}}\right. = \underline{\underline{12.8 \text{ kg / h}}}$

5.56 $\quad \dfrac{P\hat{V}}{RT} = 1 + \dfrac{B}{\hat{V}} \Rightarrow B = \dfrac{RT_c}{P_c}\left(B_o + \omega B_1\right)$

From Table B.1 $\quad T_c(CH_3OH) = 513.2$ K, $P_c = 78.50$ atm

$\qquad\qquad\qquad T_c(C_3H_8) = 369.9$ K, $P_c = 42.0$ atm

From Table 5.3-1 $\quad \omega(CH_3OH) = 0.559, \ \omega(C_3H_8) = 0.152$

$B_o(CH_3OH) = 0.083 - \dfrac{0.422}{T_r^{1.6}} = 0.083 - \dfrac{0.422}{\left(373.2K \middle/ 513.2K\right)^{1.6}} = -0.619$

$B_o(C_3H_8) = 0.083 - \dfrac{0.422}{T_r^{1.6}} = 0.083 - \dfrac{0.422}{\left(373.2K \middle/ 369.9K\right)^{1.6}} = -0.333$

$B_1(CH_3OH) = 0.139 - \dfrac{0.172}{T_r^{4.2}} = 0.139 - \dfrac{0.172}{\left(373.2K \middle/ 513.2K\right)^{4.2}} = -0.516$

$B_1(C_3H_8) = 0.139 - \dfrac{0.172}{T_r^{4.2}} = 0.139 - \dfrac{0.172}{\left(373.2K \middle/ 369.9K\right)^{4.2}} = -0.0270$

$B(CH_3OH) = \dfrac{RT_c}{P_c}\left(B_o + \omega B_1\right)$

$\qquad\qquad = \dfrac{0.08206 \text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} \left|\dfrac{513.2K}{78.5 \text{ atm}}\right.\left(-0.619 - (0.559)0.516\right) = -0.4868 \ \tfrac{\text{L}}{\text{mol}}$

$B(C_3H_8) = \dfrac{RT_c}{P_c}\left(B_o + \omega B_1\right)$

$\qquad\qquad = \dfrac{0.08206 \text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} \left|\dfrac{369.9 \text{ K}}{42.0 \text{ atm}}\right.\left(-0.333 - (0.152)0.0270\right) = -0.2436 \ \tfrac{\text{L}}{\text{mol}}$

$B_{mix} = \displaystyle\sum_i \sum_j y_i y_j B_{ij} \Rightarrow B_{ij} = 0.5\left(B_{ii} + B_{jj}\right)$

$B_{ij} = 0.5(-0.4868 - 0.2436)\text{L / mol} = -0.3652 \text{ L / mol}$

$B_{mix} = (0.30)(0.30)(-0.4868) + 2(0.30)(0.70)(-0.3652) + (0.70)(0.70)(-0.2436)$

$\qquad\quad = -0.3166 \text{ L / mol}$

$\dfrac{P\hat{V}^2}{RT} - \hat{V} - B_{mix} = \left(\dfrac{10.0 \text{ atm}}{373.2K} \middle| \dfrac{\text{mol}\cdot\text{K}}{0.08206 \text{ L}\cdot\text{atm}}\right)\hat{V}^2 - \hat{V} + 0.3166 = 0$

Solve for $\hat{V}$: $\hat{V} = \dfrac{1 \pm \sqrt{1 - 4(0.326 \text{ mol / L})(0.3166 \text{ L / mol})}}{2(0.326 \text{ mol / L})} = 2.70 \text{ L / mol}, \ 0.359 \text{ L / mol}$

$\hat{V}_{ideal} = \dfrac{RT}{P} = \dfrac{0.08206 \text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} \left|\dfrac{373.2 \text{ K}}{10.0 \text{ atm}}\right. = 3.06 \text{ L / mol} \Rightarrow \underline{\underline{\hat{V}_{virial} = 2.70 \text{ L / mol}}}$

$\dot{V} = \hat{V}\dot{n} = \dfrac{2.70 \text{ L / mol}}{} \left|\dfrac{15.0 \text{ kmol } CH_3OH \text{ / h}}{0.30 \text{ kmol } CH_3OH \text{ / kmol}}\right| \dfrac{1000 \text{ mol}}{1 \text{ kmol}} \left|\dfrac{1 \text{ m}^3}{1000 \text{ L}}\right. = \underline{\underline{135 \text{ m}^3 \text{ / h}}}$

5.57 a. van der Waals equation: $P = \dfrac{RT}{\left(\hat{V} - b\right)} - \dfrac{a^2}{\hat{V}^2}$

Multiply both sides by $\hat{V}^2\left(\hat{V} - b\right) \Rightarrow P\hat{V}^3 - P\hat{V}^2 b = RT\hat{V}^2 - a\hat{V} + ab$

$P\hat{V}^3 + \left(\text{-}Pb - RT\right)\hat{V}^2 + a\hat{V} - ab = 0$

$c_3 = P = \underline{50.0\ \text{atm}}$

$c_2 = \left(\text{-}Pb - RT\right) = \left(-50.0\ \text{atm}\right)\left(0.0366\ \text{L / mol}\right) - \left(0.08206\ \tfrac{\text{L·atm}}{\text{mol·K}}\right)\left(223\ \text{K}\right) = \underline{-20.1\ \text{L} \cdot \text{atm / mol}}$

$c_1 = -a = \underline{1.33\ \text{atm} \cdot \text{L}^2\ /\ \text{mol}^2}$

$c_0 = -ab = -\left(1.33\ \text{atm} \cdot \text{L}^2\ /\ \text{mol}^2\right)\left(0.0366\ \text{L / mol}\right)$

$\underline{\underline{= -0.0487\ \dfrac{\text{atm} \cdot \text{L}^3}{\text{mol}^3}}}$

b. $\hat{V}_{\text{ideal}} = \dfrac{RT}{P} = \dfrac{0.08206\ \text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}\bigg|\dfrac{223\ \text{K}}{50.0\ \text{atm}} = 0.366\ \text{L / mol}$

c.

T(K)	P(atm)	c3	c2	c1	c0	V(ideal) (L/mol)	V (L/mol)	f(V)	% error
223	1.0	1.0	-18.336	1.33	-0.0487	18.2994	18.2633	0.0000	0.2
223	10.0	10.0	-18.6654	1.33	-0.0487	1.8299	1.7939	0.0000	2.0
223	50.0	50.0	-20.1294	1.33	-0.0487	0.3660	0.3313	0.0008	10.5
223	100.0	100.0	-21.9594	1.33	-0.0487	0.1830	0.1532	-0.0007	19.4
223	200.0	200.0	-25.6194	1.33	-0.0487	0.0915	0.0835	0.0002	9.6

← b

d. 1 eq. in 1 unknown - use Newton-Raphson.

$(1) \Rightarrow g\left(\hat{V}\right) = 50.0\hat{V}^3 + \left(\text{-}20.1294\right)\hat{V}^2 + \left(1.33\right)\hat{V} - .0487 = 0$

Eq. (A.2-13) $\Rightarrow a = \dfrac{\partial g}{\partial \hat{V}} = 150\hat{V}^2 - 40.259\hat{V} + 1.33$

Eq. (A.2-14) $\Rightarrow ad = -g \overset{\text{solve}}{\Rightarrow} d = \dfrac{-g}{a}$

Then $\hat{V}^{(k+1)} = \hat{V}^{(k)} + d$ Guess $\hat{V}^{(1)} = \hat{V}_{\text{ideal}} = 0.3660\ \text{L / mol}$.

	$\hat{V}^{(k)}$	$\hat{V}^{(k+1)}$	
1	0.3660	0.33714	
2	0.33714	0.33137	
3	0.33137	0.33114	
4	0.33114	0.33114	converged

5.58 $\underline{C_3H_8}$: $T_C = 369.9$ K $P_C = 42.0$ atm$\left(4.26 \times 10^6 \text{ Pa}\right)$ $\omega = 0.152$

$\underline{\text{Specific Volume}}$ $\dfrac{5.0 \text{ m}^3}{75 \text{ kg}} \bigg| \dfrac{44.09 \text{ kg}}{1 \text{ kmol}} \bigg| \dfrac{1 \text{ kmol}}{10^3 \text{ mol}} = 2.93 \times 10^{-3}$ m^3/mol

$\underline{\text{Calculate constants}}$

$$a = \frac{0.42747}{} \bigg| \frac{\left(8.314 \text{ m}^3 \cdot \text{Pa}/\text{mol} \cdot \text{K}\right)^2}{4.26 \times 10^6 \text{ Pa}} \bigg| \left(369.9 \text{ K}\right)^2 = 0.949 \text{ m}^6 \cdot \text{Pa}/\text{mol}^2$$

$$b = \frac{0.08664}{} \bigg| \frac{\left(8.314 \text{ m}^3 \cdot \text{Pa}/\text{mol} \cdot \text{K}\right)}{4.26 \times 10^6 \text{ Pa}} \bigg| \left(369.9 \text{ K}\right) = 6.25 \times 10^{-5} \text{ m}^3/\text{mol}$$

$$m = 0.48508 + 1.55171(0.152) - 0.15613(0.152)^2 = 0.717$$

$$\alpha = \left[1 + 0.717\left(1 - \sqrt{298.2/369.9}\right)\right]^2 = 1.15$$

$\underline{\text{SRK Equation:}}$

$$P = \frac{\left(8.314 \text{ m}^3 \cdot \text{Pa}/\text{mol} \cdot \text{K}\right)(298.2 \text{ K})}{\left(2.93 \times 10^{-3} - 6.25 \times 10^{-5}\right)\text{m}^3/\text{mol}} - \frac{1.15\left(0.949 \text{ m}^6 \cdot \text{Pa}/\text{mol}^2\right)}{2.93 \times 10^{-3} \text{ m}^3/\text{mol}\left(2.93 \times 10^{-3} + 6.25 \times 10^{-5}\right)\text{m}^3/\text{mol}}$$

$$\Rightarrow P = 7.40 \times 10^6 \text{ Pa} \Rightarrow \underline{7.30 \text{ atm}}$$

$\underline{\text{Ideal:}}$ $P = \dfrac{RT}{\hat{V}} = \dfrac{\left(8.314 \text{ m}^3 \cdot \text{Pa}/\text{mol} \cdot \text{K}\right)(298.2 \text{ K})}{2.93 \times 10^{-3} \text{ m}^3/\text{mol}} = 8.46 \times 10^6 \text{ Pa} \Rightarrow 8.35 \text{ atm}$

$\underline{\text{Percent Error:}}$ $\dfrac{(8.35 - 7.30) \text{ atm}}{7.30 \text{ atm}} \times 100\% = \underline{\underline{14.4\%}}$

5.59 $\underline{CO_2}$: $T_C = 304.2$ K $P_C = 72.9$ atm $\omega = 0.225$
$\underline{\text{Ar:}}$ $T_C = 151.2$ K $P_C = 48.0$ atm $\omega = -0.004$
$P = 51.0$ atm, $\hat{V} = 35.0$ L / 50.0 mol $= 0.70$ L/mol

$\underline{\text{Calculate constants (use }R = 0.08206 \text{ L} \cdot \text{atm}/\text{mol} \cdot \text{K})}$

$\underline{CO_2}$: $a = 3.65 \dfrac{\text{L}^2 \cdot \text{atm}}{\text{mol}^2}$, $m = 0.826$, $b = 0.0297 \dfrac{\text{L}}{\text{mol}}$, $\alpha = \left[1 + 0.826\left(1 - \sqrt{T/304.2}\right)\right]^2$

$\underline{\text{Ar:}}$ $a = 1.37 \dfrac{\text{L}^2 \cdot \text{atm}}{\text{mol}^2}$, $m = 0.479$, $b = 0.0224 \dfrac{\text{L}}{\text{mol}}$, $\alpha = \left[1 + 0.479\left(1 - \sqrt{T/151.2}\right)\right]^2$

$$f(T) = \frac{RT}{\hat{V} - b} - \frac{a}{\hat{V}(\hat{V} + b)}\left[1 + m\left(1 - \sqrt{T/T_C}\right)\right]^2 - P = 0$$

Use E-Z Solve. Initial value (ideal gas):

$$T_{\text{ideal}} = (51.0 \text{ atm})\left(0.70 \frac{\text{L}}{\text{mol}}\right)\bigg/\left(0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}\right) = \underline{\underline{435.0 \text{ K}}}$$

$$\text{E - Z Solve} \Rightarrow \left(T_{\text{max}}\right)_{CO_2} = 455.4 \text{ K}, \ \left(T_{\text{max}}\right)_{\text{Ar}} = 431.2 \text{ K}$$

5.60 O_2: $T_C = 154.4$ K; $P_C = 49.7$ atm; $\omega = 0.021$; $T = 208.2$ K $(65°$ C$)$; $P = 8.3$ atm; $\dot{m} = 250$ kg/h; $R = 0.08206$ L·atm/mol·K

SRK constants: $a = 1.38$ L^2·atm/mol^2; $b = 0.0221$ L/mol; $m = 0.517$; $\alpha = 0.840$

SRK equation: $f(\hat{V}) = \dfrac{RT}{(\hat{V} - b)} - \dfrac{a\alpha}{\hat{V}(\hat{V} + b)} - P = 0 \overset{\text{E-Z Solve}}{=====}> \hat{V} = 2.01$ L / mol

$$\Rightarrow \dot{V} = \frac{250 \text{ kg}}{\text{h}} \left| \frac{\text{kmol}}{32.00 \text{ kg}} \right| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \left| \frac{2.01 \text{ L}}{\text{mol}} \right. = \underline{\underline{15,700 \text{ L/h}}}$$

5.61

$\sum F_y = P_{CO_2} \cdot A - W = 0$ where $W = mg = 5500$ kg$\left(9.81 \frac{m}{s^2}\right) = 53900$ N

$P_{CO_2} \cdot A$
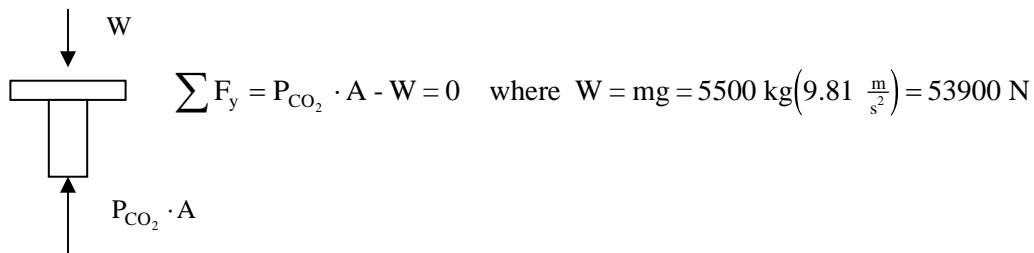
a. $P_{CO_2} = \dfrac{W}{A_{piston}} = \dfrac{53900 \text{ N}}{\frac{\pi}{4}(0.15 \text{ m})^2} \left| \dfrac{1 \text{ atm}}{1.013 \times 10^5 \text{ N / m}^2} \right. = \underline{\underline{30.1 \text{ atm}}}$

b. SRK equation of state: $P = \dfrac{RT}{(\hat{V} - b)} - \dfrac{\alpha a}{\hat{V}(\hat{V} + b)}$

For CO_2: $T_c = 304.2$, $P_c = 72.9$ atm, $\omega = 0.225$

$a = 3.654$ m^6·atm / kmol^2, $b = 0.02967$ m^3 / kmol, $m = 0.8263$, $\alpha(25°$C$) = 1.016$

$$30.1 \text{ atm} = \frac{\left(0.08206 \frac{\text{m}^3 \cdot \text{atm}}{\text{kmol·K}}\right)(298.2 \text{ K})}{\left(\hat{V} - 0.02967 \frac{\text{m}^3}{\text{kmol}}\right)} - \frac{(1.016)\left(3.654 \frac{\text{m}^6 \cdot \text{atm}}{\text{kmol}^2}\right)}{\hat{V}\left(\hat{V} + 0.02967\right) \frac{\text{m}^6}{\text{kmol}^2}}$$

$\overset{\text{E-Z Solve}}{=====}> \hat{V} = \underline{\underline{0.675 \text{ m}^3 / \text{kmol}}}$

$V(\text{before expansion}) = 0.030$ m^3

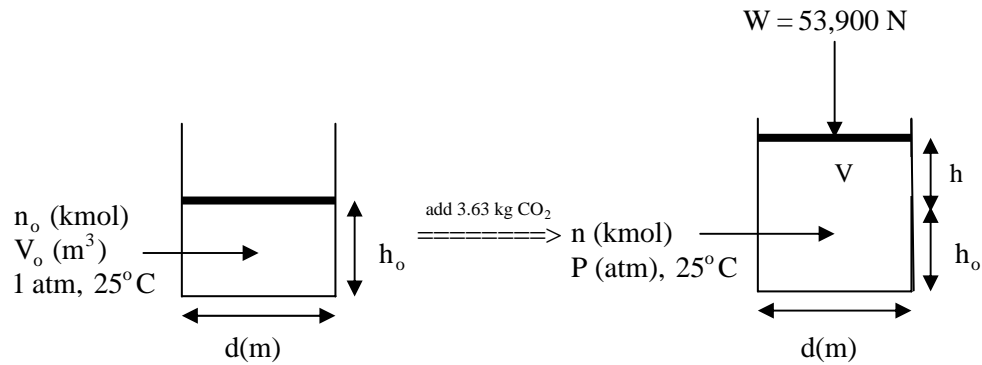$V(\text{after expansion}) = 0.030$ m$^3 + \frac{\pi}{4}(0.15$ m$)^2(1.5$ m$) = 0.0565$ m^3

$m_{CO_2} = \dfrac{V}{\hat{V}} MW = \dfrac{0.0565 \text{ m}^3}{0.675 \text{ m}^3 / \text{kmol}} \left| \dfrac{44.01 \text{ kg}}{\text{kmol}} \right. = 3.68$ kg

$m_{CO_2}(\text{initially}) = \dfrac{PV}{RT} MW = \dfrac{1 \text{ atm}}{0.08206 \frac{\text{m}^3 \cdot \text{atm}}{\text{kmol·K}}} \left| \dfrac{0.030 \text{ m}^3}{298.2 \text{ K}} \right| \dfrac{44.01 \text{ kg}}{\text{kmol}} = 0.0540$ kg

$m_{CO_2}(\text{added}) = 3.68 - 0.0540 \text{ kg} = \underline{\underline{3.63 \text{ kg}}}$

5.61 (cont'd)

c.

$W = 53,900 \text{ N}$

Given T, V_o, h, find d

<u>Initial</u>: $n_o = \dfrac{V_o}{RT}$ $(P_o = 1)$

<u>Final</u>: $V = V_o + \dfrac{\pi d^2 h}{4}$, $n = n_o + \dfrac{3.63 \text{ (kg)}}{44 \text{ (kg / kmol)}} = \dfrac{V_o}{RT} + 0.0825$

$\hat{V} = \dfrac{V}{n} = \dfrac{V_o + \dfrac{\pi d^2 h}{4}}{\dfrac{V_o}{RT} + 0.0825}$

$P = \dfrac{W}{A_{piston}} = \dfrac{RT}{\hat{V} - b} - \dfrac{\alpha a}{\hat{V}(\hat{V} + b)} \Rightarrow \dfrac{53,900}{\pi d^2 / 4} = \dfrac{RT}{\hat{V} - b} - \dfrac{\alpha a}{\hat{V}(\hat{V} + b)}$ (1)

Substitute expression for $\hat{V}$ in (1) $\Rightarrow$ one equation in one unknown. Solve for d.

5.62 **a.** Using ideal gas assumption:

$P_g = \dfrac{nRT}{V} - P_{atm} = \dfrac{35.3 \text{ lb}_m \text{ O}_2}{} \left|\dfrac{1 \text{ lb - mole}}{32.0 \text{ lb}_m}\right| \dfrac{10.73 \text{ ft}^3 \cdot \text{psia}}{\text{lb - mole} \cdot {}^o\text{R}} \left|\dfrac{509.7^o \text{ R}}{2.5 \text{ ft}^3}\right| - 14.7 \text{ psia} = \underline{\underline{2400 \text{ psig}}}$

b. <u>SRK Equation of state</u>: $P = \dfrac{RT}{(\hat{V} - b)} - \dfrac{\alpha a}{\hat{V}(\hat{V} + b)}$

$\hat{V}_{ideal} = \dfrac{2.5 \text{ ft}^3}{} \left|\dfrac{32.0 \text{ lb}_m \text{ / lb-mole}}{35.3 \text{ lb}_m}\right| = 2.27 \dfrac{\text{ft}^3}{\text{lb-mole}}$

(Use as a first estimate when solving the SRK equation)

For O$_2$: $T_c = 277.9^o \text{R}$, $P_c = 730.4$ psi, $\omega = 0.021$

$a = 5203.8 \dfrac{\text{ft}^6 \cdot \text{psi}}{\text{lb - mole}^2}$, $b = 0.3537 \dfrac{\text{ft}^3}{\text{lb - mole}}$, $m = 0.518$, $\alpha(50^o \text{F}) = 0.667$

$(2400 + 14.7) \text{ psi} = \dfrac{\left(10.73 \frac{\text{ft}^3 \cdot \text{psi}}{\text{lb-mole} \cdot {}^o \text{R}}\right)\left(509.7^o \text{ R}\right)}{\left(\hat{V} - 0.3537\right)\frac{\text{ft}^3}{\text{lb-mole}}} - \dfrac{(0.667)\left(5203.8 \frac{\text{ft}^6 \cdot \text{psi}}{\text{lb-mole}^2}\right)}{\hat{V}\left(\hat{V} + 0.3537\right)\frac{\text{ft}^6}{\text{lb-mole}^2}}$

E - Z Solve $\Rightarrow \hat{V} = 2.139 \text{ ft}^3 \text{ / lb - mole}$

5.62 (cont'd)

$$m_{O_2} = \frac{V}{\hat{V}} MW = \frac{2.5 \text{ ft}^3}{2.139 \text{ ft}^3 / \text{lb - mole}} \left| \frac{32.0 \text{ lb}_m}{\text{lb - mole}} \right. = \underline{\underline{37.4 \text{ lb}_m}}$$

Ideal gas gives a conservative estimate. It calls for charging less O_2 than the tank can safely hold.

c. 1. Pressure gauge is faulty
2. The room temperature is higher than 50°F
3. Crack or weakness in the tank
4. Tank was not completely evacuated before charging and O_2 reacted with something in the tank
5. Faulty scale used to measure O_2
6. The tank was mislabeled and did not contain pure oxygen.

5.63 a. SRK Equation of State: $P = \dfrac{RT}{\left(\hat{V} - b\right)} - \dfrac{\alpha a}{\hat{V}\left(\hat{V} + b\right)}$

$\Rightarrow$ multiply both sides of the equation by $\hat{V}\left(\hat{V} - b\right)\left(\hat{V} + b\right)$:

$$f\left(\hat{V}\right) = P\hat{V}\left(\hat{V} - b\right)\left(\hat{V} + b\right) - RT\hat{V}\left(\hat{V} + b\right) + \alpha a\left(\hat{V} - b\right) = 0$$

$$f\left(\hat{V}\right) = P\hat{V}^3 - RT\hat{V}^2 + \left(\alpha a - b^2 P - bRT\right)\hat{V} - \alpha ab = 0$$

b.

Problem 5.63-SRK Equation Spreadsheet

Species	CO2	
Tc(K)	304.2	R=0.08206 m^3 atm/kmol K
Pc(atm)	72.9	
ω	0.225	
a	3.653924 m^6 atm/kmol^2	
b	0.029668 m^3/kmol	
m	0.826312	

f(V)=B14*E14^3-0.08206*A14*E14^2+(B7*C14-B8^2*B14-B8*0.08206*A14)*E14-C14*B7*B8

T(K)	P(atm)	alpha	V(ideal)	V(SRK)	f(V)
200	6.8	1.3370	2.4135	2.1125	0.0003
250	12.3	1.1604	1.6679	1.4727	0.0001
300	6.8	1.0115	3.6203	3.4972	0.0001
300	21.5	1.0115	1.1450	1.0149	0.0000
300	50.0	1.0115	0.4924	0.3392	0.0001

c. E-Z Solve solves the equation f(V)=0 in one step. Answers identical to V_{SRK} values in part b.

d. REAL T, P, TC, PC, W, R, A, B, M, ALP, Y, VP, F, FP
INTEGER I
CHARACTER A20 GAS
DATA R 10.08206/
READ (5, *) GAS
WRITE (6, *) GAS
10 READ (5, *) TC, PC, W

5.63 (cont'd)

```
      READ (5, *) T, P
      IF (T.LT.Q.) STOP
      R = 0.42747 *R*R/PC*TC*TC
      B = 0.08664 *R*TC/PC
      M = 0.48508 + W = (1.55171 − W*0.15613)

      ALP = (1.+M*(1 − (T / TC)**0.5))**2 .

      VP = R*T / P
      DO 20  I = 7, 15
      V = VP
      F = R * T/(V − B) − ALP * A/V/(V + B) − P
      FP = ALP * A * (2. * V + B)/V/V/(V + B) ** 2 − R * T/(V − B) ** 2.
      VP = V − F/FP
      IF (ABS(VP − V)/VP.LT.0.0001) GOTO 30
20    CONTINUE
      WRITE (6, 2)
2     FORMAT ('DID NOT CONVERGE')
      STOP
30    WRITE (6, 3) T, P, VP
3     FORMAT (F6.1, 'K', 3X, F5.1, 'ATM', 3X, F5.2, 'LITER/MOL')
      GOTO 10
      END
```

```
$ DATA
CARBON            DIOXIDE
  304.2      72.9          0.225
  200.0       6.8
  250.0      12.3
  300.0      21.5
   −1         0.
```

RESULTS
CARBON DIOXIDE

200.0 K	6.8 ATM	2.11 LITER/MOL
250.0 K	12.3 ATM	1.47 LITER/MOL
300.0 K	6.8 ATM	3.50 LITER/MOL
300.0 K	21.5 ATM	1.01 LITER/MOL
300.0 K	50.0 ATM	0.34 LITER/MOL

5.64 a.

N_2: $T_C = 126.2$ K
$P_C = 33.5$ atm
$\Rightarrow$

$T_r = (40 + 273.2)/126.2 = 2.48$

$P_r = \dfrac{40 \text{ MPa}}{33.5 \text{ atm}} \left| \dfrac{10 \text{ atm}}{1.013 \text{ MPa}} \right. = 11.78$

Fig. 5.4-4 $\Rightarrow$ $\underline{z = 1.2}$

b.

He: $T_C = 5.26$ K
$P_C = 2.26$ atm
$\Rightarrow$

$T_r = (−200 + 273.2)/(5.26 + 8) = 5.52$

$P_r = 350/(2.26 + 8) = 34.11$

Fig. 5.4-4 $\Rightarrow$ $\underline{z = 1.6}$

$\uparrow$
Newton's correction

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

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

b. $\left. \begin{array}{l} T_r = 465/310 = 1.5 \\ P_r = 9.0/4.5 = 2.0 \end{array} \right\} \overset{Fig.\ 5.4\text{-}3}{\Rightarrow} z = 0.84$

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

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

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

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

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

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

5.67 $\underline{O_2}$: $\begin{array}{ll} T_C = 154.4\ K & T_{r_1} = 298/154.4 = 1.93 \\ P_C = 49.7\ atm & P_{r_1} = 1/49.7 = 0.02 \end{array} \left. \rule{0pt}{18pt} \right\} z_1 = 1.00$ (Fig. 5.4-2)

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

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

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

5.68 $\underline{O_2}$: $\begin{array}{ll} T_C = 154.4\ K & T_r = (27+273.2)/154.4 = 1.94 \\ P_C = 49.7\ atm & P_{r_1} = 175/49.7 = 3.52 \Rightarrow z_1 = 0.95 \qquad \text{(Fig. 5.3-2)} \\ & P_{r_2} = 1.1/49.7 = 0.02 \Rightarrow z_2 = 1.00 \end{array}$

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

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

$P = \dfrac{RT}{\hat{V}} = \dfrac{82.06 \text{ mL} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \bigg| \dfrac{1000 \text{ K}}{440.1 \text{ mL / mol}} = \underline{\underline{186 \text{ atm}}}$

b.   For CO_2: $T_c = 304.2$ K, $P_c = 72.9$ atm

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

$V_r^{ideal} = \dfrac{\hat{V} P_c}{R T_c} = \dfrac{440.1 \text{ mL}}{\text{mol}} \bigg| \dfrac{72.9 \text{ atm}}{304.2 \text{ K}} \bigg| \dfrac{\text{mol} \cdot \text{K}}{82.06 \text{ mL} \cdot \text{atm}} = 1.28$

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

$P = \dfrac{zRT}{\hat{V}} = \dfrac{1.02}{} \bigg| \dfrac{82.06 \text{ mL} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \bigg| \dfrac{\text{mol}}{440.1 \text{ mL}} \bigg| \dfrac{1000 \text{ K}}{} = \underline{\underline{190 \text{ atm}}}$

c. $a = 3.654 \times 10^6 \text{ mL}^2 \cdot \text{atm / mol}^2$, $b = 29.67 \text{ mL / mol}$, $m = 0.8263$, $\alpha(1000K) = 0.1077$

$P = \dfrac{\left(82.06 \frac{\text{mL} \cdot \text{atm}}{\text{mol} \cdot \text{K}}\right)(1000 \text{ K})}{(440.1 - 29.67) \frac{\text{mL}}{\text{mol}}} - \dfrac{(0.1077)\left(3.654 \times 10^6 \frac{\text{mL}^2 \cdot \text{atm}}{\text{mol}^2}\right)}{440.1(440.1 + 29.67) \frac{\text{mL}^2}{\text{mol}^2}} = \underline{\underline{198 \text{ atm}}}$

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 $x_{O_2} = 10 \times 10^{-6}$. Since the O_2 is so dilute at this condition, the properties of the gas will be that of N_2.

$T_c = 126.2$ K, $P_c = 33.5$ atm, $T_r = 2.36$

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

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

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

$\hat{V} = \dfrac{5000 \text{ L}}{4.29 \times 10^6 \text{ mol}} = 1.16 \times 10^{-3} \text{ L / mol}$

$\hat{V}_r^{ideal} = \dfrac{\hat{V} P_c}{R T_c} = \dfrac{1.16 \times 10^{-3} \text{ L}}{\text{mol}} \bigg| \dfrac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \bigg| \dfrac{33.5 \text{ atm}}{126.2 \text{ K}} = 3.8 \times 10^{-3}$

$\Rightarrow$ not found on compressibility charts

Ideal gas: $P = \dfrac{RT}{\hat{V}} = \dfrac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \bigg| \dfrac{298.2 \text{ K}}{1.16 \times 10^{-3} \text{ L / mol}} = \underline{\underline{2.1 \times 10^4 \text{ atm}}}$

The pressure required will be higher than 2.1×10^4 atm if $z \geq 1$, which from Fig. 5.3 - 3 is very likely.

$n_{added} = 4.29 \times 10^6 - 204.3 \cong \left(4.29 \times 10^6 \text{ mol } N_2\right)(0.028 \text{ kg } N_2 \text{ / mol}) = \underline{\underline{1.20 \times 10^5 \text{ kg } N_2}}$
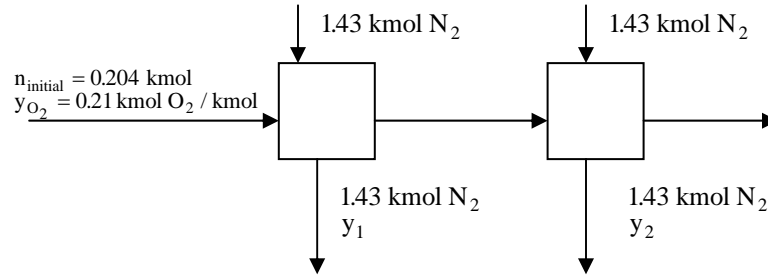
5.70 (cont'd)

    c.

$n_{initial} = 0.204$ kmol
$y_{O_2} = 0.21$ kmol O_2 / kmol

1.43 kmol N_2 1.43 kmol N_2

1.43 kmol N_2 y_1 1.43 kmol N_2 y_2

N_2 at 700 kPa gauge $= 7.91$ atm abs. $\Rightarrow P_r = 0.236$, $T_r = 2.36 \overset{\text{Fig 5.4-2}}{=====\!=\!=\!=>} z = 0.99$

$$n_2 = \frac{P_2 V}{zRT} = \frac{7.91 \text{ atm}}{0.99} \left| \frac{5000 \text{ L}}{0.08206 \frac{\text{L·atm}}{\text{mol·K}}} \right| \frac{}{298.2 \text{ K}} = 1.633 \text{ kmol}$$

$$y_1 = \frac{y_{init} n_{init}}{1.634} = \frac{(0.21)0.204}{1.634} = 0.026$$

$$y_2 = \frac{y_1 n_{init}}{1.634} = y_{init}\left(\frac{n_{init}}{1.634}\right)^2 = 0.0033$$

$$y_n = y_{init}\left(\frac{n_{init}}{1.634}\right)^n \Rightarrow n = \frac{\ln\left(\dfrac{y_n}{y_{init}}\right)}{\ln\left(\dfrac{n_{init}}{1.634}\right)} = \underline{\underline{4.8 \Rightarrow \text{Need at least 5 stages}}}$$

Total $N_2 = 5(1.43 \text{ kmol } N_2)(28.0 \text{ kg / kmol}) = \underline{\underline{200 \text{ kg } N_2}}$

    d. Multiple cycles use less N_2 and require lower operating pressures. The disadvantage is that it takes longer.

5.71   **a.** $\dot{m} = MW\dfrac{P\dot{V}}{RT} \Rightarrow \text{Cost } (\$/h) = \dot{m}S = MW\dfrac{SP\dot{V}}{RT} = \left(\dfrac{44.09 \text{ lb}_m / \text{lb - mol}}{0.7302 \frac{\text{ft}^3 \cdot \text{atm}}{\text{lb-mol·°R}}}\right)\dfrac{SP\dot{V}}{T} = \underline{\underline{60.4\dfrac{SP\dot{V}}{T}}}$

    b. $\begin{matrix} T_c = 369.9 \text{ K} = 665.8°\text{R} \Rightarrow T_r = 0.85 \\ P_c = 42.0 \text{ atm} \quad\quad\quad\quad \Rightarrow P_r = 0.16 \end{matrix} \Bigg\} \overset{\text{Fig. 5.4-2}}{\Rightarrow} z = 0.91$

         $\dot{m} = 60.4\dfrac{P\dot{V}}{zT} = \dfrac{\dot{m}_{ideal}}{z} = 1.10\dot{m}_{ideal}$

         $\Rightarrow \underline{\underline{\text{Delivering 10\% more than they are charging for (undercharging their customer)}}}$

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

<u>After heater</u>: $T_r = \dfrac{609.7^\circ \text{R}}{227.16^\circ \text{R}} = 2.68$

$\left. \phantom{\begin{array}{c} a \\ b \end{array}} \right\} \Rightarrow z = 1.02$

$P_r = \dfrac{600 \text{ psia}}{33.5 \text{ atm}} \left| \dfrac{1 \text{ atm}}{14.7 \text{ psia}} \right. = 1.2$

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

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

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

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

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

<u>Initially</u>: $T_{r1} = \dfrac{300 \text{ K}}{133.0 \text{ K}} = 2.26$

$\left. \phantom{\begin{array}{c} a \\ b \end{array}} \right\} \begin{array}{l} \text{Fig. 5.4-3} \\ \Rightarrow \quad z = 1.02 \end{array}$

$P_{r1} = \dfrac{2514.7 \text{ psia}}{34.5 \text{ atm}} \left| \dfrac{1 \text{ atm}}{14.7 \text{ psia}} \right. = 5.0$

$n_1 = \dfrac{2514.7 \text{ psia}}{1.02} \left| \dfrac{150 \text{ L}}{300 \text{ K}} \right| \dfrac{1 \text{ atm}}{14.7 \text{ psia}} \left| \dfrac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \right. = 1022 \text{ mol}$

<u>After 60h</u>: $T_{r1} = \dfrac{300 \text{ K}}{133.0 \text{ K}} = 2.26$

$\left. \phantom{\begin{array}{c} a \\ b \end{array}} \right\} \begin{array}{l} \text{Fig. 5.4-3} \\ \Rightarrow \quad z = 1.02 \end{array}$

$P_{r1} = \dfrac{2258.7 \text{ psia}}{34.5 \text{ atm}} \left| \dfrac{1 \text{ atm}}{14.7 \text{ psia}} \right. = 4.5$

$n_2 = \dfrac{2259.7 \text{ psia}}{1.02} \left| \dfrac{150 \text{ L}}{300 \text{ K}} \right| \dfrac{1 \text{ atm}}{14.7 \text{ psia}} \left| \dfrac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \right. = 918 \text{ mol}$

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

b. $n_2 = y_2 n_{\text{air}} = y_2 \dfrac{PV}{RT} = \dfrac{200 \times 10^{-6} \text{ mol CO}}{\text{mol air}} \left| \dfrac{1 \text{ atm}}{0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}} \right| \dfrac{30.7 \text{ m}^3}{300 \text{ K}} \left| \dfrac{1000 \text{ L}}{\text{m}^3} \right. = 0.25 \text{ mol}$

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

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

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.

5.74 $\underline{CH_4}$: $T_c = 190.7$ K, $P_c = 45.8$ atm

$\underline{C_2H_6}$: $T_c = 305.4$ K, $P_c = 48.2$ atm

$\underline{C_2H_4}$: $T_c = 283.1$ K, $P_c = 50.5$ atm

Pseudocritical temperature: $T_c' = (0.20)(190.7) + (0.30)(305.4) + (0.50)(283.1) = 271.3$ K

Pseudocritical pressure: $P_c' = (0.20)(45.8) + (0.30)(48.2) + (0.50)(50.5) = 48.9$ atm

$$\left.\begin{array}{l}
\underline{\text{Reduced temperature:}} \quad\quad T_r = \dfrac{(90+273.2)\text{K}}{271.3 \text{ K}} = 1.34 \\[4mm]
\underline{\text{Reduced pressure:}} \quad\quad P_r = \dfrac{200 \text{ bars}}{48.9 \text{ atm}}\left|\dfrac{1 \text{ atm}}{1.01325 \text{ bars}}\right. = 4.04
\end{array}\right\} \begin{array}{l}\text{Figure 5.4-3} \\ \Rightarrow \quad z = 0.71\end{array}$$

Mean molecular weight of mixture:

$$\overline{M} = (0.20)M_{CH_4} + (0.30)M_{C_2H_6} + (0.50)M_{C_2H_4}$$
$$= (0.20)(16.04) + (0.30)(30.07) + (0.50)(28.05)$$
$$= 26.25 \text{ kg/kmol}$$

$$V = \frac{znRT}{P} = \frac{0.71}{}\left|\frac{10 \text{ kg}}{}\right.\left|\frac{1 \text{ kmol}}{26.25 \text{ kg}}\right.\left|\frac{0.08314 \text{ m}^3 \cdot \text{bar}}{\text{kmol} \cdot \text{K}}\right.\left|\frac{(90+273) \text{ K}}{200 \text{ bars}}\right. = \underline{\underline{0.041 \text{ m}^3}}(41 \text{ L})$$

5.75 $\underline{N_2}$: $T_c = 126.2$ K, $P_C = 33.5$ atm $\left.\right\}$ $T_c' = 0.10(309.5) + 0.90(126.2) = 144.5$ K

$\underline{N_2O}$: $T_c = 309.5$ K, $P_C = 71.7$ atm $\left.\right\}$ $P_c' = 0.10(71.7) + 0.90(33.5) = 37.3$ atm

$\overline{M} = 0.10(44.02) + 0.90(28.02) = 29.62$

$n = 5.0 \text{ kg}(1 \text{ kmol}/29.62 \text{ kg}) = 0.169 \text{ kmol} = 169 \text{ mol}$

a. $T_r = (24 + 273.2)/144.5 = 2.06$

$$\left.\hat{V}_r = \frac{30 \text{ L}}{169 \text{ mol}}\left|\frac{37.3 \text{ atm}}{144.5 \text{ K}}\right.\left|\frac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}}\right. = 0.56\right\} \Rightarrow z = 0.97 (\text{Fig. } 5.4\text{-}3)$$

$$P = \frac{0.97}{}\left|\frac{169 \text{ mol}}{30 \text{ L}}\right.\left|\frac{297.2 \text{ K}}{}\right.\left|\frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}\right. = 133 \text{ atm} \Rightarrow \underline{\underline{132 \text{ atm gauge}}}$$

b. $\left.\begin{array}{l} P_r = 273/37.3 = 7.32 \\ \hat{V}_r = 0.56 \text{ (from a.)} \end{array}\right\} \Rightarrow z = 1.14 \text{ (Fig. } 5.4\text{-}3)$

$$T = \frac{273 \text{ atm}}{1.14}\left|\frac{30 \text{ L}}{169 \text{ mol}}\right.\left|\frac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}}\right. = 518 \text{ K} \Rightarrow \underline{\underline{245°\text{C}}}$$

5.76 CO: $T_c = 133.0$ K, $P_c = 34.5$ atm $\left.\right\}$ $T_c' = 0.60(133.0) + 0.40(33 + 8) = 96.2$ K
  H$_2$: $T_c = 33$ K, $P_c = 12.8$ atm $\left.\right\}$ $P_c' = 0.60(34.5) + 0.40(12.8 + 8) = 29.0$ atm

Turbine inlet: $T_r = (150 + 273.2)/96.2 = 4.4$ $\left.\right\}$

$$P_r = \frac{2000 \text{ psi}}{29.0 \text{ atm}} \left| \frac{1 \text{ atm}}{14.7 \text{ psi}} = 4.69 \right\} \xrightarrow{\text{Fig. 5.4-1}} z \approx 1.01$$

Turbine exit: $T_r = 373.2/96.2 = 3.88$ $\left.\right\}$
      $P_r = 1/29.0 = 0.03$ $\left.\right\}$ $\Rightarrow z = 1.0$

$$\frac{P_{in}\dot{V}_{in}}{P_{out}\dot{V}_{out}} = \frac{z_{in}\,nRT_{in}}{z_{out}\,n\,RT_{out}} \Rightarrow \dot{V}_{in} = \dot{V}_{out} \times \frac{P_{out}}{P_{in}} \frac{z_{in}}{z_{out}} \frac{T_{in}}{T_{out}} = 15{,}000\frac{\text{ft}^3}{\text{min}} \left| \frac{14.7 \text{ psia}}{2000 \text{ psia}} \right| \frac{1.01}{1.00} \left| \frac{423.2\text{K}}{373.2} \right.$$

$$= \underline{126 \text{ ft}^3 / \text{min}}$$

If the ideal gas equation of state were used, the factor 1.01 would instead be 1.00

  $\Rightarrow$ $\underline{-1\% \text{ error}}$

5.77 CO: $T_c = 133.0$ K, $P_c = 34.5$ atm $\left.\right\}$ $T_c' = 0.97(133.0) + 0.03(304.2) = 138.1$ K
  CO$_2$: $T_c = 304.2$ K, $P_c = 72.9$ atm $\left.\right\}$ $P_c' = 0.97(34.5) + 0.03(72.9) = 35.7$ atm $= 524.8$ psi

Initial: $T_r = 303.2/138.1 = 2.2$ $\left.\right\}$ $\xrightarrow{\text{Fig. 5.4-3}} z_1 = 0.97$
      $P_r = 2014.7/524.8 = 3.8$ $\left.\right\}$

Final: $P_r = 1889.7/524.8 = 3.6 \Rightarrow z_1 = 0.97$

Total moles leaked:

$$n_1 - n_2 = \left(\frac{P_1}{z_1} - \frac{P_2}{z_2}\right)\frac{V}{RT} = \frac{(2000 - 1875)\text{psi}}{0.97} \left| \frac{30.0 \text{ L}}{303 \text{ K}} \right| \frac{1 \text{ atm}}{14.7 \text{ psi}} \left| \frac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \right.$$
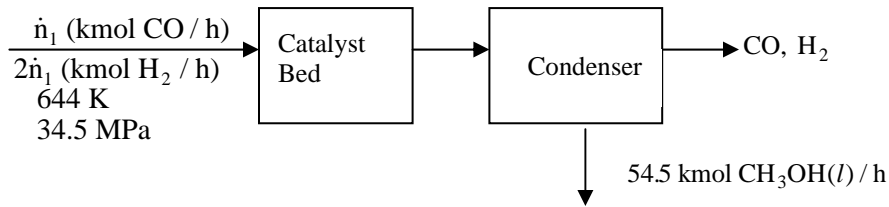
    $= 10.6$ mol leaked

Moles CO leaked: $0.97(10.6) = 10.3$ mol CO

Total moles in room: $\dfrac{24.2 \text{ m}^3}{} \left| \dfrac{10^3 \text{ L}}{1 \text{ m}^3} \right| \dfrac{273 \text{ K}}{303 \text{ K}} \left| \dfrac{1 \text{ mol}}{22.4 \text{ L(STP)}} = 973.4 \right.$ mol

Mole% CO in room $= \dfrac{10.3 \text{ mol CO}}{973.4 \text{ mol}} \times 100\% = \underline{1.0\% \text{ CO}}$

5.78 <u>Basis: 54.5 kmol CH_3OH/h</u> $CO + 2H_2 \rightarrow CH_3OH$

$\dot{n}_1$ (kmol CO / h)
$2\dot{n}_1$ (kmol H_2 / h)
644 K
34.5 MPa

→ Catalyst Bed → Condenser → CO, H_2

54.5 kmol $CH_3OH(l)/h$

a. $\dot{n}_1 = \dfrac{54.5 \text{ kmol } CH_3OH}{h} \left| \dfrac{1 \text{ kmol CO react}}{1 \text{ kmol } CH_3OH} \right| \dfrac{1 \text{ kmol CO fed}}{0.25 \text{ kmol CO react}} = 218 \text{ kmol/h CO}$

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

<u>CO</u>: $T_c = 133.0 \text{ K}$ $P_c = 34.5 \text{ atm}$

<u>H_2</u> : $T_c = 33 \text{ K}$ $P_c = 12.8 \text{ atm}$

$\Downarrow$ Newton's corrections

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

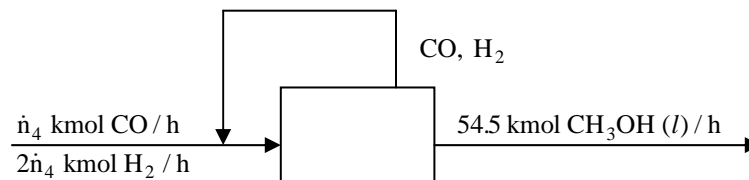$P_c' = \dfrac{1}{3}(34.5) + \dfrac{2}{3}(12.8 + 8) = 25.4 \text{ atm}$

$T_r = 644/71.7 = 8.98$

$P_r = \dfrac{34.5 \text{ MPa}}{24.5 \text{ atm}} \left| \dfrac{10 \text{ atm}}{1.013 \text{ MPa}} \right. = 13.45 \left.\begin{array}{c}\\\\\end{array}\right\} \xrightarrow{\text{Fig. 5.4-4}} z_1 = 1.18$

$\dot{V}_{feed} = \dfrac{1.18}{} \left| \dfrac{654 \text{ kmol}}{h} \right| \dfrac{644 \text{ K}}{34.5 \text{ MPa}} \left| \dfrac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \dfrac{1.013 \text{ MPa}}{10 \text{ atm}} = \underline{\underline{120 \text{ m}^3/h}}$

$V_{cat} = \dfrac{120 \text{ m}^3/h}{} \left| \dfrac{1 \text{ m}^3 \text{ cat}}{25,000 \text{ m}^3 / h} \right. = \underline{\underline{0.0048 \text{ m}^3 \text{ catalyst (4.8 L)}}}$

b.

CO, H_2

$\dot{n}_4$ kmol CO / h
$2\dot{n}_4$ kmol H_2 / h

54.5 kmol CH_3OH (l) / h

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

<u>Fresh feed:</u>   54.5 kmol CO/h
$\dfrac{109.0 \text{ kmol } H_2/h}{163.5 \text{ kmol feed gas/h}}$

$\dot{V}_{feed} = \dfrac{1.18}{} \left| \dfrac{163.5 \text{ kmol}}{h} \right| \dfrac{644 \text{ K}}{34.5 \text{ MPa}} \left| \dfrac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \dfrac{1.013 \text{ MPa}}{10 \text{ atm}} = \underline{\underline{29.9 \text{ m}^3/h}}$

5-51

5.79 $\underline{H_2}$: $T_c = (33.3 + 8)\ K = 41.3\ K$ $\qquad$ $\underline{1\text{-butene}}$: $T_c = 419.6\ K$

$\qquad\qquad$ $P_c = (12.8 + 8)\ atm = 20.8\ atm$ $\qquad\qquad\qquad$ $P_c = 39.7\ atm$

$T_c' = 0.15(41.3\ K) + 0.85(419.6\ K) = 362.8\ K$ $\qquad$ $T_r' = 0.89$ $\left.\begin{array}{l}\\ \\\end{array}\right\}$ $\overset{\text{Fig. 5.4-2}}{\Rightarrow}$ $z = 0.86$

$P_c' = 0.15(20.8\ atm) + 0.85(39.7\ atm) = 36.9\ atm$ $\qquad$ $P_r' = 0.27$

$$\dot{V} = \frac{z\dot{n}RT}{P} = \frac{0.86 \left| 35\ kmol \right| 0.08206\ m^3 \cdot atm \left| 323\ K \right| \quad 1\ h}{\left| \quad h \quad \right| \qquad kmol \cdot K \left| 10\ atm \right| 60\ min} = 1.33\ m^3\ /\ min$$

$$\dot{V}\left(\frac{m^3}{min}\right) = u\left(\frac{m}{min}\right)A\left(m^2\right) = u \times \frac{\pi d^2}{4} \Rightarrow d = \sqrt{\frac{4\dot{V}}{\pi u}} = \sqrt{\frac{4\left(1.33\ m^3\ /\ min\right)}{\pi\left(150\ m\ /\ min\right)}}\left(\frac{100\ cm}{m}\right) = \underline{\underline{10.6\ cm}}$$

5.80 $\underline{CH_4}$: $\quad T_c = 190.7\ K \quad P_c = 45.8\ atm$

$\underline{C_2H_4}$: $\quad T_c = 283.1\ K \quad P_c = 50.5\ atm$

$\underline{C_2H_6}$: $\quad T_c = 305.4\ K \quad P_c = 48.2\ atm$

$T_c' = 0.15(190.7\ K) + 0.60(283.1\ K) + 0.25(305.4\ K) = 274.8\ K \overset{T=90^o C}{=\!=\!=\!=\!\Rightarrow} \quad T_r' = 1.32$ $\left.\begin{array}{l}\\ \\\end{array}\right\}$

$P_c' = 0.15(45.8\ atm) + 0.60(50.5\ atm) + 0.25(48.2\ atm) = 49.2\ atm \overset{P=175\ bar}{=\!=\!=\!=\!=\!\Rightarrow} P_r' = 3.5$

$\xrightarrow{\quad\text{Fig. 5.4-3}\quad} z = 0.67$

$$\dot{V}\left(\frac{m^3}{s}\right) = u\left(\frac{m}{s}\right)A\left(m^2\right) = \left(10\ \frac{m}{s}\right)\left(60\ \frac{s}{min}\right)\frac{\pi}{4}(0.02\ m)^2 = 0.188\ \frac{m^3}{min}$$

$$\dot{n} = \frac{P\dot{V}}{zRT} = \frac{175\ bar \left| \quad 1\ atm \quad \right| \qquad kmol \cdot K \left| 0.188\ m^3\ /\ min \right.}{0.67 \left| 1.013\ bar \right| .08206\ m^3 \cdot atm \left| \qquad 363\ K \right.} = \underline{\underline{1.63\ kmol\ /\ min}}$$

5.81 $\underline{N_2}$: $\qquad T_c = 126.2\ K = 227.16^o R \quad P_c = 33.5\ atm$

$\underline{\text{acetonitrile}}$: $\quad T_c = 548\ K = 986.4^o R \qquad P_c = 47.7\ atm$

$\underline{\text{Tank 1 (acetonitrile)}}$: $T_1 = 550^o F$, $P_1 = 4500\ psia \Rightarrow T_{r1} = 1.02 \quad P_{r1} = 6.4 \overset{\text{Fig. 5.4-3}}{\Rightarrow} z_1 = 0.80$

$$\Rightarrow \quad \dot{n}_1 = \frac{P_1 V_1}{z_1 R T_1} = \frac{306\ atm \left| 0.200\ ft^3 \right| \qquad lb\text{-}mole \cdot^o R}{0.80 \left| 1009.7^o R \right| 0.7302\ ft^3 \cdot atm} = 0.104\ lb\text{-}mole$$

$\underline{\text{Tank 2 (}N_2\text{)}}$: $T_2 = 550^o F$, $P_2 = 10\ atm \Rightarrow T_{r2} = 4.4$, $P_{r2} = 6.4 \overset{\text{Fig. 5.4-3}}{\Rightarrow} z_2 = 1.00$

$$\Rightarrow \quad \dot{n}_2 = \frac{P_2 V_2}{z_2 R T_2} = \frac{10.0\ atm \left| 2.00\ ft^3 \right| \qquad lb\text{-}mole \cdot^o R}{1.00 \left| 1009.7^o R \right| .7302\ ft^3 \cdot atm} = 0.027\ lb\text{-}mole$$

5.81 (cont'd)
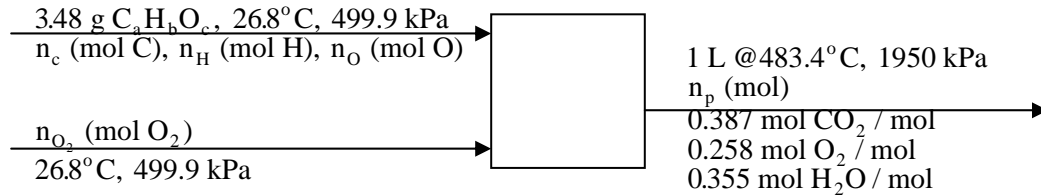
Final: $T_c' = \left(\dfrac{0.104}{0.131}\right)986.4^\circ R + \left(\dfrac{0.027}{0.131}\right)227.16^\circ R = 830^\circ R \xrightarrow{\;T=550^\circ F\;} \quad T_r' = 1.22$

$P_c' = \left(\dfrac{0.104}{0.131}\right)47.7\text{ atm} + \left(\dfrac{0.027}{0.131}\right)33.5\text{ atm} = 44.8\text{ atm}$

$\left(\hat{V}_r\right)_{ideal} = \dfrac{\hat{V}P_c'}{RT_c'} = \dfrac{2.2\text{ ft}^3}{0.131\text{ lb - mole}}\left|\dfrac{44.8\text{ atm}}{830^\circ R}\right|\dfrac{\text{lb - mole}\cdot^\circ R}{0.7302\text{ ft}^3\cdot\text{atm}} = 1.24 \quad\overset{\text{Fig. 5.4-2}}{\Rightarrow}\quad z = 0.85$

$P = \dfrac{znRT}{V} = \dfrac{0.85}{}\left|\dfrac{0.131\text{ lb - mole}}{}\right|\dfrac{.7302\text{ ft}^3\cdot\text{atm}}{\text{lb - mole}\cdot^\circ R}\left|\dfrac{1009.7^\circ R}{2.2\text{ ft}^3}\right| = \underline{\underline{37.3\text{ atm}}}$

5.82

3.48 g $C_aH_bO_c$, 26.8°C, 499.9 kPa
n_c (mol C), n_H (mol H), n_O (mol O)

n_{O_2} (mol O_2)
26.8°C, 499.9 kPa

1 L @483.4°C, 1950 kPa
n_p (mol)
0.387 mol CO_2 / mol
0.258 mol O_2 / mol
0.355 mol H_2O / mol

a. Volume of sample: $3.42\text{ g}\left(1\text{ cm}^3/1.59\text{ g}\right) = 2.15\text{ cm}^3$

O_2 in Charge:

$$n_{O_2} = \dfrac{\left[1.000\text{ L} - 2.15\text{ cm}^3\left(10^{-3}\text{ L/km}^3\right)\right]}{0.08206\;\dfrac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\dfrac{499.9\text{ kPa}}{300\text{ K}}\right|\dfrac{1\text{ atm}}{101.3\text{ kPa}} = 0.200\text{ mol }O_2$$

Product

$$n_p = \dfrac{1.000\text{ L}}{0.08206\;\dfrac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\dfrac{1950\text{ kPa}}{756.6\text{ K}}\right|\dfrac{1\text{ atm}}{101.3\text{ kPa}} = 0.310\text{ mol product}$$

Balances:

$\underline{O}:\; 2(0.200) + n_O = 0.310\left[2(0.387) + 2(0.258) + 0.355\right] \Rightarrow n_O = 0.110\text{ mol O in sample}$

$\underline{C}:\; n_C = 0.387(0.310) = 0.120\text{ mol C in sample}$

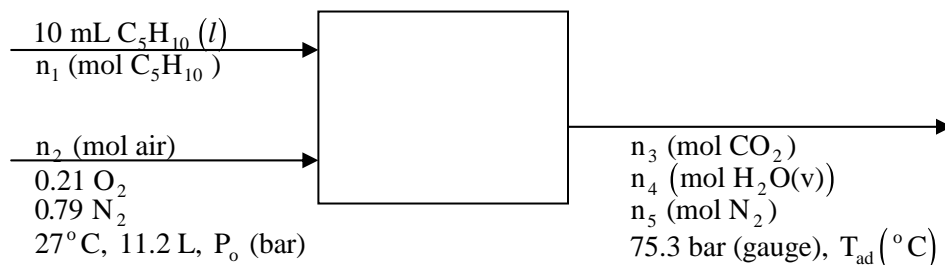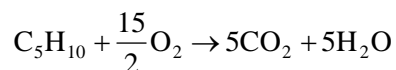$\underline{H}:\; n_H = 2(0.355)(0.310) = 0.220\text{ mol H in sample}$

Assume $c = 1 \Rightarrow a = 0.120/0.110 = 1.1 \quad b = 0.220/0.110 = 2$
Since a, b, and c must be integers, possible solutions are $(a,b,c) = (11,20,10), (22,40,20)$, etc.

b. $MW = 12.01a + 1.01b + 16.0c = 12.01(1.1c) + 1.01(2c) + 16.0c = 31.23c$

$300 < MW < 350 \Rightarrow c = 10 \Rightarrow \underline{\underline{C_{11}H_{20}O_{10}}}$

5.83 Basis: 10 mL $C_5H_{10}(l)$ charged to reactor $C_5H_{10} + \dfrac{15}{2}O_2 \rightarrow 5CO_2 + 5H_2O$

$$
\begin{array}{ccc}
\underline{10 \text{ mL } C_5H_{10}\ (l)} & & \\
n_1 \text{ (mol } C_5H_{10}\text{)} & & \\
& & n_3 \text{ (mol } CO_2\text{)} \\
\underline{n_2 \text{ (mol air)}} & & n_4 \left(\text{mol } H_2O(v)\right) \\
0.21\ O_2 & & n_5 \text{ (mol } N_2\text{)} \\
0.79\ N_2 & & 75.3 \text{ bar (gauge)},\ T_{ad}\left(^\circ C\right) \\
27^\circ C,\ 11.2 \text{ L},\ P_o \text{ (bar)} & &
\end{array}
$$

a. $n_1 = \dfrac{10.0 \text{ mL } C_5H_{10}(l)}{} \bigg| \dfrac{0.745 \text{ g}}{\text{mL}} \bigg| \dfrac{1 \text{ mol}}{70.13 \text{ g}} = 0.1062 \text{ mol } C_5H_{10}$

Stoichiometric air: $n_2 = \dfrac{0.1062 \text{ mol } C_5H_{10}}{} \bigg| \dfrac{7.5 \text{ mol } O_2}{1 \text{ mol } C_2H_{10}} \bigg| \dfrac{1 \text{ mol air}}{0.21 \text{ mol } O_2} = 3.79 \text{ mol air}$

$P_o = \dfrac{nRT}{V} = \dfrac{3.79 \text{ mol}}{11.2 \text{ L}} \bigg| \dfrac{0.08314 \text{ L} \cdot \text{bar}}{\text{mol} \cdot \text{K}} \bigg| \dfrac{300\text{K}}{} = 8.44 \text{ bars}$

(We neglect the C_5H_{10} that may be present in the gas phase due to evaporation)

Initial gauge pressure $= 8.44 \text{ bar} - 1 \text{ bar} = \underline{7.44 \text{ bar}}$

b.

$n_3 = \dfrac{0.1062 \text{ mol } C_5H_{10}}{} \bigg| \dfrac{5 \text{ mol } CO_2}{1 \text{ mol } C_5H_{10}} = 0.531 \text{ mol } CO_2$

$n_4 = \dfrac{0.531 \text{ mol } CO_2}{} \bigg| \dfrac{1 \text{ mol } H_2O}{1 \text{ mol } CO_2} = 0.531 \text{ mol } H_2O \quad \Big\} \Rightarrow 4.052 \text{ mol product gas}$

$n_5 = 0.79(3.79) = 2.99 \text{ mol } N_2$

$\underline{CO_2}$: $y_3 = 0.531/4.052 = 0.131 \text{ mol } CO_2 / \text{mol},\ T_c = 304.2 \text{ K}\quad P_c = 72.9 \text{ atm}$

$\underline{H_2O}$: $y_4 = 0.531/4.052 = 0.131 \text{ mol } H_2O / \text{mol},\quad T_c = 647.4 \text{ K}\quad P_c = 218.3 \text{ atm}$

$\underline{N_2}$: $y_5 = 2.99/4.052 = 0.738 \text{ mol } N_2 / \text{mol},\quad\quad T_c = 126.2 \text{ K}\quad P_c = 33.5 \text{ atm}$

$T_c' = 0.131(304.2 \text{ K}) + 0.131(647.4 \text{ K}) + 0.738(126.2 \text{ K}) = 217.8 \text{ K}$

$P_c' = 0.131(72.9 \text{ atm}) + 0.131(218.3 \text{ atm}) + 0.738(33.5 \text{ atm}) = 62.9 \text{ atm} \Rightarrow P_r' = 1.21$

$\hat{V}_r^{\text{ideal}} = \dfrac{\hat{V}P_c'}{RT_c'} = \dfrac{11.2 \text{ L}}{4.052 \text{ mol}} \bigg| \dfrac{62.9 \text{ atm}}{217.8 \text{ K}} \bigg| \dfrac{\text{mol} \cdot \text{K}}{.08206 \text{ L} \cdot \text{atm}} = 9.7 \Rightarrow z \approx 1.04 \text{ (Fig. 5.4 - 3)}$

$T = \dfrac{PV}{znR} = \dfrac{(75.3+1)\text{bars}}{1.04} \bigg| \dfrac{11.2 \text{ L}}{4.052 \text{ mol}} \bigg| \dfrac{\text{mol} \cdot \text{K}}{0.08314 \text{ L} \cdot \text{bar}} = 2439 \text{ K} - 273 = \underline{\underline{2166^\circ C}}$

CHAPTER SIX

6.1   **a.**   <u>AB:</u> Heat liquid - -$V \approx$ constant

         <u>BC:</u> Evaporate liquid - -V increases, system remains at point on vapor - liquid equilibrium

               curve as long as some liquid is present. $T = 100°\,C$.

         <u>CD:</u> Heat vapor - -T increases, V increases .

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

    <u>Point C</u>: H_2O (v, 100°C)

$$n = \frac{10 \text{ mL} \,\Big|\, 1.00 \text{ g} \,\Big|\, 1 \text{ mol}}{\phantom{10 \text{ mL} \,\Big|}\; \text{mL} \,\Big|\, 18.02 \text{ g}} = 0.555 \text{ mol}$$

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

6.2   **a.** $P_{\text{final}} = \underline{\underline{243 \text{ mm Hg}}}$. Since liquid is still present, the pressure and temperature must lie on the

    vapor-liquid equilibrium curve, where by definition the pressure is the vapor pressure of the
species at the system temperature.

b.   Assuming ideal gas behavior for the vapor,

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

$$m(\text{liquid}) = \frac{10 \text{ mL} \,\Big|\, 1.489 \text{ g}}{\phantom{10 \text{ mL} \,\Big|}\; \text{mL}} = 14.89 \text{ g}$$

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

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

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

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

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

6.3 (cont'd)

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

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

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

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

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

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

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

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

6.5 $\quad$ **In p* = A/T(K) + B**

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

y = -7075.9x + 21.666
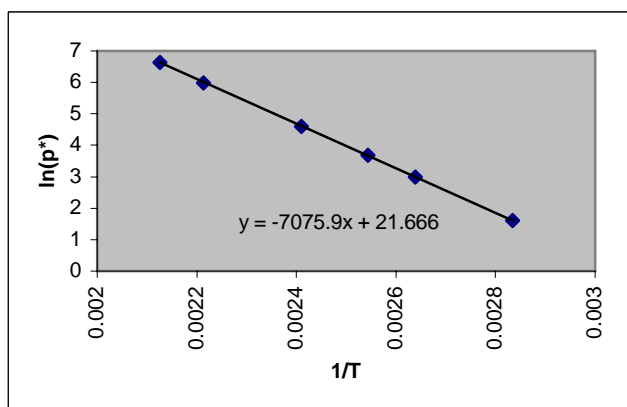
6.6 a.

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

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

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

$$\Delta \hat{H}_v = \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \left| \frac{5143.8 \text{ K}}{} \right| \frac{1 \text{ kJ}}{10^3 \text{ J}} = \underline{\underline{42.8 \text{ kJ/mol}}}$$

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

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

Perry's Handbook, Table 3-8:

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

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

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

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

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

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

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

$a = \dfrac{\ln(p_2*/p_1*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \dfrac{\ln(200/50)}{\frac{1}{45+273.2} - \frac{1}{25+273.2}} = -6577.1$

$b = \ln p_1* - \dfrac{a}{T_1} = \ln(50) + \dfrac{6577.1}{25 + 273.2} = 25.97$

$\left. \right\} \Rightarrow$

$\ln[p*(35°C)] = -\dfrac{6577.1}{35 + 273.2} + 25.97 = 4.630$

$p*(35°C) = e^{4.630} = 102.5 \text{ mm Hg}$

$\underline{\text{Moles in gas phase: }} n = \dfrac{150 \text{ mL}}{} \left| \dfrac{273 \text{ K}}{(35 + 273.2) \text{ K}} \right| \dfrac{102.5 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \dfrac{1 \text{ L}}{10^3 \text{ m}L} \right| \dfrac{1 \text{ mol}}{22.4 \text{ L(STP)}}$

$= \underline{\underline{8.0 \times 10^{-4} \text{ mol}}}$

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

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

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

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

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

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

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

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

6.11 a. At the dew point,

$$p^*(H_2O) = p(H_2O) = 500 \times 0.1 = 50 \text{ mm Hg} \Rightarrow \underline{T = 38.1° \text{C}} \text{ from Table B.3.}$$

  b. $V_{H_2O} = \dfrac{30.0 \text{ L}}{} \left| \dfrac{273 \text{ K}}{(50+273) \text{ K}} \right| \dfrac{500 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \dfrac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right| \dfrac{0.100 \text{ mol } H_2O}{\text{mol}} \left| \dfrac{18.02 \text{ g}}{\text{mol}} \right| \dfrac{1 \text{ cm}^3}{\text{g}} = \underline{1.34 \text{ cm}^3}$

  c. (iv) (the gauge pressure)

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

$T_2 = 110°\text{C}$, $p_2* = 755 \text{ mm Hg} - (577 - 222)\text{mm Hg} = 400 \text{ mm Hg}$
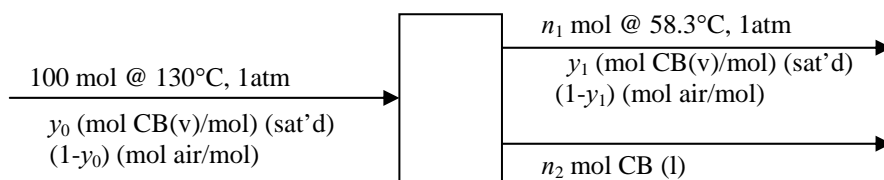
$$\ln p* = \frac{a}{T(K)} + b$$

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

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

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

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

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

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

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

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

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

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

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)

$$h_m = \frac{0.0281}{1 - 0.0281} = \underline{\underline{0.0289 \text{ mol } H_2O/\text{mol dry air}}}$$

$$\underline{h_a} = \frac{0.0289 \text{ mol } H_2O}{\text{mol dry air}} \left| \frac{18.02 \text{ g } H_2O}{\text{mol } H_2O} \right| \frac{\text{mol dry air}}{29.0 \text{ g dry air}} = \underline{\underline{0.0180 \text{ g } H_2O/\text{g dry air}}}$$

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

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

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

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

Mass of air: $\dfrac{0.012 \text{ mol } H_2O}{} \left| \dfrac{18.02 \text{ g}}{1 \text{ mol}} + \dfrac{0.988 \text{ mol dry air}}{} \right| \dfrac{29.0 \text{ g}}{1 \text{ mol}} = 28.87 \text{ g}$

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

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

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

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

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

Mass of air: $\dfrac{0.020 \text{ mol } H_2O}{} \left| \dfrac{18.02 \text{ g}}{1 \text{ mol}} + \dfrac{0.980 \text{ mol dry air}}{} \right| \dfrac{29.0 \text{ g}}{1 \text{ mol}} = 28.78 \text{ g}$

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

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

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

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

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

6.14 (cont'd)

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

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

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

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

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

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

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

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

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

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

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

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

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

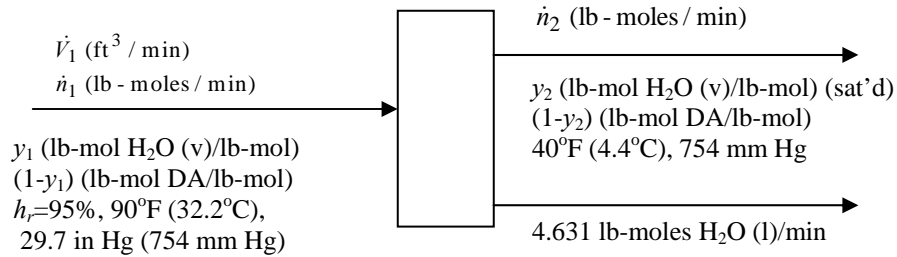Dry air balance: $0.654(33.6) = n_1 (1 - 0.0313) \Rightarrow n_1 = 22.7 \text{ mol}$

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

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

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

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

$\dot{V}_1$ (ft^3 / min)
$\dot{n}_1$ (lb - moles / min)

y_1 (lb-mol H$_2$O (v)/lb-mol)
$(1-y_1)$ (lb-mol DA/lb-mol)
h_r=95%, 90°F (32.2°C),
29.7 in Hg (754 mm Hg)

$\dot{n}_2$ (lb - moles / min)

y_2 (lb-mol H$_2$O (v)/lb-mol) (sat'd)
$(1-y_2)$ (lb-mol DA/lb-mol)
40°F (4.4°C), 754 mm Hg

4.631 lb-moles H$_2$O (l)/min

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

$\xrightarrow{\text{Table B.3}}$ $y_{\text{H}_2\text{O}} = \frac{0.95(36.068 \text{ mm Hg})}{754.4 \text{ mm Hg}} = 0.045$ lb - mol H$_2$O/lb - mol

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

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

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

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

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

$$p_{\text{final}} = \frac{760 \text{ mm Hg}}{} \left| \frac{(15+273) \text{ K}}{(200+273) \text{ K}} \right. = 462.7 \text{ mm Hg} \Rightarrow (p_{\text{H}_2\text{O}})_{\text{final}} = 0.20 \times 462.7 = 92.6 \text{ mm Hg}$$
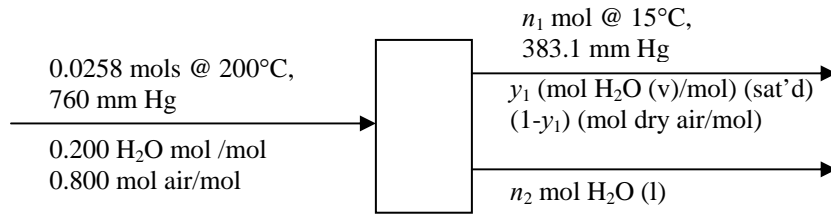
$p^*(15°\text{C}) = 12.79 \text{ mm Hg} < p_{\text{H}_2\text{O}}$. Impossible $\Rightarrow$ condensation occurs.

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

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

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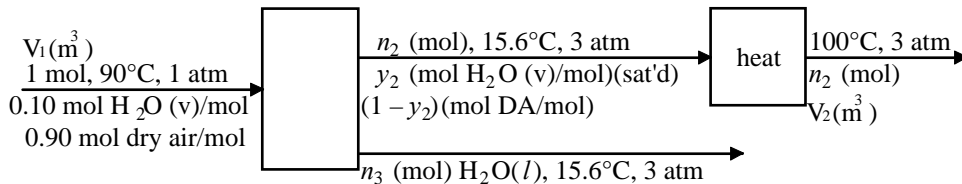
6.17 (cont'd)

0.0258 mols @ 200°C, 760 mm Hg

0.200 H$_2$O mol /mol
0.800 mol air/mol

n_1 mol @ 15°C, 383.1 mm Hg
y_1 (mol H$_2$O (v)/mol) (sat'd)
(1-y_1) (mol dry air/mol)

n_2 mol H$_2$O (l)

Saturation Condition: $y_1 = \dfrac{p_{H_2O}^*(15°C)}{P} = \dfrac{12.79 \text{ mm Hg}}{383.1 \text{ mm Hg}} = 0.03339 \text{ mol } H_2O/mol$

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

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

Mass of water condensed $= \dfrac{0.00445 \text{ mol}}{} \Bigg| \dfrac{18.02 \text{ g}}{mol} = 0.0802 \text{ g}$

6.18 Basis: 1 mol feed

V$_1$(m^3)
1 mol, 90°C, 1 atm
0.10 mol H$_2$O (v)/mol
0.90 mol dry air/mol

n_2 (mol), 15.6°C, 3 atm
y_2 (mol H$_2$O (v)/mol)(sat'd)
$(1 - y_2)$(mol DA/mol)

heat

100°C, 3 atm
n_2 (mol)
V$_2$(m^3)

n_3 (mol) H$_2$O(l), 15.6°C, 3 atm

Saturation: $y_2 = \dfrac{p_{H_2O}^*(15.6°C)}{P}$ $\xrightarrow{\text{Table B.3}}$ $y_2 = \dfrac{13.29 \text{ mm Hg}}{3 \text{ atm}} \Bigg| \dfrac{\text{atm}}{760 \text{ mm Hg}} = 0.00583$

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

H$_2$O mol balance: $0.10(1) = 0.00583(0.9053) + n_3 \Rightarrow n_3 = 0.0947 \text{ mol}$

Fraction H$_2$O condensed: $\dfrac{0.0947 \text{ mol condensed}}{0.100 \text{ mol fed}} = 0.947 \text{ mol condense/mol fed}$

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

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

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

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

6.19 Liquid H_2O initially present: $\dfrac{25 \text{ L}}{}\bigg|\dfrac{1.00 \text{ kg}}{\text{L}}\bigg|\dfrac{1 \text{ kmol}}{18.02 \text{ kg}} = 1.387 \text{ kmol } H_2O \text{ (l)}$

Saturation at outlet: $y_{H_2O} = \dfrac{p^*_{H_2O}(25°C)}{P} = \dfrac{23.76 \text{ mm Hg}}{1.5 \times 760 \text{ mm Hg}} = 0.0208 \text{ mol } H_2O/\text{mol air}$

$\Rightarrow \dfrac{0.0208}{1 - 0.0208} = 0.0212 \text{ mol } H_2O/\text{mol dry air}$

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

Evaporation Rate: $\dfrac{0.670 \text{ mol dry air}}{\text{min}}\bigg|\dfrac{0.0212 \text{ mol } H_2O}{\text{mol dry air}} = 0.0142 \text{ mol } H_2O/\text{min}$

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

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

$(SG)_{C_8H_{18}} = 0.703 \Rightarrow \dfrac{5.288 \times 10^4 \text{ gal}}{\text{day}}\bigg|\dfrac{1 \text{ ft}^3}{7.481 \text{ gal}}\bigg|\dfrac{0.703 \times 62.43 \text{ lb}_m}{\text{ft}^3}$

$= \underline{\underline{3.10 \times 10^5 \text{ lb}_m \text{ } C_8H_{18} / \text{day}}}$

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

c. Table B.4: $p^*_{C_8H_{18}}(90°F) = \dfrac{20.74 \text{ mm Hg}}{}\bigg|\dfrac{14.696 \text{ psi}}{760 \text{ mm Hg}} = 0.40 \text{ lb}_f / \text{in}^2 = p_{\text{octane}} = y_{\text{octane}} P$

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

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

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

Mole fraction of C_8H_{18}: $y = \dfrac{p_{C_8H_{18}}}{P} = \dfrac{0.40 \text{ psi}}{(16.0 + 14.7) \text{ psi}} = 0.0130 \text{ lb - mole } C_8H_{18} / \text{lb - mole}$

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

d. A mixture of octane and air could ignite.

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

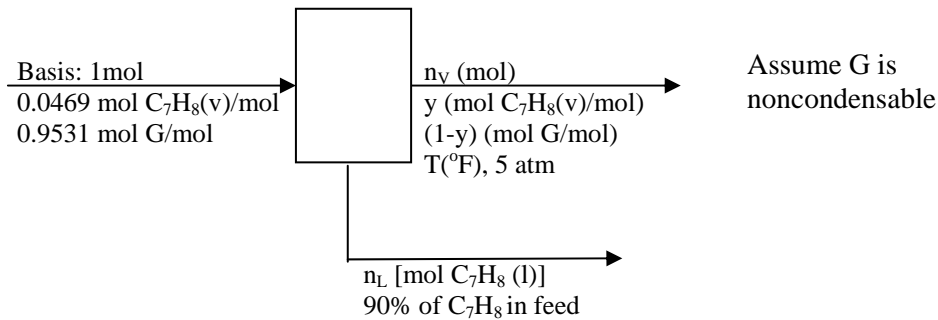Mole fraction of toluene in gas: $y = \dfrac{p_{tol}}{P} = \dfrac{35.63 \text{ mmHg}}{760 \text{ mmHg}} = 0.0469$ lb - mole toluene / lb - mole

Toluene displaced $= yn_{total} = \dfrac{yPV}{RT}$

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

$= 1.31 \text{ lb}_m$ toluene displaced

b.

Basis: 1mol
0.0469 mol C$_7$H$_8$(v)/mol
0.9531 mol G/mol

n_V (mol)
y (mol C$_7$H$_8$(v)/mol)
(1-y) (mol G/mol)
T($^\circ$F), 5 atm

Assume G is noncondensable

n_L [mol C$_7$H$_8$ (l)]
90% of C$_7$H$_8$ in feed

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

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

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

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

Antoine equation:

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

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

b. Antoine Equation:

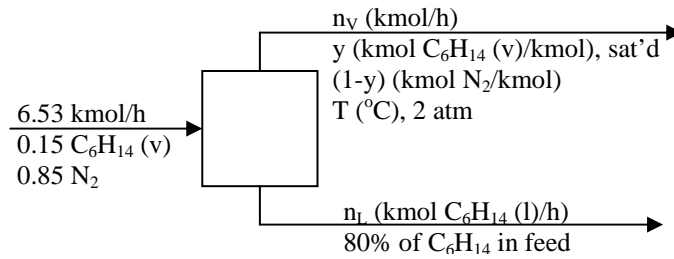$$\log_{10} p_{Hex}^*(100^\circ\text{C}) = 6.88555 - \frac{1175.817}{100+224.867} = 3.26601$$
$$\Rightarrow p^* = 1845 \text{ mm Hg}$$

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

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

6.22 (cont'd)

c.

80% condensation: $\quad n_L = 0.80(0.15)(6.53 \text{ kmol / h}) = 0.7836 \text{ kmol } C_6H_{14}(l) / h$

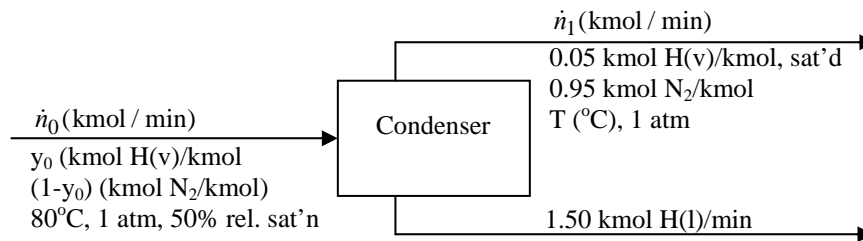Mole balance: $\quad 6.53 = n_V + 0.7836 \Rightarrow n_V = 5.746 \text{ kmol / h}$

Hexane balance: $\quad 0.15(6.53) = y(5.746) + 0.7836 \Rightarrow y = 0.03409 \text{ kmol } C_6H_{14} / \text{kmol}$

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

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

6.23 Let H=n-hexane

a.

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

$\xRightarrow{\text{Table B.4}} \quad y_o = \dfrac{(0.500)(1068 \text{ mmHg})}{760 \text{ mmHg}} = 0.703 \text{ kmolH / kmol}$

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

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

Mole balance: $\dot{n}_0 = \dot{n}_1 + 1.50$
N$_2$ balance: $(1 - 0.703)\dot{n}_0 = 0.95\dot{n}_1$ $\left.\begin{array}{l} \\ \\ \end{array}\right\} \Rightarrow \left\{\begin{array}{l} \dot{n}_0 = 2.18 \text{ kmol / min} \\ \dot{n}_1 = 0.682 \text{ kmol / min} \end{array}\right.$

N$_2$ volume: $\dot{V}_{N_2} = \dfrac{(0.95)0.682 \text{ kmol}}{\text{min}} \left| \dfrac{22.4 \text{ m}^3 (\text{STP})}{\text{kmol}} \right. = \underline{\underline{14.5 \text{ SCMM}}}$

6.23 (cont'd)

    b. Assume no condensation occurs during the compression

$\dot{V}_1$ (m^3 / min)
0.682 kmol/min
0.05 H(v), sat'd
0.95 N$_2$
T_1 (^{o}C), 10 atm

$\dot{V}_0$(m^3 / min)
2.18 kmol/min
0.703 H(v)
0.297 N$_2$
T_0 (^{o}C), 10 atm, 50% R.S.

2.18 kmol/min
0.703 H(v)
0.297 N$_2$
80°C, 1 atm

Compressor

Condenser

1.5 kmol H(l)/min
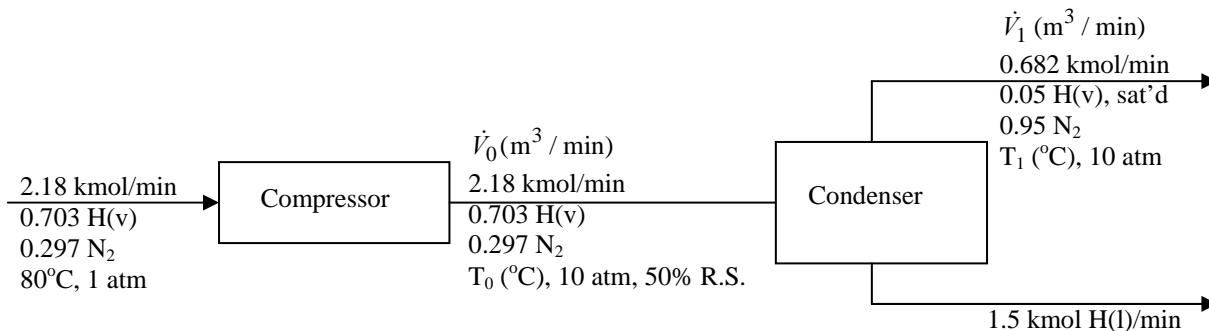
    <u>50% relative saturation at condenser inlet:</u>

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

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

    <u>Volume ratio:</u> $\dfrac{\dot{V}_1}{\dot{V}_0} = \dfrac{n_1 RT_1 / P}{n_0 RT_0 / P} = \dfrac{n_1(T_1 + 273.2)}{n_0(T_0 + 273.2)} = \dfrac{0.682 \text{ kmol/min}}{2.18 \text{ kmol/min}} \times \dfrac{321 \text{ K}}{460 \text{ K}} = \underline{\underline{0.22}} \dfrac{\text{m}^3 \text{ out}}{\text{m}^3 \text{ in}}$

    c. The cost of cooling to -3.26°C (installed cost of condenser + utilities and other operating costs) vs. the cost of compressing to 10 atm and cooling at 10 atm.

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

$$n_{\max} = \dfrac{15 \text{ L C}_9\text{H}_{20}(l)}{} \begin{array}{c} (SG)_{\text{nonane}} \\ \nwarrow \\ 0.718 \times 1.00 \text{ kg} \\ \hline \text{L C}_9\text{H}_{20} \end{array} \begin{array}{c} \text{kmol} \\ \hline 128.25 \text{ kg} \end{array} = 0.084 \text{ kmol C}_9\text{H}_{20}$$

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

$$n_{gas} = \dfrac{2 \times 10^4 \text{ L}}{} \begin{array}{c} 273 \text{ K} \\ \hline 298 \text{ K} \end{array} \begin{array}{c} 1 \\ \hline 22.4 \times 10^3 \end{array} \begin{array}{c} \text{kmol} \\ \hline \text{L(STP)} \end{array} = 0.818 \text{ kmol}$$

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

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

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

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

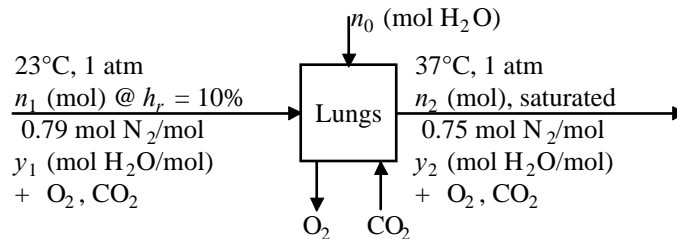$$T_2 = 66.0^\circ \text{C} = 339 \text{ K},\ p_2^* = 40.0 \text{ mmHg}$$

6.24 (cont'd)

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

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

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

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

$$\begin{array}{c}
n_0 \text{ (mol } H_2O) \\
\downarrow
\end{array}$$

23°C, 1 atm
n_1 (mol) @ h_r = 10%
0.79 mol N_2/mol
y_1 (mol H_2O/mol)
+ O_2, CO_2

Lungs

37°C, 1 atm
n_2 (mol), saturated
0.75 mol N_2/mol
y_2 (mol H_2O/mol)
+ O_2, CO_2

$O_2 \quad CO_2$

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

$= 356$ mol inhaled/day

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

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

H_2O balance: $n_0 = n_2 y_2 - n_1 y_1 \Rightarrow (n_0)_{10\% \text{ rh}} - (n_0)_{50\% \text{ rh}} = (n_1 y_1)_{50\%} - (n_1 y_1)_{10\%}$

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

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 $n_0 (18) = (n_2 y_2 - n_1 y_1)18 = 329$ g/day.

6.26 **a.** To increase profits and reduce pollution.

b.
Assume condensation occurs. A=acetone
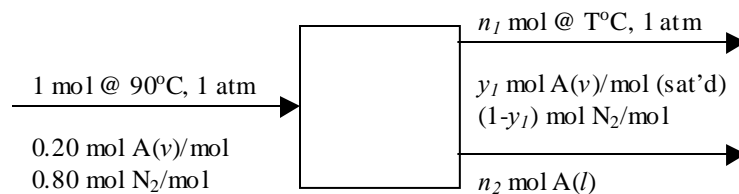
For cooling water at 20°C

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

<u>Saturation</u>: $y_1 \cdot P = p_A^*\left(20°C\right) \Rightarrow y_1 = \frac{184.6}{760} = 0.243 > 0.2$, so no saturation occurs.

For refrigerant at –35°C

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

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

<u>Saturation</u>: $y_1 \cdot P = p_A^*\left(-35°C\right) \Rightarrow y_1 = \frac{7.61}{760} = 0.0100$

<u>N$_2$ mole balance</u>: $1(0.8) = n_1(1 - 0.01) \Rightarrow n_1 = 0.808$ mol
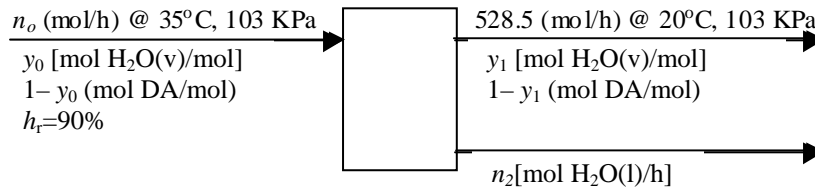
<u>Total mole balance</u>: $1 = 0.808 + n_2 \Rightarrow n_2 = 0.192$ mol

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

c.
Costs of acetone, nitrogen, cooling tower, cooling water and refrigerant

d.
The condenser temperature could never be as low as the initial cooling fluid temperature because heat is transferred between the condenser and the surrounding environment. It will lower the percentage acetone recovery.

6.27

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

n_o (mol/h) @ 35°C, 103 KPa
y_0 [mol H_2O(v)/mol]
$1-y_0$ (mol DA/mol)
h_r=90%

528.5 (mol/h) @ 20°C, 103 KPa
y_1 [mol H_2O(v)/mol]
$1-y_1$ (mol DA/mol)

n_2[mol H_2O(l)/h]

Inlet: $y_o = \dfrac{h_r \cdot p^*_{H_2O}\left(35°C\right)}{P} = \dfrac{0.90\times 42.175\ \text{mmHg}}{103000\ \text{Pa}}\left|\dfrac{101325\ \text{Pa}}{760\ \text{mmHg}}\right. = 0.04913\ \text{mol}\ H_2O/\text{mol}$

Outlet: $y_1 = \dfrac{p^*_{H_2O}\left(20°C\right)}{P} = \dfrac{17.535\ \text{mmHg}}{103000\ \text{Pa}}\left|\dfrac{101325\ \text{Pa}}{760\ \text{mmHg}}\right. = 0.02270\ \text{mol}\ H_2O\ /\ \text{mol}$

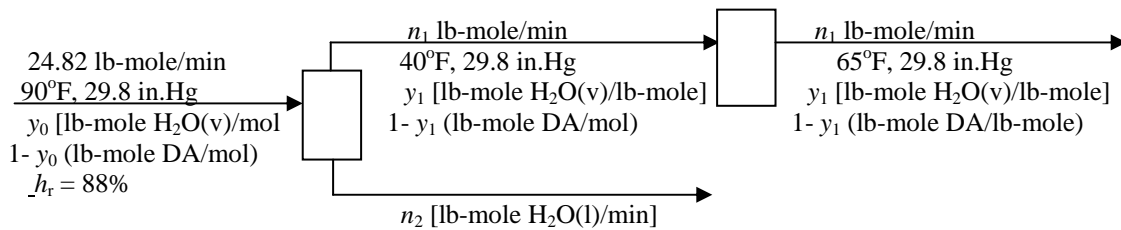Dry air balance: $(1-0.04913)n_o = (1-0.02270)(528.5) \Rightarrow n_o = 543.2\ \text{mol / h}$

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

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

Condensation rate: $\dfrac{14.7\ \text{mol}}{\text{h}}\left|\dfrac{18.02\ \text{g}\ H_2O}{1\ \text{mol}\ H_2O}\right|\dfrac{1\ \text{kg}}{1000\ \text{g}} = \underline{\underline{0.265\ \text{kg / h}}}$

6.28

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

24.82 lb-mole/min
90°F, 29.8 in.Hg
y_0 [lb-mole H_2O(v)/mol]
$1-y_0$ (lb-mole DA/mol)
$h_r = 88\%$

n_1 lb-mole/min
40°F, 29.8 in.Hg
y_1 [lb-mole H_2O(v)/lb-mole]
$1-y_1$ (lb-mole DA/mol)

n_1 lb-mole/min
65°F, 29.8 in.Hg
y_1 [lb-mole H_2O(v)/lb-mole]
$1-y_1$ (lb-mole DA/lb-mole)

n_2 [lb-mole H_2O(l)/min]

Inlet: $y_o = \dfrac{h_r \cdot p^*_{H_2O}\left(90°F\right)}{P} = \dfrac{0.88(36.07\ \text{mmHg})}{29.8\ \text{in Hg}}\left|\dfrac{1\ \text{in Hg}}{25.4\ \text{mmHg}}\right. = 0.0419\ \text{lb-mol}\ H_2O\ /\ \text{lb-mol}$

Outlet: $y_1 = \dfrac{p^*_{H_2O}\left(40°F\right)}{P} = \dfrac{6.274\ \text{mmHg}}{29.8\ \text{in Hg}}\left|\dfrac{1\ \text{in Hg}}{25.4\ \text{mmHg}}\right. = 0.00829\ \text{lb-mol}\ H_2O\ /\ \text{lb-mol}$

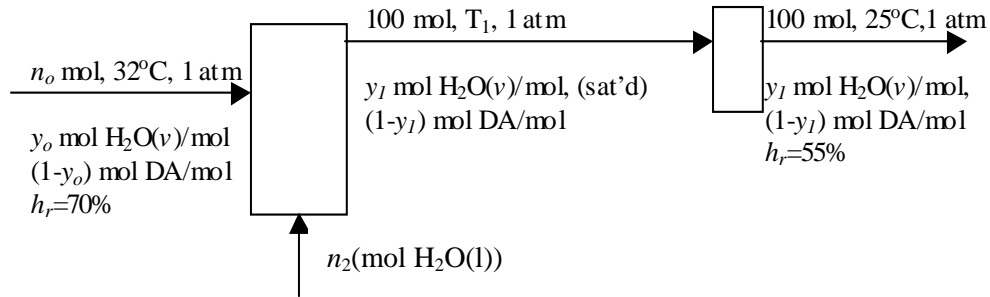Dry air balance: $24.82(1-0.0419) = n_1(1-0.00829) \Rightarrow n_1 = 23.98\ \text{lb-mol / min}$

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

6.28 (cont'd)

<u>Condensation rate:</u> $\dfrac{0.84 \text{ lb - mol}}{\text{min}} \bigg| \dfrac{18.02 \text{ lb}_\text{m}}{\text{lb} - \text{mol}} \bigg| \dfrac{1 \text{ ft}^3}{62.4 \text{ lb}_\text{m}} \bigg| \dfrac{7.48 \text{ gal}}{1 \text{ ft}^3} = \underline{\underline{1.81 \text{ gal / min}}}$

<u>Air delivered @ 65°F:</u> $\dfrac{23.98 \text{ lb - mol}}{\text{min}} \bigg| \dfrac{359 \text{ ft}^3 (\text{STP})}{1 \text{ lb} - \text{mol}} \bigg| \dfrac{525° \text{ R}}{492° \text{R}} \bigg| \dfrac{29.92 \text{ in Hg}}{29.8 \text{ in Hg}} = \underline{\underline{9223 \text{ ft}^3 \text{ / min}}}$

6.29 <u>Basis: 100 mol product gas</u>

<u>Outlet:</u> $y_1 = \dfrac{h_r \cdot p^*_{\text{H}_2\text{O}}(25° \text{ C})}{P} = \dfrac{0.55(23.756)}{760} = 0.0172 \text{ mol H}_2\text{O / mol}$

<u>Saturation at T_1:</u> $0.0172(760) = 13.07 = p^*_{\text{H}_2\text{O}}(T_1) \Rightarrow T_1 = \underline{\underline{15.3° \text{ C}}}$

<u>Inlet:</u> $y_\text{o} = \dfrac{h_r \cdot p^*_{\text{H}_2\text{O}}(32° \text{C})}{P} = \dfrac{0.70(35.663)}{760} = 0.0328 \text{ mol H}_2\text{O / mol}$

<u>Dry air balance:</u> $n_\text{o}(1 - 0.0328) = 100(1 - 0.0172) \Rightarrow n_\text{o} = 101.6 \text{ mol}$

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

<u>kg H$_2$O removed :</u> $\dfrac{1.6 \text{ mol}}{} \bigg| \dfrac{18.02 \text{ g}}{1 \text{ mol}} \bigg| \dfrac{1 \text{ kg}}{1000 \text{ g}} = 0.0288 \text{ kg H}_2\text{O}$

<u>kg dry air:</u> $\dfrac{100(1 - 0.0172) \text{ mol}}{} \bigg| \dfrac{29.0 \text{ g}}{1 \text{ mol}} \bigg| \dfrac{1 \text{ kg}}{1000 \text{ g}} = 2.85 \text{ kg dry air}$

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

6.30 a. Room air $- T = 22°C$, $P = 1$ atm, $h_r = 40\%$:

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

Second sample $- T = 50°C$, $P = 839$ mm Hg, saturated:

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

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

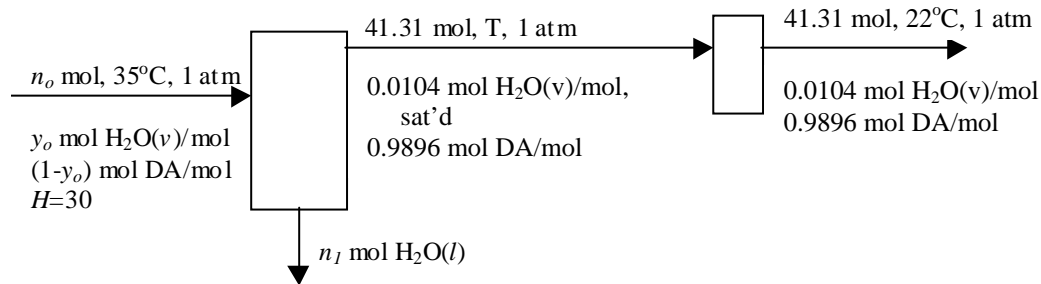$$b = \frac{\ln(y_2/y_1)}{H_2 - H_1} = \frac{\ln(0.1103/0.01044)}{48 - 5} = 0.054827$$

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

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

b.

Basis: $\dfrac{1 \text{ m}^3 \text{ delivered air}}{} \left| \dfrac{273\text{K}}{(22 + 273)\text{K}} \right| \dfrac{1 \text{ k mol}}{22.4\text{m}^3(\text{STP})} \left| \dfrac{10^3 \text{ mol}}{1 \text{ kmol}} \right. = 41.31$ mol air delivered

Saturation condition prior to reheat stage:

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

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

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

Overall dry air balance: $n_0(1 - y_0) = 41.31(0.9896) \Rightarrow n_0 = \dfrac{(41.31)(0.9896)}{(1 - 0.0411)} = 42.63$ mol
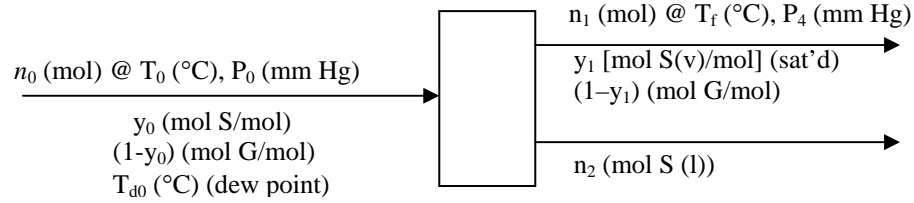
Overall water balance: $n_0 y_0 = n_1 + (41.31)(0.0104) \Rightarrow n_1 = (42.63)(0.0411) - (41.31)(0.0104)$
$$= 1.32 \text{ mol H}_2\text{O condensed}$$

Mass of condensed water $= \dfrac{1.32 \text{ mol H}_2\text{O}}{} \left| \dfrac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} \right| \dfrac{1 \text{ kg}}{10^3 \text{ g}}$

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

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

$$n_1 \text{ (mol) @ } T_f \text{ (°C), } P_4 \text{ (mm Hg)}$$

n_0 (mol) @ T_0 (°C), P_0 (mm Hg)

y_1 [mol S(v)/mol] (sat'd)
$(1-y_1)$ (mol G/mol)

y_0 (mol S/mol)
$(1-y_0)$ (mol G/mol)
T_{d0} (°C) (dew point)

n_2 (mol S (l))

<u>Inlet dew point</u> $= T_0 \Rightarrow y_o P_o = p*(T_{do}) \Rightarrow y_o = \dfrac{p*(T_{do})}{P_o}$ (1)

<u>Saturation condition at outlet</u>: $y_1 P_f = p*(T_f) \Rightarrow y_1 = \dfrac{p*(T_f)}{P_f}$ (2)

<u>Fractional condensation of S</u> $= f \Rightarrow n_2 = n_0 y_0 f \xrightarrow{(1)} n_2 = n_0 f p*(T_0)/P_0$ (3)

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

<u>S balance</u>: $(n_0)(y_0) = n_1 y_1 + n_2$

(1) - (4)

$$\frac{\dot{n}_0 p*(T_{do})}{P_o} = \left[\dot{n}_0 - \frac{\dot{n}_0 f p*(T_{do})}{P_o} \right]\left(\frac{p*(T_f)}{P_f} \right) + \frac{\dot{n}_0 f p*(T_{do})}{p_o}$$

$$\Rightarrow \frac{(1-f)p*(T_{do})}{P_o} = \left[1 - \frac{f p*(T_{do})}{P_o} \right]\frac{p*(T_f)}{P_f} \Rightarrow P_f = \frac{p*(T_f)\left[1 - \dfrac{f p*(T_{do})}{P_o} \right]}{(1-f)\dfrac{p*(T_{do})}{P_o}}$$

b.

Condensation of ethylbenzene from nitrogen											
Antoine constants for ethylbenzene											
A= 6.9565											
B= 1423.5											
C= 213.09											
Run	T0	P0	Td0	f	Tf	p* (Td0)	p*(Tf)	Pf	Crefr	Ccomp	Ctot
1	50	765	40	0.95	45	21.472	27.60	19139	2675	107027	109702
2	50	765	40	0.95	40	21.472	21.47	14892	4700	83329	88029
3	50	765	40	0.95	35	21.472	16.54	11471	8075	64239	72314
4	50	765	40	0.95	**20**	21.472	7.07	4902	26300	27582	**53882**

6.31 (cont'd)

    c.   When T_f decreases, P_f decreases. Decreasing temperature and increasing pressure both to increase the fractional condensation. When you decrease T_f, less compression is required to achieve a specified fractional condensation.

    d.   A lower T_f requires more refrigeration and therefore a greater refrigeration cost (C_{refr}). However, since less compression is required at the lower temperature, C_{comp} is lower at the lower temperature. Similarly, running at a higher T_f lowers the refrigeration cost but raises the compression cost. The sum of the two costs is a minimum at an intermediate temperature.

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

Cmpd.	$T_c(K)$	$P_c(\text{atm})$	$(T_c)_{corr}$.	$(P_c)_{corr}$	(Apply Newton's corrections for H_2)
H_2	33.2	12.8	41.3	20.8	
CO	133.0	34.5	–	–	
CO_2	304.2	72.9	–	–	
CH_4	190.7	45.8	–	–	

$$T_c' = \sum y_i T_{ci} = 0.40(41.3) + 0.35(133.0) + 0.20(304.2) + 0.05(190.7) = 133.4\,K$$

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

<u>Feed gas to cooler</u>

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

$$\hat{V} = \frac{1.02}{35\text{ atm}} \left| \frac{8.314\text{ N}\cdot\text{m}}{\text{mol}\cdot\text{K}} \right| \frac{1273\text{ K}}{} \left| \frac{1\text{ atm}}{101325\text{ N}/\text{m}^3} \right. = 3.04 \times 10^{-3}\ \text{m}^3/\text{mol}$$

$$\frac{120\text{ m}^3}{\text{min}} \left| \frac{\text{mol}}{3.04 \times 10^{-3}\text{ m}^3} \right| \frac{1\text{ kmol}}{10^3\text{ mol}} = 39.5\ \text{kmol/min}$$
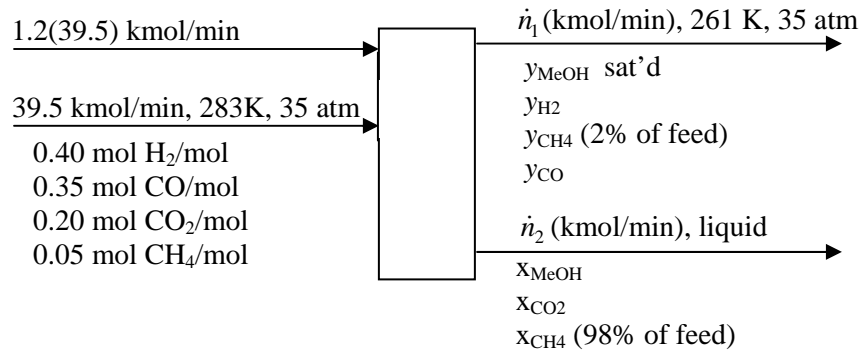
<u>Feed gas to absorber</u>

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

$$\hat{V} = \frac{0.98}{35\text{ atm}} \left| \frac{8.314\text{ N}\cdot\text{m}}{\text{mol}\cdot\text{K}} \right| \frac{283\text{ K}}{} \left| \frac{1\text{ atm}}{101325\text{ N}/\text{m}^3} \right. = 6.50 \times 10^{-4}\ \text{m}^3/\text{mol}$$

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

6.32 (cont'd)

1.2(39.5) kmol/min → [box] → $\dot{n}_1$ (kmol/min), 261 K, 35 atm

39.5 kmol/min, 283K, 35 atm →

0.40 mol H_2/mol
0.35 mol CO/mol
0.20 mol CO_2/mol
0.05 mol CH_4/mol

y_{MeOH} sat'd
y_{H2}
y_{CH4} (2% of feed)
y_{CO}

$\dot{n}_2$ (kmol/min), liquid

x_{MeOH}
x_{CO2}
x_{CH4} (98% of feed)

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

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

$$y_{McOH} = \frac{n_{MeOH}}{\underset{\underset{\text{=input}}{\uparrow}}{n_{MeOH}} + \underset{\underset{\text{=0.02 of input}}{\uparrow}}{n_{H_2}} + \underset{}{n_{CH_4}} + \underset{\underset{\text{=input}}{\uparrow}}{n_{CO}}} = \frac{n_{MeOH}}{n_{MeOH} + 39.5\underset{\Downarrow}{(0.40 + 0.02(0.05) + 0.35)}}$$

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

b. The gas may be used as a fuel. CO_2 has no fuel value, so that the cost of the added energy required to pump it would be wasted.

6.33

$\dot{n}_0$ (kmol/min wet air) @ 28°C, 760 mmHg

y_1 (mol H_2O/mol)
$(1-y_1)$ (mol dry air/mol)
50% rel. sat.

1500 kg/min wet pulp

0.75 /(1 + 0.75) kg H_2O/kg
1/1.75 kg dry pulp/kg

$\dot{n}_1$ (kmol/min wet air) @ 80°C, 770

y_2 (mol H_2O/mol)
$(1-y_2)$ (mol dry air/mol)
$T_{\text{dew point}} = 40.0^\circ C$

$\dot{m}_1$ (kg/min wet pulp)

0.0015 kg H_2O/kg
0.9985 kg dry pulp/kg
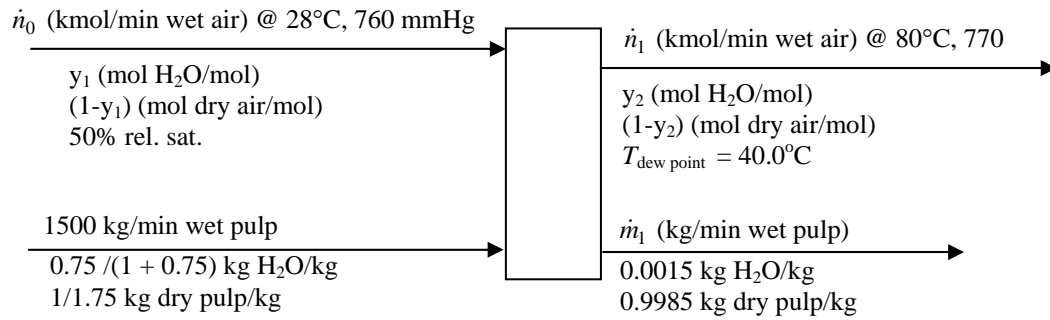
<u>Dry pulp balance:</u> $1500 \times \dfrac{1}{1+0.75} = \dot{m}_1(1-0.0015) \Rightarrow \dot{m}_1 = 858$ kg / min

<u>50% rel. sat'n at inlet:</u> $y_1 P = 0.50\, p_{H_2O}^*(28^\circ C) \Rightarrow y_1 = 0.50(28.349$ mm Hg$)/(760$ mm Hg$)$

$= 0.0187$ mol H_2O/mol

<u>40°C dew point at outlet:</u> $y_2 P = p_{H_2O}^*(40^\circ C) \Rightarrow y_2 = (55.324$ mm Hg$) / (770$ mm Hg$)$

$= 0.0718$ mol H_2O / mol

<u>Mass balance on dry air:</u>
$\dot{n}_0(1-0.0187) = \dot{n}_1(1-0.0718)$ (1)

<u>Mass balance on water:</u>
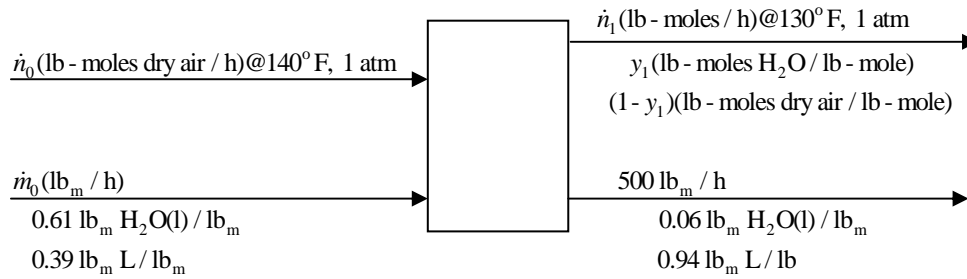$\dot{n}_0(0.0187)(18.0$ kg / kmol$) + 1500(0.75 / 1.75) = \dot{n}_1(0.0718)(18) + 858(0.0015)$ (2)

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

<u>Mass of water removed from pulp:</u> [1500(0.75/1.75)–858(.0015)]kg H_2O = <u>642 kg / min</u>

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

6.34 Basis: 500 lb_m/hr dried leather (L)

$\dot{n}_0$ (lb - moles dry air / h)@140° F, 1 atm

$\dot{n}_1$ (lb - moles / h)@130° F, 1 atm
y_1 (lb - moles H_2O / lb - mole)
$(1 - y_1)$(lb - moles dry air / lb - mole)

$\dot{m}_0$ (lb_m / h)
0.61 lb_m H_2O(l) / lb_m
0.39 lb_m L / lb_m

500 lb_m / h
0.06 lb_m H_2O(l) / lb_m
0.94 lb_m L / lb

Dry leather balance: $0.39 m_0 = (0.94)(500) \Rightarrow m_0 = 1205\ lb_m$ wet leather/hr

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

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

$$\Downarrow$$

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

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

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

6.35 a. Basis: 1 kg dry solids

n_1 (kmol)N_2, 85°C

1.00 kg solids
0.78 kg Hex

dryer

n_2 (kmol) 80°C, 1 atm
y_2 (mol Hex/mol)
$(1 - y_2)$ (mols N_2/mol)
70% rel. sat.

0.05 kg Hex
1.00 kg solids

condenser

n_3 (kmol) 28°C, 5.0 atm
y_3 (mol Hex/mol) sat'd
$(1 - y_3)$ (mols N_2/mol)
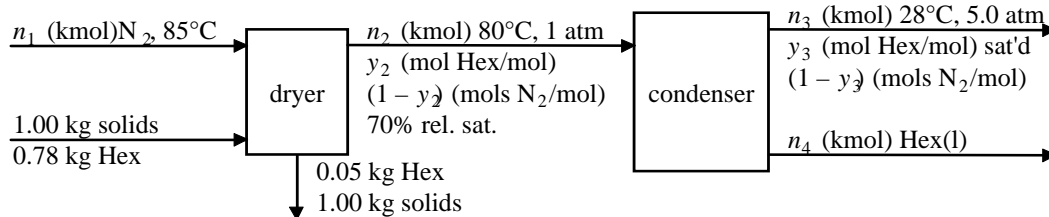
n_4 (kmol) Hex(l)

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

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

(Antoine eq. ↓)

6.35 (cont'd)

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

$\underline{N_2 \text{ balance on dryer:}}$ $n_1 = (1 - 0.984)0.0086 = 1.376 \times 10^{-4} \text{ kmol}$

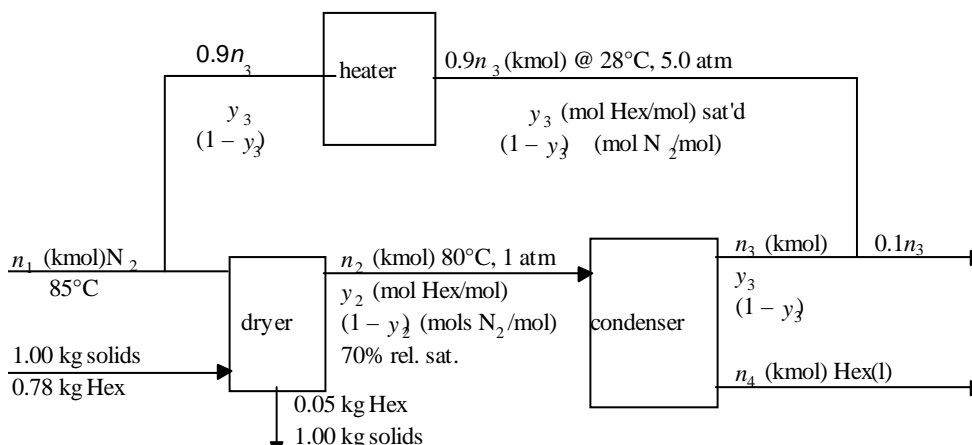$$\underline{\text{Saturation at outlet:}} \quad y_3 = \frac{p*_{hex} \overset{\overset{\text{Antoine Eq.}}{\downarrow}}{(28°C)}}{P} = \frac{10^{6.88555 - 1175.817/(28+224.867)}}{5(760)} = 0.0452 \text{ mol Hex/mol}$$

$\underline{\text{Overall } N_2 \text{ balance:}}$ $1.376 \times 10^{-4} = n_3(1 - 0.0452) \Rightarrow n_3 = 1.44 \times 10^{-4} \text{ kmol}$

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

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

b. Basis: 1 kg dry solids

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

$\underline{N_2 \text{ balance on dryer:}}$ $n_1 + 0.9 n_3(1 - 0.0452) = n_2(1 - 0.984)$ (2)
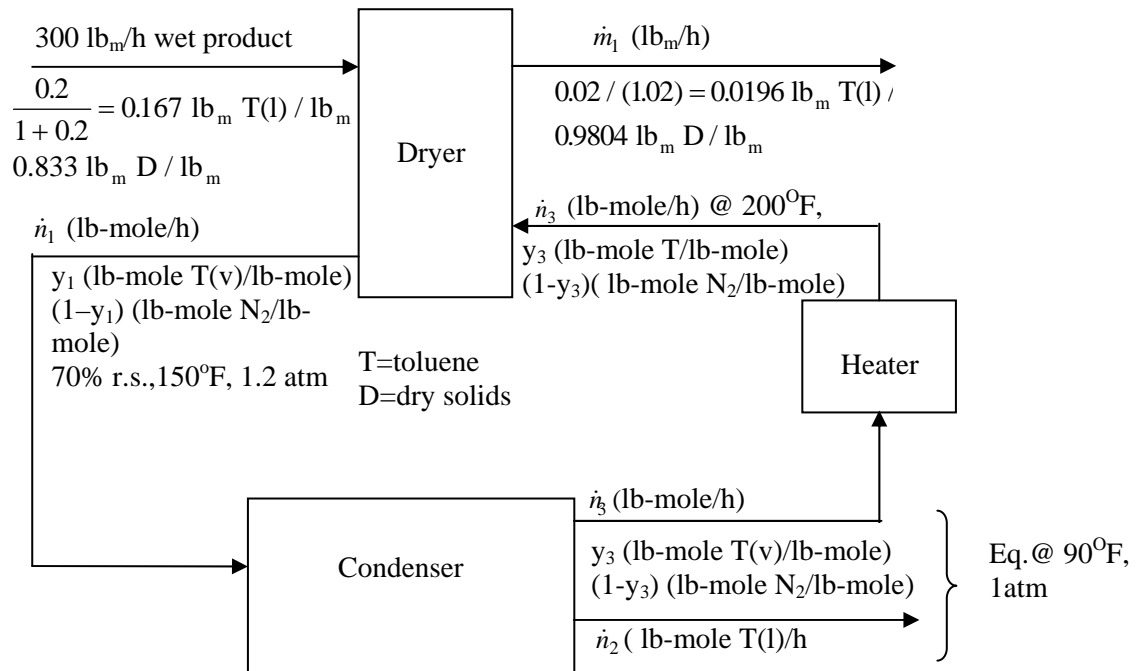
$\underline{\text{Overall } N_2 \text{ balance:}}$ $n_1 = 0.1 n_3(1 - 0.0452)$ (3)

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

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

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

6.36 b.

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

Relative saturation $\Rightarrow y_{1;}$, Gas and liquid equilibrium $\Rightarrow y_3$

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

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

Dry Solids Balance: $300 \times 0.833 = \dot{m}_1 \times 0.9804$

70% relative saturation of dryer outlet gas:

$$p^*_{C_7H_8}(150^O\text{F}{=}65.56^O\text{C}){=}10^{(6.95805-\frac{1346.773}{65.56+219.693})} = 172.47 \text{ mmHg}$$

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

Saturation at condenser outlet:

$$p^*_{C_7H_8}(90^O\text{F}{=}32.22^O\text{C}){=}10^{(6.95805-\frac{1346.773}{65.56+219.693})} = 40.90 \text{ mmHg}$$

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

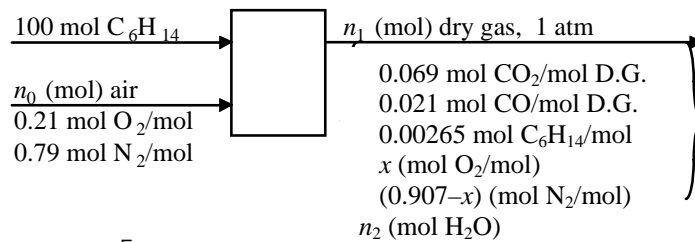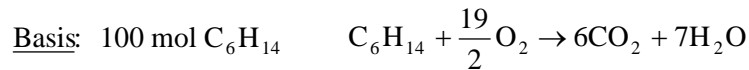Condenser Toluene Balance: $\dot{n}_1 \times 0.1324 = 0.488 + \dot{n}_3 \times 0.0538$ $\left.\right\}$ $\Rightarrow \left\{\begin{array}{l} \dot{n}_1 = 5.875 \text{ lb - mole} / \text{h} \\ \dot{n}_3 = 5.387 \text{ lb - mole} / \text{h} \end{array}\right.$

Condenser N_2 Balance: $\dot{n}_1 \times (1 - 0.1324) = \dot{n}_3 \times (1 - 0.0538)$

6.36 (cont'd)

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

$$= \underline{\underline{0.182 \text{ lb}_m / \text{h}}}$$

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

6.37

$\underline{\text{Basis}}$: 100 mol C_6H_{14} $C_6H_{14} + \dfrac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O$

100 mol C_6H_{14}

n_0 (mol) air
0.21 mol O_2/mol
0.79 mol N_2/mol

n_1 (mol) dry gas, 1 atm
0.069 mol CO_2/mol D.G.
0.021 mol CO/mol D.G.
0.00265 mol C_6H_{14}/mol
x (mol O_2/mol)
(0.907–x) (mol N_2/mol)
n_2 (mol H_2O)

$\underline{\text{C balance}}$: $6(100) = n_1 \left[\underset{(CO_2)}{0.069} + \underset{(CO)}{0.021} + \underset{(C_6H_{14})}{6(0.00265)} \right] \Rightarrow n_1 = 5666$ mol dry gas

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

$\underline{\text{H balance}}$: $14(100) = 2n_2 + 5666(14)(0.00265) \Rightarrow n_2 = 595$ mol H_2O

$\underline{\text{Dew point}}$: $y_{H_2O} = \dfrac{595}{595 + 5666} = \dfrac{p*(T_{dp})}{760 \text{ mm Hg}} \Rightarrow p*(T_{dp}) = 72.2 \text{ mm Hg} \overset{\text{Table B.3}}{\Rightarrow} \underline{\underline{T_{dp} = 45.1^\circ C}}$
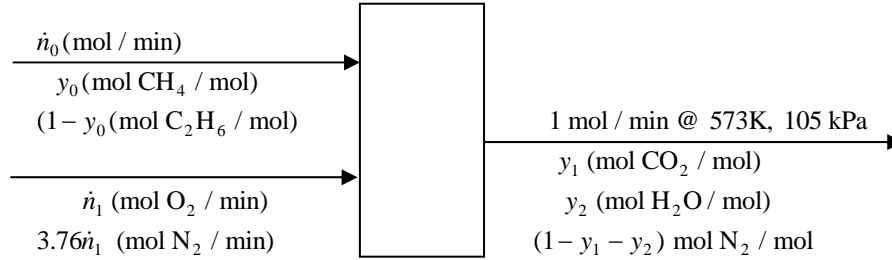
$\underline{N_2 \text{ balance}}$: $0.79n_0 = 5666(0.907 - x)$

$\underline{\text{O balance}}$: $0.21(n_0)(2) = 5666[(0.069)(2) + 0.021 + 2x) + 595$

Solve simultaneously to obtain $n_0 = 5888$ mol air, $x = 0.086$ mol O_2/mol

$\underline{\text{Theoretical air}}$: $\dfrac{100 \text{ mol } C_2H_{14}}{} \left| \dfrac{19 \text{ mol } O_2}{2 \text{ mol } C_2H_{14}} \right| \dfrac{1 \text{ mol air}}{0.21 \text{ mol } O_2} = 4524$ mol air

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

6.38 <u>Basis</u>: 1 mol outlet gas/min

$\dot{n}_0$ (mol / min)
y_0 (mol CH_4 / mol)
$(1 - y_0$ (mol C_2H_6 / mol)

$\dot{n}_1$ (mol O_2 / min)
$3.76\dot{n}_1$ (mol N_2 / min)

1 mol / min @ 573K, 105 kPa
y_1 (mol CO_2 / mol)
y_2 (mol H_2O / mol)
$(1 - y_1 - y_2)$ mol N_2 / mol

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

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

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

<u>C balance</u>: $n_o y_o + 2n_o(1 - y_o) = 0.1016$ (2)

<u>N_2 balance</u>: $3.76 n_1 = 1 - y_1 - y_2$ (3)

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

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

<u>Dew point</u>:

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

6.39   Basis: 100 mol dry stack gas

n_P (mol C_3H_8)
n_B (mol C_4H_{10})

n_{out} (mol)
0.21 O_2
0.79 N_2

$P = 780$ mm Hg
Stack gas: $T_{dp} = 46.5°C$
$\begin{cases} 100 \text{ mol dry gas} \\ 0.000527 \text{ mol } C_3H_8/\text{mol} \\ 0.000527 \text{ mol } C_4H_{10}/\text{mol} \\ 0.0148 \text{ mol CO}/\text{mol} \\ 0.0712 \text{ mol CO}_2/\text{mol} \\ \quad + O_2 N_2 \end{cases}$
n_w (mol H_2O)

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$
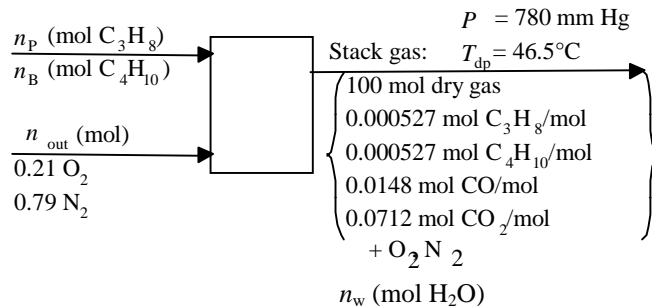
6.39 (cont'd)

Dew point $= 46.5°C \Rightarrow y_w P = p*_w (46.5°C) \Rightarrow y_w = \dfrac{77.6 \text{ mm Hg}}{780 \text{ mm Hg}} = 0.0995 \dfrac{\text{mol } H_2O}{\text{mol}}$

But $y_w = \dfrac{n_w}{100 + n_w} = 0.0995 \Rightarrow n_w = 11.05 \text{ mol } H_2O$ (Rounding off strongly affects the result)

C balance: $3n_p + 4n_B = (100)[(0.000527)(3) + (0.000527)(4) + 0.0148 + 0.0712]$
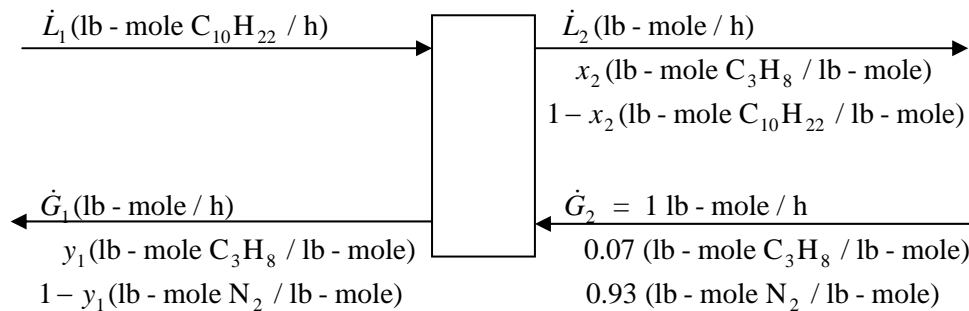
$\Rightarrow \quad 3n_p + 4n_B = 8.969 \quad (1)$

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

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

Solve (1) & (2) simultaneously: $\Rightarrow \begin{cases} n_p = 1.25 \text{ mol } C_3H_8 \\ n_B = 1.30 \text{ mol } C_4H_{10} \end{cases} \Rightarrow \begin{cases} \underline{\underline{49\% \ C_3H_8}} \\ \underline{\underline{51\% \ C_4H_{10}}} \end{cases}$

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

6.40 a.

$\dot{L}_1 \text{ (lb - mole } C_{10}H_{22} \text{ / h)}$ → [box] → $\dot{L}_2 \text{ (lb - mole / h)}$
$x_2 \text{ (lb - mole } C_3H_8 \text{ / lb - mole)}$
$1 - x_2 \text{ (lb - mole } C_{10}H_{22} \text{ / lb - mole)}$

← $\dot{G}_1 \text{ (lb - mole / h)}$
$y_1 \text{ (lb - mole } C_3H_8 \text{ / lb - mole)}$
$1 - y_1 \text{ (lb - mole } N_2 \text{ / lb - mole)}$

← $\dot{G}_2 \ = \ 1 \text{ lb - mole / h}$
$0.07 \text{ (lb - mole } C_3H_8 \text{ / lb - mole)}$
$0.93 \text{ (lb - mole } N_2 \text{ / lb - mole)}$

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

N_2 balance: $(1)(0.93) = \dot{G}_1(1 - y_1) \Rightarrow \dot{G}_1(1 - y_1) = 0.93 \hspace{2cm} (1)$

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

(1) & $(2) \Rightarrow \dot{G}_1 = 0.93105 \text{ lb - mol/h}$, $y_1 = 1.128 \times 10^{-3} \text{ mol } C_3H_8/\text{mol}$

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

From Cox Chart (Figure 6.1-4), $p*_{C_3H_8} (80° F) = 160 \text{ lb / in}^2 = 10.89 \text{ atm}$

Raoult's law: $x_2 p*_{C_3H_8} (80° F) = 0.07 p \Rightarrow x_2 = \dfrac{(0.07)(1.0 \text{ atm})}{10.89 \text{ atm}} = 0.006428 \dfrac{\text{mol } H_2O}{\text{mol}}$

Propane balance: $(0.07)(1) = \dot{G}_1 y_1 + \dot{L}_2 x_2 \Rightarrow \dot{L}_2 = \dfrac{0.07 - (0.93105)(1.128 \times 10^{-3})}{0.006428}$

$= 10.726 \text{ lb - mole/h}$

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

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

6.40 (cont'd)

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

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

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

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

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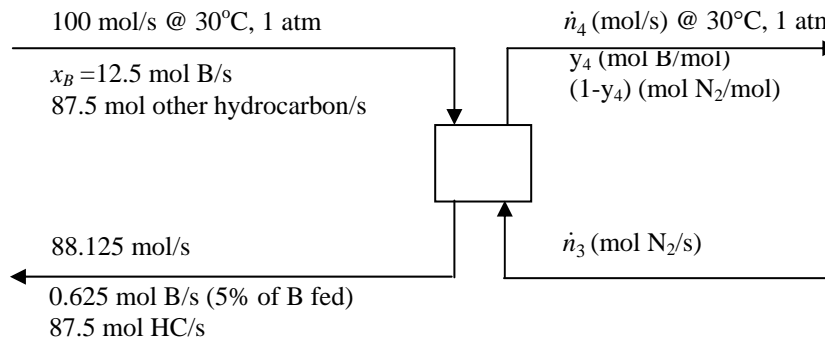
$$p_B^*(30^\circ C) \cong 41 \text{ lb / in}^2 = 2120 \text{ mm Hg (from Figure 6.1-4)}$$

<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> $\dot{n}_4 \cdot (0.3487) = (12.5)(0.95) \Rightarrow \dot{n}_4 = 34.06 \text{ mol / s}$

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

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

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

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

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

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

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

6.42 <u>Basis</u>: 100 mol NH_3
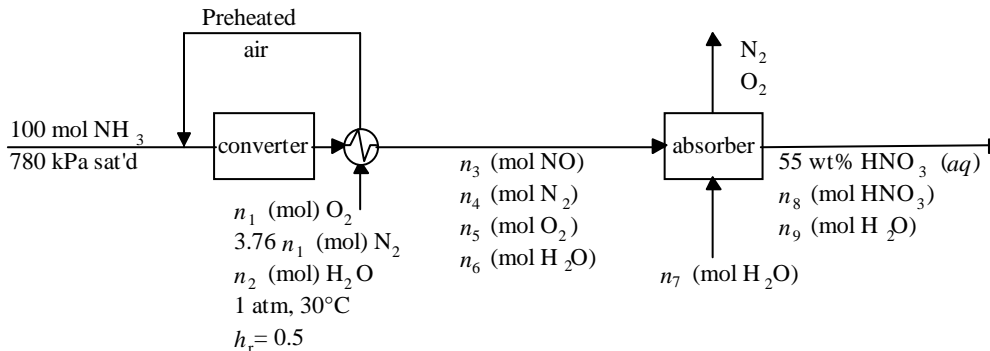
a. i) <u>NH_3 feed:</u> $P = P*(T_{sat}) = 820$ kPa $= 6150$ mm Hg $= 8.09$ atm

<u>Antoine:</u>
$$\log_{10}(6150) = 7.55466 - 1002.711/(T_{sat} + 247.885) \Rightarrow T_{sat} = 18.4°C = 291.6 \text{ K}$$

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

$$V_{NH_3} = \frac{0.92(100 \text{ mol}) \mid 8.314 \text{ Pa} \mid \quad 291.6 \text{ K}}{\mid \text{mol - K} \mid 820 \times 10^3 \text{ Pa}} = \underline{\underline{0.272 \text{ m}^3 \text{ } NH_3}}$$

<u>Air feed:</u> $NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$

$$n_1 = \frac{100 \text{ mol } NH_3 \mid 2 \text{ mol } O_2}{\mid \text{mol } NH_3} = 200 \text{ mol } O_2$$

<u>Water in Air:</u> $y_{H_2O} = \dfrac{h_r \cdot p^*(30°C)}{p} = \dfrac{0.500 \times 31.824}{760} = 0.02094$

$$\Rightarrow 0.02094 = \frac{n_2}{n_2 + \underset{\underset{(4.76 \text{ mol air/mol } O_2)}{\uparrow}}{4.76(200)}} \Rightarrow n_2 = 20.36 \text{ mol } H_2O$$

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

ii) <u>Reactions:</u> $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$, $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

<u>Balances on converter</u>

<u>NO:</u> $n_3 = \dfrac{97 \text{ mol } NH_3 \mid 4 \text{ mol NO}}{\mid 4 \text{ mol } NH_3} = 97 \text{ mol NO}$

6.42 (cont'd)

$\underline{N_2}$: $n_4 = 3.76(2.00)$ mol $+ \dfrac{3 \text{ mol NH}_3 \mid 2 \text{ mol N}_2}{4 \text{ mol NH}_3} = 753.5$ mol N_2

$\underline{O_2}$: $n_5 = 200$ mol $- \dfrac{97 \text{ mol NH}_3 \mid 5 \text{ mol O}_2}{4 \text{ mol NH}_3}$

$\qquad - \dfrac{3 \text{ mol NH}_3 \mid 3 \text{ mol O}_2}{4 \text{ mol NH}_3} = 76.5$ mol O_2

$\underline{H_2O}$: $n_6 = 20.36$ mol $+ \dfrac{100 \text{ mol NH}_3 \mid 6 \text{ mol H}_2O}{4 \text{ mol NH}_3} = 170.4$ mol H_2O

$\Rightarrow n_{total} = (97 + 753.5 + 76.5 + 170.4)$ mol

$\qquad = \underline{1097 \text{ mol converter effluent}}$

$\qquad \underline{\underline{8.8\% \text{ NO, } 68.7\% \text{ N}_2, \ 7.0\% \text{ O}_2, \ 15.5\% \text{ H}_2O}}$

iii) <u>Reaction:</u> $4NO + 3O_2 + 2H_2O \rightarrow 4HNO_3$

<u>HNO_3 bal. in absorber:</u> $n_8 = \dfrac{97 \text{ mol NO react} \mid 4 \text{ mol HNO}_3}{4 \text{ mol NO}} = 97$ mol HNO_3

<u>H_2O in product:</u> $n_9 = \dfrac{97 \text{ mol HNO}_3 \mid 63.02 \text{ g HNO}_3 \mid 45 \text{ g H}_2O \mid 1 \text{ mol H}_2O}{\text{mol} \mid 55 \text{ g HNO}_3 \mid 18.02 \text{ g H}_2O}$

$\qquad = 277.56$ mol H_2O

<u>H balance on absorber:</u> $(170.4)(2) + 2n_7 = 97 + (277.6)(2)$ (mol H)

$\Rightarrow n_7 = 155.7$ mol H_2O added

$V_{H_2O} = \dfrac{155.7 \text{ mol H}_2O \mid 18.02 \text{ g H}_2O \mid 1 \text{ cm}^3 \mid 1 \text{ m}^3}{1 \text{ mol} \mid 1 \text{ g} \mid 10^6 \text{ cm}^3} = \underline{\underline{2.81 \times 10^{-3} \text{ m}^3 \text{ H}_2O(l)}}$

b.
$\underline{M_{acid} \text{ in old basis}} = \dfrac{97 \text{ mol HNO}_3 \mid 63.02 \text{ g HNO}_3}{\text{mol}} + \dfrac{277.6 \text{ mol H}_2O \mid 18.02 \text{ g H}_2O}{\text{mol}}$
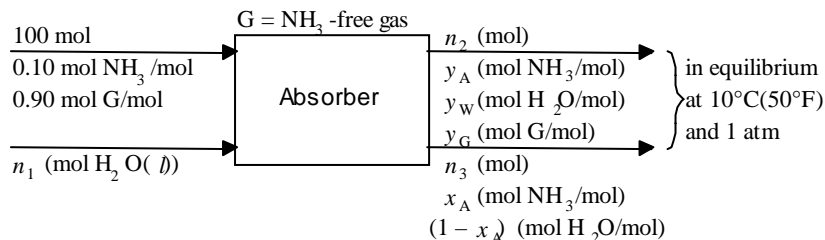
$\qquad = 11115$ g $= 11.115$ kg

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

$V_{NH_3} = (8.997 \times 10^4)(0.272 \text{ m}^3 \text{ NH}_3) = \underline{\underline{2.45 \times 10^4 \text{ m}^3 \text{ NH}_3}}$

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

$V_{H_2O} = (8.997 \times 10^4)(2.81 \times 10^{-3} \text{ m}^3 \text{ H}_2O) = \underline{\underline{253 \text{ m}^3 \text{ H}_2O(l)}}$

6.43 a. Basis: 100 mol feed gas

Composition of liquid effluent . Basis: 100 g solution

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

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

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

Composition of gas effluent

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

$$y_A = 1.21/14.7 = 0.0823 \text{ mol NH}_3/\text{mol}$$
$$\Rightarrow y_W = 0.155/14.7 = 0.0105 \text{ mol H}_2\text{O}/\text{mol}$$
$$y_G = 1 - y_A - y_W = 0.907 \text{ mol G}/\text{mol}$$

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

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

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

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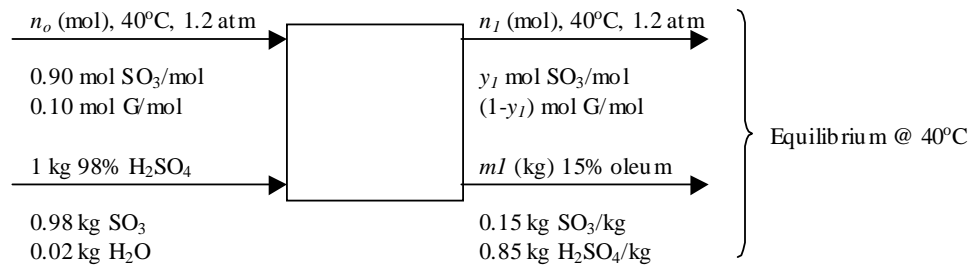
6.44 a.

15% oleum: Basis - 100kg

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

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

6.44 (cont'd)

b. Basis 1 kg liquid feed

n_o (mol), 40°C, 1.2 atm → [box] → n_1 (mol), 40°C, 1.2 atm

0.90 mol SO$_3$/mol
0.10 mol G/mol

y_1 mol SO$_3$/mol
$(1-y_1)$ mol G/mol

1 kg 98% H$_2$SO$_4$ → [box] → $m1$ (kg) 15% oleum

0.98 kg SO$_3$
0.02 kg H$_2$O

0.15 kg SO$_3$/kg
0.85 kg H$_2$SO$_4$/kg

Equilibrium @ 40°C

i) $y_1 = \dfrac{p_{SO_3}(40°C,\ 84.4\%)}{P} = \dfrac{1.15}{760} = \underline{\underline{1.51 \times 10^{-3}}}$ mol SO$_3$/mol

ii) H balance: $\dfrac{0.98 \text{ kg H}_2\text{SO}_4}{} \left|\dfrac{2.02 \text{ kg H}}{98.08 \text{ kg H}_2\text{SO}_4}\right. + \dfrac{0.02 \text{ kg H}_2\text{O}}{} \left|\dfrac{2.02 \text{ kg H}}{18.02 \text{ kg H}_2\text{O}}\right.$

$= \dfrac{0.85 \text{ m}_1 \text{ H}_2\text{SO}_4}{} \left|\dfrac{2.02 \text{ kg H}}{98.08 \text{ kg H}_2\text{SO}_4}\right. \Rightarrow m_1 = 1.28 \text{ kg}$

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

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

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

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

⇓

$n_0 = 3.89$ mol

$n_1 = 0.39$ mol

$V = \dfrac{3.89 \text{ mol}}{1 \text{ kg liquid feed}} \left|\dfrac{22.4 \text{ L (STP)}}{\text{mol}}\right| \dfrac{313\text{K}}{273\text{K}} \left|\dfrac{1 \text{ atm}}{1.2 \text{ atm}}\right| \dfrac{1 \text{ m}^3}{10^3 \text{ L}}$

$= \underline{\underline{8.33 \times 10^{-2} \text{ m}^3/\text{kg liquid feed}}}$

6.45 a. Raoult's law can be used for water and Henry's law for nitrogen.
b. Raoult's law can be used for each component of the mixture, but Henry's law is not valid here.
c. Raoult's law can be used for water, and Henry's law can be used for CO$_2$.

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

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

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

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

$y_{N_2} = 1 - 0.0711 - 0.0439 = \underline{\underline{0.885 \text{ mol N}_2/\text{mol}}}$

6.47 N_2 - Henry's law: Perry's Chemical Engineers' Handbook, Page. 2 - 127, Table 2 - 138

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

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

$\underline{H_2O \text{ - Raoult's law:}}$ $p_{H_2O}^*(80°C) = \dfrac{355.1 \ \text{mm Hg}}{} \left| \dfrac{1 \ \text{atm}}{760 \ \text{mm Hg}} \right. = 0.467 \ \text{atm}$

$$\Rightarrow p_{H_2O} = (x_{H_2O})(p_{H_2O}^*) = (0.997)(0.467) = 0.466 \ \text{atm}$$

Total pressure: $P = p_{N_2} + p_{H_2O} = 378 + 0.466 = \underline{378.5 \ \text{atm}}$

Mole fractions: $y_{H_2O} = p_{H_2O}/P = 0.466/378.5 = \underline{\underline{1.23 \times 10^{-3} \ \text{mol} \ H_2O/\text{mol gas}}}$

$$y_{N_2} = 1 - y_{H_2O} = \underline{\underline{0.999 \ \text{mol} \ N_2/\text{mol gas}}}$$

6.48 $\underline{H_2O \text{ - Raoult's law:}}$ $p_{H_2O}^*(70°C) = \dfrac{233.7 \ \text{mm Hg}}{} \left| \dfrac{1 \ \text{atm}}{760 \ \text{mm Hg}} \right. = 0.3075 \ \text{atm}$

$$\Rightarrow p_{H_2O} = x_{H_2O} p_{H_2O}^* = (1 - x_m)(0.3075)$$

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

$\underline{\text{Total pressure:}}$ $P = p_m + p_{H_2O} = x_m \cdot 6.66 \times 10^4 + (1 - x_m)(0.3075) = 10$

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

6.49 a.

$\underline{\text{Moles of water:}}$ $n_{H_2O} = \dfrac{1000 \ \text{cm}^3}{} \left| \dfrac{1 \ \text{g}}{\text{cm}^3} \right| \dfrac{\text{mol}}{18.02 \ \text{g}} = 55.49 \ \text{mol}$

$\underline{\text{Moles of nitrogen:}}$

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

$\underline{\text{Moles of oxygen:}}$

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

$\underline{\text{Mole fractions of dissolved gases:}}$

$$x_{N_2} = \dfrac{n_{N_2}}{n_{H_2O} + n_{N_2} + n_{O_2}} = \dfrac{4.192 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 7.554 \times 10^{-6} \ \dfrac{\text{mol} \ N_2}{\text{mol}}$$

$$x_{O_2} = \dfrac{n_{O_2}}{n_{H_2O} + n_{N_2} + n_{O_2}} = \dfrac{2.102 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 3.788 \times 10^{-6} \ \text{mol} \ O_2 \ / \ \text{mol}$$

6.49 (cont'd)

Henry's law

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

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

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

$$m_{O_2} = \dfrac{2.102 \times 10^{-4} \text{ mol}}{} \, \dfrac{32.0 \text{ g}}{\text{mol}} = 6.726 \times 10^{-3} \text{ g}$$

Mass flow rate of blood: $\dot{m}_{\text{blood}} = \dfrac{0.4 \text{ g O}_2}{\text{min}} \, \dfrac{1 \text{ L blood}}{6.72 \times 10^{-3} \text{ g O}_2} = \underline{\underline{59 \text{ L blood / min}}}$

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

6.50 a. Basis: $1 \text{ cm}^3 \text{ H}_2\text{O}(l)$

$\xrightarrow{(SG)_{H2O}=1.0} \dfrac{1 \text{ g H}_2\text{O}}{} \, \dfrac{1 \text{ mol}}{18.0 \text{ g}} = 0.0555 \text{ mol H}_2\text{O}$

$\xrightarrow{(SC)_{CO2} = 0.0901} \dfrac{0.0901 \text{ cm}^3 \text{ (STP)CO}_2}{} \, \dfrac{1 \text{ mol}}{22{,}400 \text{ cm}^3 \text{(STP)}} = 4.022 \times 10^{-6} \text{ mol CO}_2$

$p_{CO_2} = 1 \text{ atm} \Rightarrow x_{CO_2} = \dfrac{\left(4.022 \times 10^{-6}\right) \text{ mol CO}_2}{\left(0.0555 + 4.022 \times 10^{-6}\right) \text{ mol}} = 7.246 \times 10^{-5} \text{ mol CO}_2/\text{mol}$

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

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

$x_{CO_2} = p_{CO_2}/H = (3.5 \text{ atm})/(13800 \text{ atm/mole fraction}) = 2.536 \times 10^{-4} \text{ mol CO}_2/\text{mol}$

$n_{CO_2} = \dfrac{12 \text{ oz}}{} \, \dfrac{1 \text{ L}}{33.8 \text{ oz}} \, \dfrac{10^3 \text{ g H}_2\text{O}}{1 \text{ L}} \, \dfrac{1 \text{ mol H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \, \dfrac{2.536 \times 10^{-4} \text{ mol CO}_2}{1 \text{ mol H}_2\text{O}} \, \dfrac{44.0 \text{ g CO}_2}{1 \text{ mol CO}_2}$

$= \underline{\underline{0.220 \text{ g CO}_2}}$

c. $V = \dfrac{0.220 \text{ g CO}_2}{} \, \dfrac{1 \text{ mol CO}_2}{44.0 \text{ g CO}_2} \, \dfrac{22.4 \text{ L (STP)}}{1 \text{ mol}} \, \dfrac{(273+37)\text{K}}{273\text{K}} = 0.127 \text{ L} = \underline{\underline{127 \text{ cm}^3}}$

6.51 a. – SO_2 is hazardous and should not be released directly into the atmosphere, especially if the analyzer is inside.

   – From Henry's law, the partial pressure of SO_2 increases with the mole fraction of SO_2 in the liquid, which increases with time. If the water were never replaced, the gas leaving the bubbler would contain 1000 ppm SO_2 (nothing would be absorbed), and the mole fraction of SO_2 in the liquid would have the value corresponding to 1000 ppm SO_2 in the gas phase.

b. Calculate $x(\text{mol } SO_2/\text{mol})$ in terms of $r(\text{g } SO_2/100 \text{ g } H_2O)$

   Basis: 100 g $H_2O(1 \text{ mol}/18.02 \text{ g}) = 5.55$ mol H_2O

$$r \text{ (g } SO_2)(1 \text{ mol}/64.07 \text{ g}) = 0.01561r \text{ (mol } SO_2)$$

$$\Rightarrow x_{SO_2} = \frac{0.01561r}{5.55 + 0.01561r}\left(\frac{\text{mol } SO_2}{\text{mol}}\right)$$

From this relation and the given data, $p_{SO_2} = 0$ mmHg $\Leftrightarrow x_{SO_2} = 0$ mol SO_2/mol

42	1.4×10^{-3}
85	2.8×10^{-3}
129	4.2×10^{-3}
176	5.6×10^{-3}

A plot of p_{SO_2} vs. x_{SO_2} is a straight line. Fitting the line using the method of least squares (Appendix A.1) yields $\left(p_{SO_2} = H_{SO_2} x_{SO_2}\right)$, $H_{SO_2} = 3.136 \times 10^4 \dfrac{\text{mm Hg}}{\text{mole fraction}}$

c.   100 ppm $SO_2 \Rightarrow y_{SO_2} = \dfrac{100 \text{ mol } SO_2}{10^6 \text{ mols gas}} = 1.00 \times 10^{-4} \dfrac{\text{mol } SO_2}{\text{mol}}$

$$\Rightarrow p_{SO_2} = y_{SO_2}P = \left(1.0 \times 10^{-4}\right)(760 \text{ mm Hg}) = 0.0760 \text{ mm Hg}$$

Henry's law $\Rightarrow x_{SO_2} = \dfrac{p_{SO_2}}{H_{SO_2}} = \dfrac{0.0760 \text{ mm Hg}}{3.136 \times 10^4 \text{ mm Hg/mole fraction}}$

$$= 2.40 \times 10^{-6} \text{ mol } SO_2/\text{mol}$$

Since x_{SO_2} is so low, we may assume for simplicity that $V_{\text{final}} \approx V_{\text{initial}} = 140$ L , and

$$n_{\text{final}} \approx n_{\text{initial}} = \frac{140 \text{ L}}{} \left| \frac{10^3 \text{ g } H_2O(l)}{1 \text{ L}} \right| \frac{1 \text{ mol}}{18 \text{ g}} = 7.78 \times 10^3 \text{ moles}$$

$$\Rightarrow n_{SO_2} = \frac{7.78 \times 10^3 \text{ mol solution}}{} \left| \frac{2.40 \times 10^{-6} \text{ mol } SO_2}{1 \text{ mol solution}} \right. = 0.0187 \text{ mol } SO_2 \text{ dissolved}$$

$$\frac{0.0187 \text{ mol } SO_2 \text{ dissolved}}{140 \text{ L}} = 1.34 \times 10^{-4} \text{ mol } SO_2/\text{L}$$

Raoult's law for water:
$$y_{H_2O} = \frac{x_{H_2O} p^*_{H_2O}(30^\circ C)}{P} = \frac{(1)(31.824 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.419 \frac{\text{mol } H_2O(v)}{\text{mol}}$$

$$y_{air} = 1 - y_{SO_2} - y_{H_2O} = 0.958 \frac{\text{mol dry air}}{\text{mol}}$$

d.   Agitate/recirculate the scrubbing solution, change it more frequently. Add a base to the solution to react with the absorbed SO_2.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$P < 200$ psig, so the container is technically safe.

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

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

The temperature in a room will never reach 140°F unless a fire breaks out, so the container is adequate.

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

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

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

When the first bubble of vapor forms,

6.55 (cont'd)

$$x_{np} = \underline{\underline{0.500 \text{ mol } n\text{-}C_5H_{12}(l) / \text{mol}}} \qquad x_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-}C_5H_{12}(l)/\text{mol}}}$$

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

$$y_{np} = \frac{x_{np} \cdot p_{np}^*}{P} = \frac{0.500(6717)}{7300} = \underline{\underline{0.46 \text{ mol } n\text{-}C_5H_{12}(v)/\text{mol}}}$$

$$y_{ip} = 1 - y_{np} = 1 - 0.46 = \underline{\underline{0.54 \text{ mol } i\text{-}C_5H_{12}(v)/\text{mol}}}$$

When the last drop of liquid evaporates,

$$y_{np} = \underline{\underline{0.500 \text{ mol } n\text{-}C_5H_{12}(v) / \text{mol}}} \qquad y_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-}C_5H_{12}(v)/\text{mol}}}$$

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

$$x_{np} = \frac{0.5 * 7250 \text{ mm Hg}}{6717 \text{ mm Hg}} = \underline{\underline{0.54 \text{ mol n-}C_5H_{12}(l)/\text{mol}}}$$

$$x_{ip} = 1 - x_{np} = 1 - 0.54 = \underline{\underline{0.46 \text{ mol } i\text{-}C_5H_{12}(l)/\text{mol}}}$$

b. When the first drop of liquid forms,

$$y_{np} = \underline{\underline{0.500 \text{ mol n-}C_5H_{12}(v) / \text{mol}}} \qquad y_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-}C_{12}H_{12}(v) / \text{mol}}}$$

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

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

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

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

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

$$x_{np} = \frac{0.5 * 1960 \text{ mm Hg}}{p_{np}^*(63.1^\circ C)} = \underline{\underline{0.56 \text{ mol } n\text{-}C_5H_{12}/\text{mol}}}$$

$$x_{ip} = 1 - x_{np} = 1 - 0.56 = \underline{\underline{0.44 \text{ mol } i\text{-}C_5H_{12}/\text{mol}}}$$

When the last bubble of vapor condenses,

$$x_{np} = \underline{\underline{0.500 \text{ mol n-}C_5H_{12}(l) / \text{mol}}} \qquad x_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-}C_5H_{12}(l) / \text{mol}}}$$
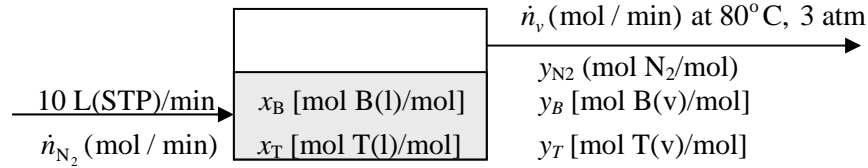
$$\text{Total pressure: } P = x_{np} \cdot p_{np}^* + x_{ip} \cdot p_{ip}^*$$

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

$$y_{np} = \frac{x_{np} \cdot p_{np}^*(62.6^\circ C)}{P} = \frac{0.5(1734)}{1960} = \underline{\underline{0.44 \text{ mol } n\text{-}C_5H_{12}(v)/\text{mol}}}$$

$$y_{ip} = 1 - y_{np} = 1 - 0.44 = \underline{\underline{0.56 \text{ mol } i\text{-}C_5H_{12}(v)/\text{mol}}}$$

6.56 B = benzene, T = toluene

$$\dot{n}_{N_2} = \frac{10.0 \text{ L(STP)} / \min}{22.4 \text{ L(STP)} / \text{mol}} = 0.4464 \text{ mol N}_2 / \min$$

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

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

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

$\underline{\text{N}_2 \text{ balance:}}$ $0.4464 \text{ mol N}_2 / \min = \dot{n}_v(1 - 0.166 - 0.0639) \Rightarrow \dot{n}_v = 0.5797 \text{ mol} / \min$

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

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

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 $\Rightarrow$ $\underline{\underline{T_{bp} = 80.5°C}} \Rightarrow \underline{\underline{y_{hex} = 0.713, \ y_{hep} = 0.287}}$

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 $\Rightarrow$ $\underline{\underline{T_{dp} = 71.1°C}} \Rightarrow \underline{\underline{x_{hex} = 0.279, \ x_{hep} = 0.721}}$

6.58 **a.** $f(T) = P - \sum_{i=1}^{N} x_i p_i^*(T) = 0 \Rightarrow T,$ where $p_i^*(T) = 10^{\left(A_i - \frac{B_i}{T + C_i}\right)}$
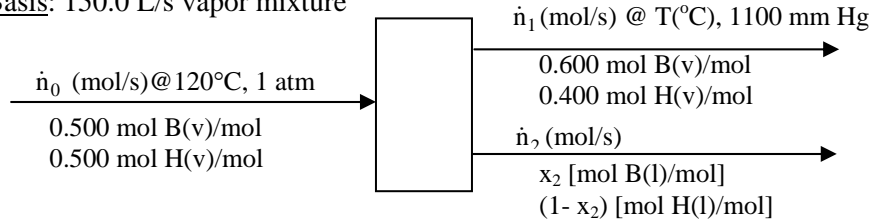
$$y_i (i = 1,2,\cdots,N) = \frac{x_i p_i^*(T)}{P}$$

b.

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

When $x_B = 1$(pure benzene), $T_{bp} = \left(T_{bp}\right)_{C_6H_6} = 80.1^oC$

When $x_{EB} = 1$(pure ethylbenzene), $T_{bp} = \left(T_{bp}\right)_{C_8H_{10}} = 136.2^oC$ $\Rightarrow T_{bp,EB} > T_{bp,T} > T_{bp,B}$

When $x_T = 1$(pure toluene), $T_{bp} = \left(T_{bp}\right)_{C_7H_8} = 110.6^oC$

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

6.59   **a.** <u>Basis</u>: 150.0 L/s vapor mixture

$\dot{n}_1$ (mol/s) @ T($^\circ$C), 1100 mm Hg
0.600 mol B(v)/mol
0.400 mol H(v)/mol

$\dot{n}_0$ (mol/s)@120°C, 1 atm
0.500 mol B(v)/mol
0.500 mol H(v)/mol

$\dot{n}_2$ (mol/s)
x_2 [mol B(l)/mol]
$(1 - x_2)$ [mol H(l)/mol]

<u>Gibbs phase rule</u>: $F = 2 + c - \pi = 2 + 2 - 2 = 2$

Since the composition of the vapor and the pressure are given, the information is enough.
<u>Equations needed</u>: Mole balances on butane and hexane, Antoine equation and Raoult's law for butane and hexane

b. <u>Molar flow rate of feed</u>: $\dot{n}_0 = \dfrac{150.0\ \text{L}}{\text{s}}\ \Bigg|\ \dfrac{273\ \text{K}}{393\ \text{K}}\ \Bigg|\ \dfrac{\text{mol}}{22.4\ \text{L (STP)}} = 4.652$ mol/s

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

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

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

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

c. From (1) and (2), $1 = \dfrac{1100(0.6)}{10^{**}(6.82485 - \frac{943.453}{T + 239.711})} + \dfrac{1100(0.4)}{10^{**}(6.88555 - \frac{1175.817}{T + 224.867})}$
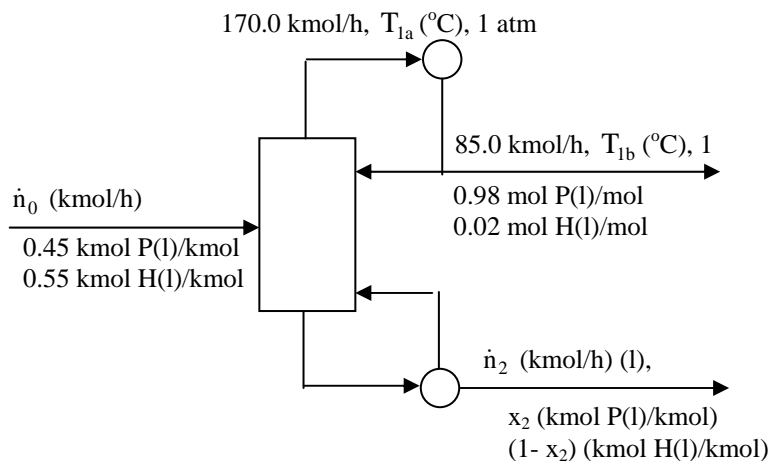
$\Rightarrow T = \underline{57.0\ ^\circ C}$

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

Solving (3) and (4) simultaneously $\Rightarrow \dot{n}_1 = \underline{\underline{3.62\ \text{mol } C_4H_{10}/s}};\ \dot{n}_2 = \underline{\underline{1.03\ \text{mol } C_6H_{14}/s}}$

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

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

170.0 kmol/h, T_{1a} ($^\circ$C), 1 atm

85.0 kmol/h, T_{1b} ($^\circ$C), 1
0.98 mol P(l)/mol
0.02 mol H(l)/mol

$\dot{n}_0$ (kmol/h)
0.45 kmol P(l)/kmol
0.55 kmol H(l)/kmol

$\dot{n}_2$ (kmol/h) (l),
x_2 (kmol P(l)/kmol)
$(1 - x_2)$ (kmol H(l)/kmol)

6.60 (cont'd)

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

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

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

b. <u>Dew point of column overhead vapor effluent:</u>

Eq. 6.4-7, Antoine equation

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

<u>Flow rate of column overhead vapor effluent.</u> Assuming ideal gas behavior,

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

<u>Flow rate of liquid distillate product.</u>

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

$$\dot{V}_{distillate} = \frac{0.98(85) \text{ kmol P}}{\text{h}} \left| \frac{72.15 \text{ kg P}}{\text{kmol P}} \right| \frac{\text{L}}{0.621 \text{ kg P}}$$

$$+ \frac{0.02(85) \text{ kmol H}}{\text{h}} \left| \frac{86.17 \text{ kg H}}{\text{kmol H}} \right| \frac{\text{L}}{0.659 \text{ kg H}} = \underline{\underline{9.9 \times 10^3 \text{ L / h}}}$$

c. <u>Reboiler temperature.</u>

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

<u>Boilup composition.</u>

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

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

d. <u>Minimum pipe diameter</u>

$$\dot{V}\left(\frac{\text{m}^3}{\text{s}}\right) = u_{max}\left(\frac{\text{m}}{\text{s}}\right) \times \frac{\pi D_{min}^2}{4}(\text{m}^2)$$

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

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

6.61 a.

Condenser

F (mol)
x_0 (mol butane/mol)

T
P

V (mol)
0.96 mol butane/mol
R (mol)
x_1 (mol butane/mol)
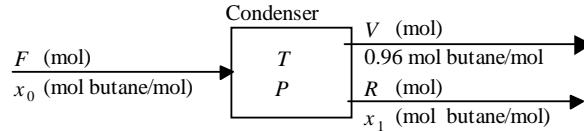
<u>Partial condenser:</u> $40°C$ is the dew point of a 96% $C_4H_{10} - 4\%$ C_5H_{12} vapor mixture at $P = P_{min}$

<u>Total condenser:</u> $40°C$ is the bubble point of a 96% C_4H_{10} - 4% C_5H_{12} liquid mixture at $P = P_{min}$

<u>Dew Point:</u> $1 = \sum x_i = \sum \dfrac{y_i P}{p_i^*(40°C)} \Rightarrow P_{min} = \dfrac{1}{\sum y_i / p_i^*(40°C)}$

(Raoult's Law)

$$\text{Antoine Eq. for } p_i^*(C_4H_{10}) = 10^{\left(6.82485 - \frac{943.453}{40+239.711}\right)} = 2830.70 \text{ mmHg}$$

$$\text{Antoine Eq. for } p_i^*(C_5H_{12}) = 10^{\left(6.84471 - \frac{1060.793}{40+231.541}\right)} = 867.22 \text{ mmHg}$$

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

<u>Bubble Point:</u> $P = \sum y_i P = \sum x_i p_i^*(40°C)$

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

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

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

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

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

<u>Equilibrium:</u> $0.96 P = x_1(2830.70)$ $\quad\left.\begin{array}{l}\end{array}\right)$ $\underline{P = 2596 \text{ mm Hg}}$

(Raoult's law) $0.04 P = (1 - x_1)(867.22)$ $\underline{x_1 = 0.8803 \text{ mol butane/mol}}$

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

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

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

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

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

6.62 (cont'd)

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

<u>Styrene – ethylbenzene is the more difficult pair to separate by distillation</u>

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

c. $\quad \alpha_{ij} = \dfrac{y_i/x_i}{y_j/x_j} \overset{\overset{y_j=1-y_i}{x_j=1-x_i}}{\Longrightarrow} \alpha_{ij} = \dfrac{y_i/x_i}{(1-y_i)/(1-x_i)} \Rightarrow \underline{\underline{y_i = \dfrac{\alpha_{ij}x_i}{1+(\alpha_{ij}-1)x_i}}}$

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

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

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

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

<u>Bubble point T:</u> $P = \sum x_i p_i^*(T)$

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

$\xrightarrow{\text{E-Z Solve}} \underline{\underline{T_1 = 67.6°\,C}}$

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

<u>B balance:</u> $y_0 \dot{n}_v + x_2 \dot{n}_l = y_1 \dot{n}_v + x_1 \dot{n}_l \Rightarrow \underline{\underline{x_2 = 0.910 \text{ mol B/mol} \Rightarrow 0.090 \text{ mol S/mol}}}$
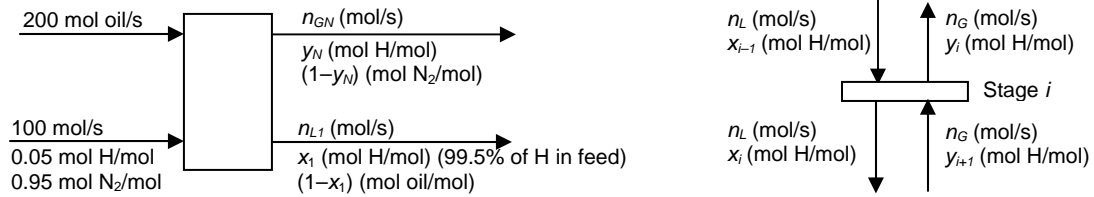
<u>Stage 2:</u>

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

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

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

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

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

a. N$_2$ balance: $0.95(100) = (1 - y_N)\dot{n}_{GN}$

99.5% absorption: $0.05(100)(0.005) = y_N \dot{n}_{GN}$ $\Biggr\} \Rightarrow$ $\dot{n}_{GN} = 95.025 \text{ mol/s}$

$y_N = 2.63 \times 10^{-4} \text{ mol H(v)/mol}$

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

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

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

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

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

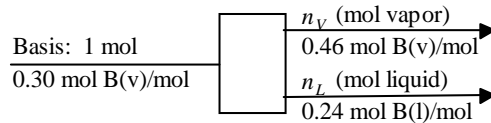**c.** The given formulas follow from Raoult's law and a hexane balance on Stage i.

d.

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

6.64 (cont'd)

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

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

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

Basis: 1 mol
0.30 mol B(v)/mol

n_V (mol vapor)
0.46 mol B(v)/mol

n_L (mol liquid)
0.24 mol B(l)/mol

Balances

$$\text{Total moles:} \quad 1 = n_V + n_L$$
$$\text{B:} \qquad\qquad 0.30 = 0.46n_V + 0.24n_L$$

$\Rightarrow \begin{matrix} n_L = 0.727 \text{ mol} \\ n_V = 0.273 \text{ mol} \end{matrix} \Rightarrow \underline{\underline{\dfrac{n_V}{n_L} = 0.375 \dfrac{\text{mol vapor}}{\text{mol liquid}}}}$

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

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

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

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

3 mol B
7 mol T

n_V (mol)
0.43 mol B/mol
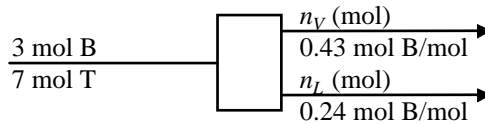
n_L (mol)
0.24 mol B/mol

$$\text{Mole bal.:} \quad 10 = n_V + n_L$$
$$\text{B bal.:} \qquad 3 = 0.43n_V + 0.24n_L$$

$\Rightarrow \begin{matrix} n_V = 3.16 \text{ mol} \\ n_L = 6.84 \text{ mol} \end{matrix} \Rightarrow \underline{\underline{\dfrac{n_v}{n_l} = 0.46 \dfrac{\text{mol vapor}}{\text{mol liquid}}}}$

Answers may vary due to difficulty of reading chart.

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

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

ii) 750 mmHg. Assume liquid volume negligible

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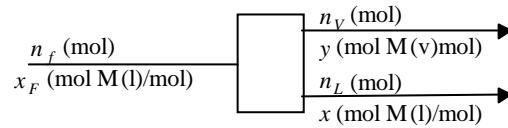
$$V = \frac{3.16 \text{ mol vapor}}{} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \frac{373 \text{ K}}{750 \text{ mm Hg}} \left| \frac{760 \text{ mm Hg}}{1 \text{ atm}} \right| - 0.6 \text{ L} = \underline{\underline{97.4 \text{ L}}}$$

(Liquid volume is about 0.6 L)

iii) 600 mm Hg

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

6.67 a. M = methanol

$$\begin{array}{c} n_f \text{ (mol)} \\ x_F \text{ (mol M(l)/mol)} \end{array} \longrightarrow \boxed{} \longrightarrow \begin{array}{c} n_V \text{ (mol)} \\ y \text{ (mol M(v)mol)} \\ n_L \text{ (mol)} \\ x \text{ (mol M(l)/mol)} \end{array}$$

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

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

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

6.68 a.

Txy diagram

(P=1 atm)
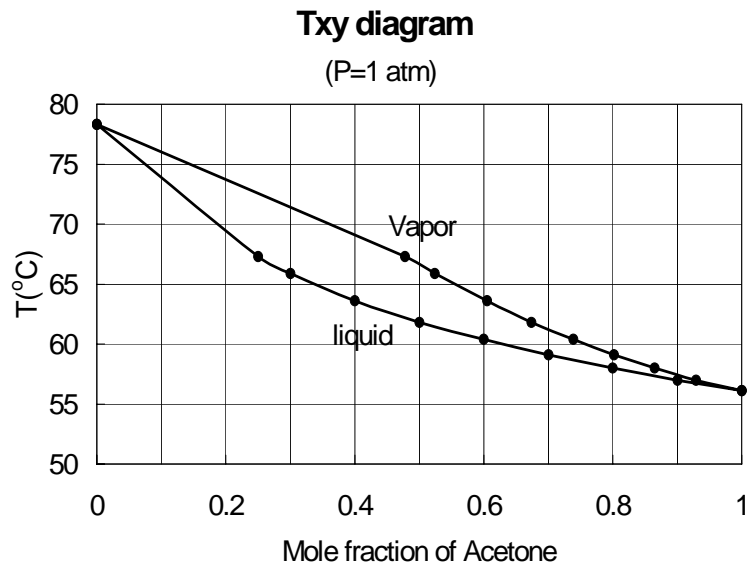
b. $\underline{\underline{x_A = 0.47; \ y_A = 0.66}}$

6.68 (cont'd)

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

(ii) Mole bal.: $1 = n_V + n_L$

A bal.: $0.50 = 0.55 n_V + 0.34 n_L$ $\Big\}$ $\Rightarrow n_V = 0.762$ mol vapor, $n_L = 0.238$ mol liquid ∂

$\Rightarrow$ 76.2 mole% vapor

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

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

$M_A = 58.08$ g/mol, $M_E = 46.07$ g/mol

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

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

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

Vapor volume:

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

Volume percent of vapor $= \dfrac{88{,}747}{88747 + 63.48} \times 100\% = 99.9$ volume% vapor

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

T	x_A	y_A	f_V
65 °C	0.34	0.55	0.333
64.5 °C	**0.36**	**0.56**	0.200

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

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

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

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

$y_A = 0.674 \Rightarrow \dfrac{\Delta y_A}{y_A(\text{real})} = \dfrac{0.696 - 0.674}{0.674} \times 100\% = 3.3\%$ error in y_A
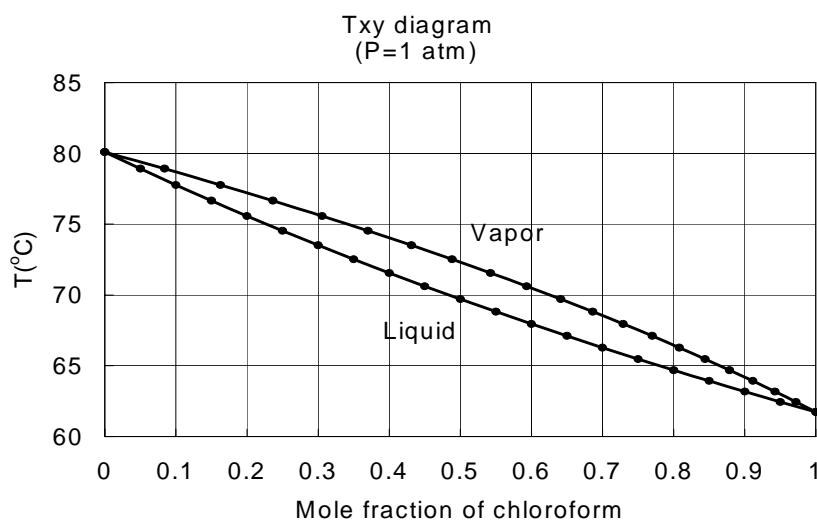
Acetone and ethanol are not structurally similar compounds (as are, for example, pentane and hexane or benzene and toluene). There is consequently no reason to expect Raoult's law to be valid for acetone mole fractions that are not very close to 1.

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

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

b.

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

Txy diagram
(P=1 atm)

6.69 (cont'd)

d.

Txy diagram
(P=1 atm)
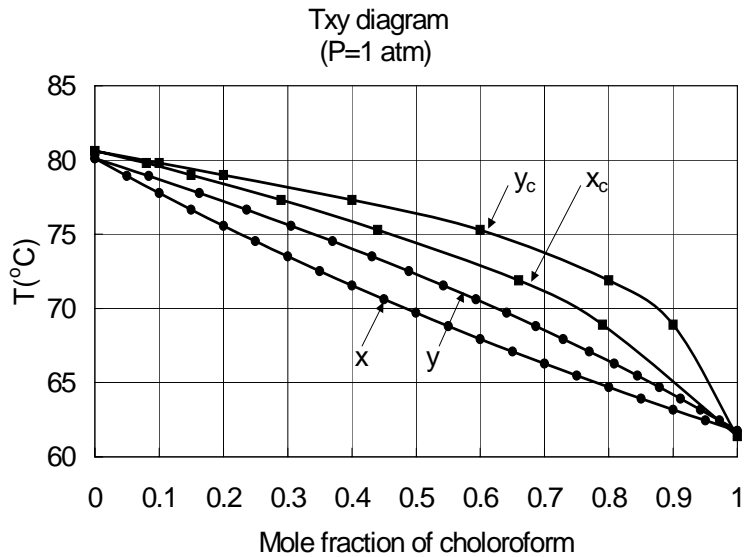
$$\text{Raoult's law: } T_{bp} = 71^\circ\text{C}, \quad y = 0.58 \Rightarrow \quad \begin{array}{l} \dfrac{\Delta T}{T_{actual}} = \dfrac{71 - 75.3}{75.3} \times 100\% = \underline{\underline{-5.7\%}} \text{ error in } T_{bp} \\[4mm] \dfrac{\Delta y}{y_{actual}} = \dfrac{0.58 - 0.60}{0.60} \times 100\% = \underline{\underline{-3.33\%}} \text{ error in } y \end{array}$$

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

6.70 $P \approx 1 \text{ atm} = 760 \text{ mm Hg} = x_m p_m^*\left(T_{bp}\right) + \left(1 - x_m\right) p_P^*\left(T_{bp}\right)$

$760 = 0.40 \times 10^{7.87863 - 1473.11/(T_{bp} + 230)} + 0.60 \times 10^{7.74416 - 1437.686/(T_{bp} + 198.463)} \xrightarrow{\text{E-Z Solve}} \underline{T = 79.9^\circ\text{C}}$

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

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

6.71 <u>Basis</u>: 1000 kg/h product

$E = C_2H_5OH \ (M = 46.05)$
$A = CH_3CHO \ (M = 44.05)$

$P = 760$ mm Hg
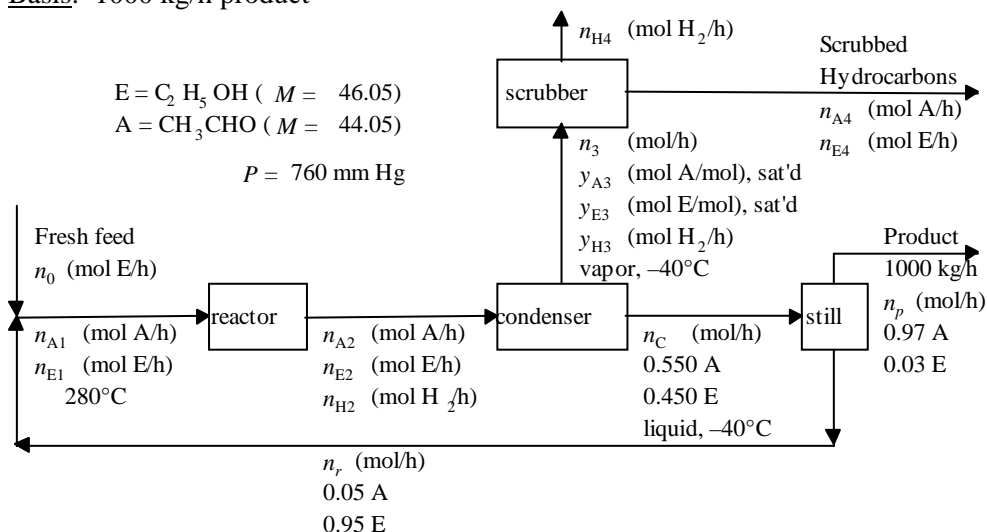
<u>Strategy</u>

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

a. <u>Molar flow rate of product</u>

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

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

<u>Table B.4</u> (Antoine) $\Rightarrow \ p_A^*(-40°C) = 44.8$ mm Hg
$$p_E^*(-40°C) = 0.360 \ \text{mm Hg}$$

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

<u>Raoult's law</u> $\Rightarrow \underline{y_{A3}} = \dfrac{0.550 p_A^*(-40 \ °C)}{P} = \dfrac{0.550(44.8)}{760} = 0.03242 \ \text{kmol A/kmol}$

6.71 (cont'd)

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

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

Mole balance about still: $\dot{n}_c = \dot{n}_p + \dot{n}_r \Rightarrow \dot{n}_c = 22.67 + \dot{n}_r$ ⎱ $\Rightarrow$ $\underline{\dot{n}_r = 29.5 \text{ kmol / h recycle}}$
A balance about still: $0.550\dot{n}_c = 0.97(22.67) + 0.05\dot{n}_r$ ⎰ $\underline{\dot{n}_c = 52.1 \text{ kmol / h}}$

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

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

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

Overall C balance:

$$\frac{\dot{n}_0 \text{ (mol E)}}{\text{h}} \left| \frac{2 \text{ mol C}}{1 \text{ mol E}} \right. = (\dot{n}_{A4})(2) + (\dot{n}_{E4})(2) + (0.97\dot{n}_p)(2) + (0.03\dot{n}_p)(2)$$

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

Overall H balance:

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

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

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

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

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

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

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

Ideal gas equation of state :

$$V_{\text{reactor feed}} = \frac{(1.47 + 51.5) \text{ kmol}}{\text{h}} \left| \frac{22.4 \text{ m}^3 \text{ (STP)}}{1 \text{ kmol}} \right. \left| \frac{(273+280)\text{K}}{273\text{K}} \right. = \underline{\underline{2.40 \times 10^3 \text{ m}^3/\text{h}}}$$
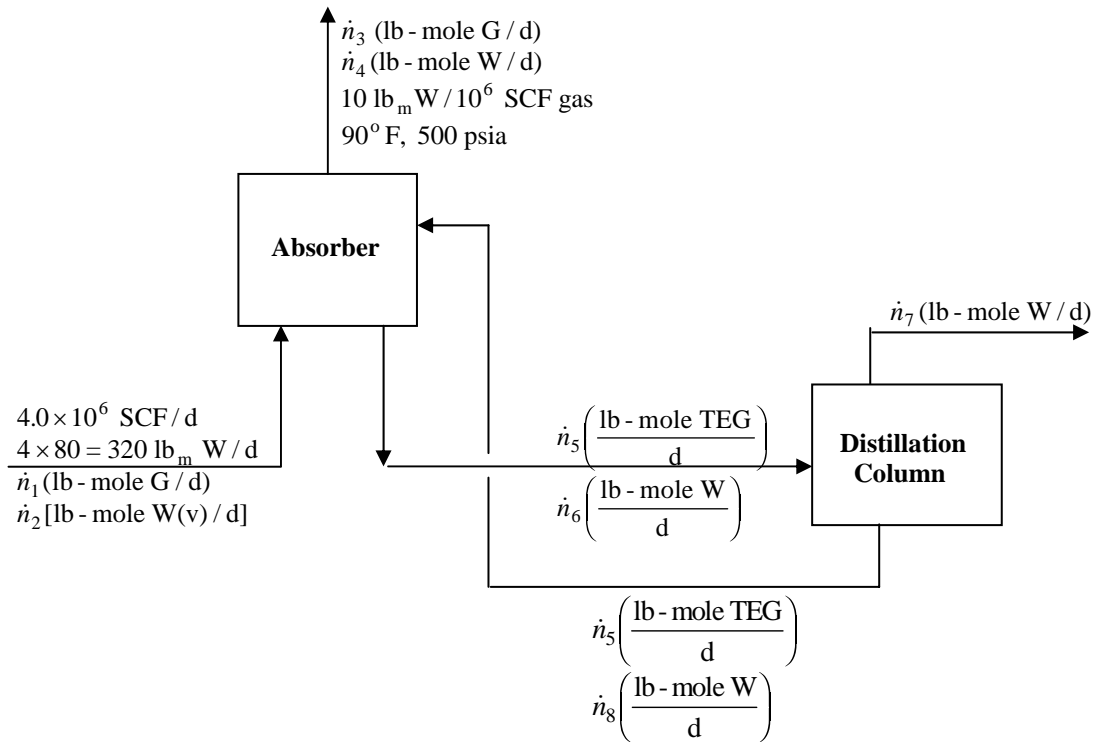
b. Overall conversion $= \dfrac{\dot{n}_0 - 0.03\dot{n}_p}{\dot{n}_0} \times 100\% = \dfrac{23.4 - (0.03)(22.67)}{23.4} \times 100\% = \underline{\underline{97\%}}$

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

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

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

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

$\dot{n}_3$ (lb - mole G / d)
$\dot{n}_4$ (lb - mole W / d)
$10 \text{ lb}_m \text{W} / 10^6$ SCF gas
90° F, 500 psia

Absorber

$\dot{n}_7$ (lb - mole W / d)

4.0×10^6 SCF / d
$4 \times 80 = 320 \text{ lb}_m$ W / d
$\dot{n}_1$ (lb - mole G / d)
$\dot{n}_2$ [lb - mole W(v) / d]

$\dot{n}_5 \left(\dfrac{\text{lb - mole TEG}}{\text{d}} \right)$

$\dot{n}_6 \left(\dfrac{\text{lb - mole W}}{\text{d}} \right)$

Distillation Column

$\dot{n}_5 \left(\dfrac{\text{lb - mole TEG}}{\text{d}} \right)$

$\dot{n}_8 \left(\dfrac{\text{lb - mole W}}{\text{d}} \right)$

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

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

<u>Dry gas feed rate:</u>

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

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

<u>Flow rate of water in dried gas:</u>

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

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

<u>Overall W balance:</u>

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

6.72 (cont'd)

b. Mole fraction of water in dried gas =

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

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

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

c. Solvent/solute mole ratio

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

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

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

Solvent stream entering absorber

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

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

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
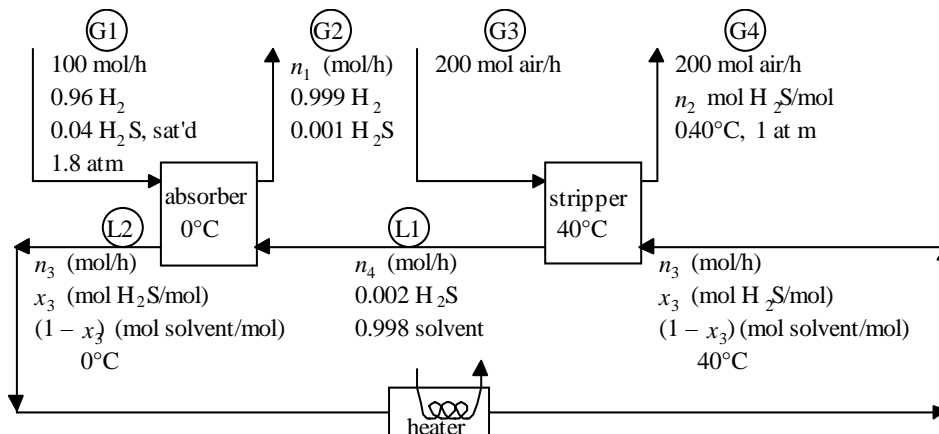
6.73 (cont'd)

Equilibrium condition: At G1, $p_{H_2S} = (0.04)(1.8 \text{ atm}) = 0.072 \text{ atm}$

$$\Rightarrow x_3 = \frac{p_{H_2S}}{H_{H_2S}} = \frac{0.072 \text{ atm}}{27 \text{ atm/mol fraction}} = 2.67 \times 10^{-3} \text{ mole } H_2S/\text{mole}$$

Strategy: Overall H_2 and H_2S balances $\Rightarrow \dot{n}_1, \dot{n}_2$
$\dot{n}_2$ + air flow rate $\Rightarrow$ volumetric flow rate at G4
H_2S and solvent balances around absorber $\Rightarrow \dot{n}_3, \dot{n}_4$
$0.998\dot{n}_4 = $ solvent flow rate

Overall H_2 balance: $(100)(0.96) = 0.999n_1 \Rightarrow \dot{n}_1 = 96.1 \text{ mol/h}$

Overall H_2S balance: $(100)(0.04) = 0.001\dot{n}_1 + \dot{n}_2 \overset{\dot{n}_1=96.1}{\Rightarrow} \dot{n}_2 = 3.90 \text{ mol } H_2S/h$

Volumetric flow rate at stripper outlet

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

H_2S and solvent balances around absorber:

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

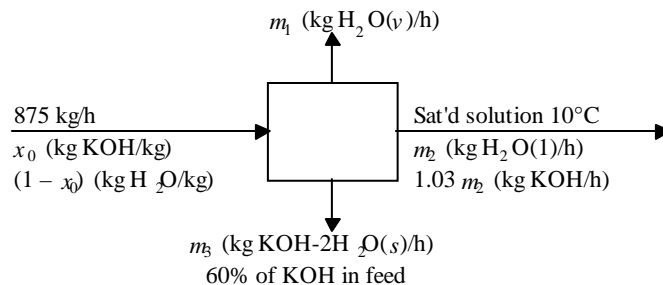Solvent flow rate $= 0.998\dot{n}_4 = 5820 \text{ mol solvent/h}$

6.74 Basis: 100 g H_2O

Sat'd solution @ 60°C
100 g H_2O
16.4 g $NaHCO_3$

Sat'd solution @ 30°C
100 g H_2O
11.1 g $NaHCO_3$
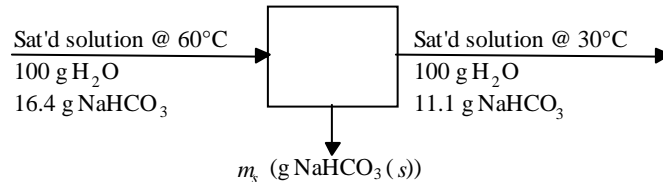
m_s (g $NaHCO_3(s)$)

$NaHCO_3$ balance $\Rightarrow 16.4 = 11.1 + m_s \Rightarrow m_s = 5.3 \text{ g } NaHCO_3(s)$

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

6.75 Basis: 875 kg/h feed solution

m_1 (kg $H_2O(v)$/h)

875 kg/h
x_0 (kg KOH/kg)
$(1 - x_0)$ (kg H_2O/kg)

Sat'd solution 10°C
m_2 (kg $H_2O(1)$/h)
1.03 m_2 (kg KOH/h)

m_3 (kg KOH·2H$_2$O(s)/h)
60% of KOH in feed

6.75 (cont'd)

Analysis of feed: $2KOH + H_2SO_4 \rightarrow K_2SO_4 + 2H_2O$

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

$$= 0.427 \text{ g KOH/g feed}$$

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

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

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

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

6.76 a.

$$C_A = \frac{\text{g A dissolved}}{\text{mL solution}}$$

R	0	30	45
C_A	0	0.200	0.300

Plot C_A vs. R $\Rightarrow$ $\underline{\underline{C_A = R/150}}$

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

The initial solution is saturated at 10.2 °C.

Solubility @ 10.2 °C $= \dfrac{160 \text{ g A}}{390 \text{ g S}} = 0.410 \text{ g A/g S} = \underline{\underline{41.0 \text{ g A/100 g S @ 10.2°C}}}$

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

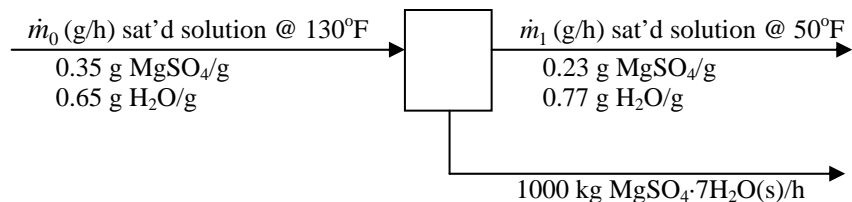Thus 1 g of solution saturated at 0°C contains 0.106 g A & 0.894 g S.

Solubility @ 0°C $\dfrac{0.106 \text{ g A}}{0.894 \text{ g S}} = 0.118 \text{ g A/g S} = \underline{\underline{11.8 \text{ g A/100 g S @ 0°C}}}$

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

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

6.77 a. Table 6.5-1 shows that at 50°F (10.0°F), the salt that crystallizes is $\underline{\underline{MgSO_4 \cdot 7H_2O}}$, which contains 48.8 wt% $MgSO_4$.

b. Basis: 1000 kg crystals/h.

$\dot{m}_0$ (g/h) sat'd solution @ 130°F
0.35 g MgSO₄/g
0.65 g H₂O/g

$\dot{m}_1$ (g/h) sat'd solution @ 50°F
0.23 g MgSO₄/g
0.77 g H₂O/g

1000 kg MgSO₄·7H₂O(s)/h

6.77 (cont'd)

<u>Mass balance:</u> $\dot{m}_0 = \dot{m}_1 + 1000$ kg / h
<u>MgSO$_4$ balance:</u> $0.35m_0 = 0.23\dot{m}_1 + 0.488(1000)$ kg MgSO$_4$ / h $\left.\right\}$ $\Rightarrow$ $\dot{m}_0 = 2150$ kg feed / h
$\dot{m}_1 = 1150$ kg soln / h

The crystals would yield 0.488×1000 kg / h $= \underline{\underline{488 \dfrac{\text{kg anhydrous MgSO}_4}{\text{h}}}}$

6.78 <u>Basis:</u> 1 lb$_m$ feed solution.

Figure 6.5-1 $\Rightarrow$ a saturated KNO$_3$ solution at 25°C contains 40 g KNO$_3$/100 g H$_2$O

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

```
          1 lb_m solution @ 80°C   ┌─────┐
          0.50 lb_m KNO₃/lb_m  ───▶│     │───▶
          0.50 lb_m H₂O/lb_m       └─────┘
```
m_1(lb$_m$) sat'd solution @ 25°C
0.286 lb$_m$ KNO$_3$/lb$_m$ soln
0.714 lb$_m$ H$_2$O/lb$_m$ soln
m_2 [lb$_m$ KNO$_3$(s)]
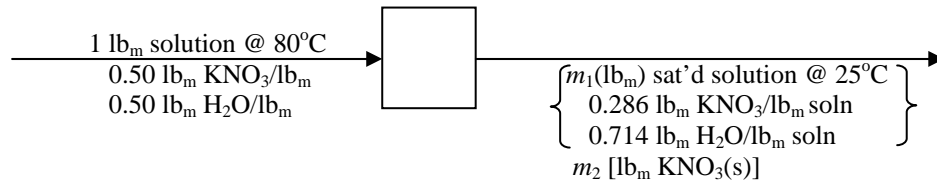
<u>Mass balance:</u> 1 lb$_m = m_1 + m_2$
<u>KNO$_3$ balance:</u> 0.50 lb$_m$ KNO$_3 = 0.286m_1 + m_2$ $\left.\right\}$ $\Rightarrow$ $m_1 = 0.700$ lb$_m$ solution / lb$_m$ feed
$m_2 = \underline{\underline{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}}$

<u>Solid / liquid mass ratio</u> $= \dfrac{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}{0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}} = \underline{\underline{0.429 \text{ lb}_m \text{ crystals / lb}_m \text{ solution}}}$

6.79 a. <u>Basis:</u> 1000 kg NaCl(s)/h.

Figure 6.5-1 $\Rightarrow$ a saturated NaCl solution at 80°C contains 39 g NaCl/100 g H$_2$O

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

$\dot{m}_2$ [kg H$_2$O(v) / h]

```
              ┌─────┐
  ṁ₀ (kg/h) solution ───▶│   │───▶ ṁ₁ (kg/h) sat'd solution @ 80°C
              └─────┘
```
$\dot{m}_0$ (kg/h) solution
0.100 kg NaCl/kg
0.900 kg H$_2$O/kg

$\dot{m}_1$ (kg/h) sat'd solution @ 80°C
0.281 kg NaCl/kg soln
0.719 kg H$_2$O/kg soln
1000 kg NaCl(s)/h
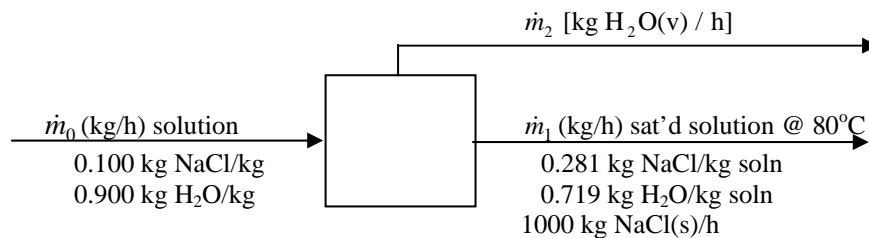
<u>Mass balance:</u> $\dot{m}_0 = \dot{m}_1 + \dot{m}_2$
<u>NaCl balance:</u> 0.100 kg NaCl $= 0.281\dot{m}_1 + \dot{m}_2$ $\left.\right\}$ $\Rightarrow$ $\dot{m}_1 = 0.700$ lb$_m$ solution / lb$_m$ feed
$\dot{m}_2 = \underline{\underline{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}}$

<u>Solid / liquid mass ratio</u> $= \dfrac{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}{0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}} = \underline{\underline{0.429 \text{ lb}_m \text{ crystals / lb}_m \text{ solution}}}$

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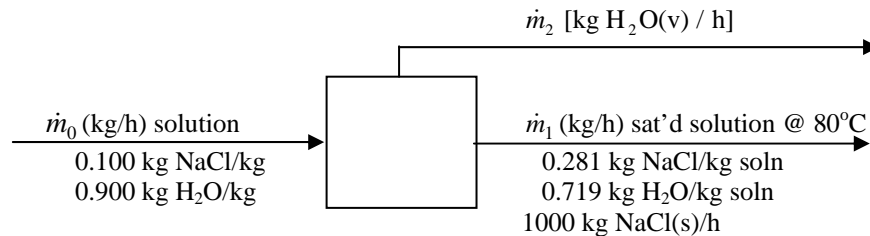
6.79 (cont'd)

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

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

<u>Exit solution flow rate:</u> $\underline{\underline{\dot{m}_1 = 0}}$

b.

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

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

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

6.80 <u>Basis:</u> 1000 kg $K_2Cr_2O_7(s)/h$. Let $K = K_2Cr_2O_7$, A = dry air, S = solution, W = water.

<u>Composition of saturated solution:</u>

$$\frac{0.20 \text{ kg K}}{\text{kg W}} \Rightarrow \frac{0.20 \text{ kg K}}{(1+0.20) \text{ kg soln}} = 0.1667 \text{ kg K/kg soln}$$
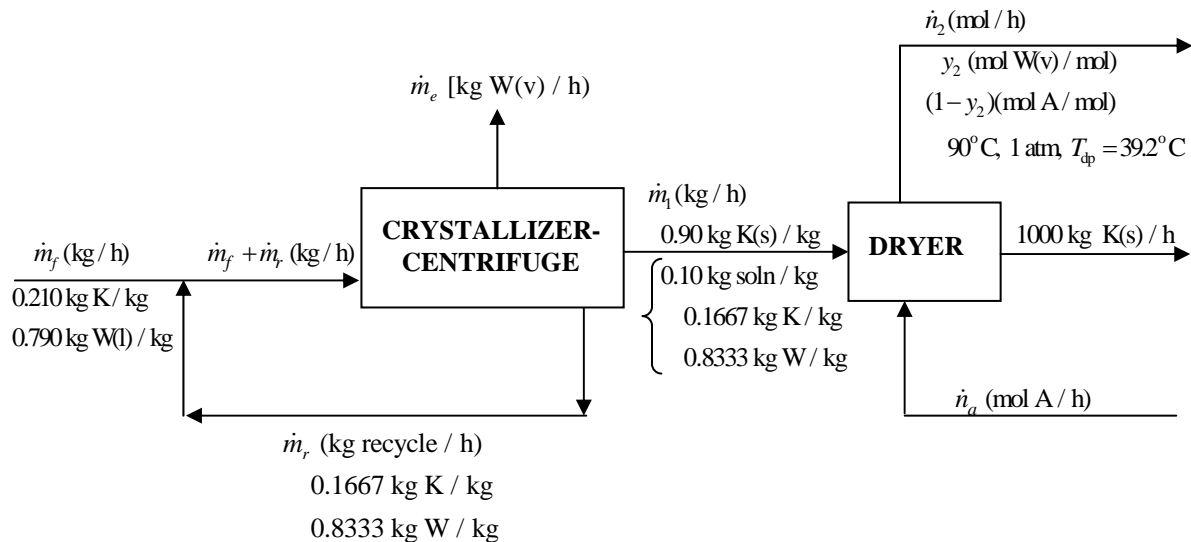
<u>Dryer outlet gas:</u> $y_2 P = p_W^*(39.2°\text{C}) \Rightarrow y_2 = \dfrac{53.01 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0698 \text{ mol W/mol}$

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

6.80 (cont'd)

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

Mass balance around crystallizer-centrifuge

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

$$95\% \text{ solution recycled} \Rightarrow \dot{m}_r = \frac{(0.10 \times 1090) \text{ kg /h not recycled}}{} \frac{95 \text{ kg recycled}}{5 \text{ kg not recycled}}$$

$$= \underline{2070 \text{ kg/h recycled}}$$

Water balance on dryer

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

Dry air balance on dryer

$$n_a = \frac{(1 - 0.0698)7.225 \times 10^4 \text{ mol}}{\text{h}} \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} = \underline{1.51 \times 10^6 \text{ L(STP)/h}}$$

6.81. Basis : 100 kg liquid feed. Assume $P_{atm}=1$ atm
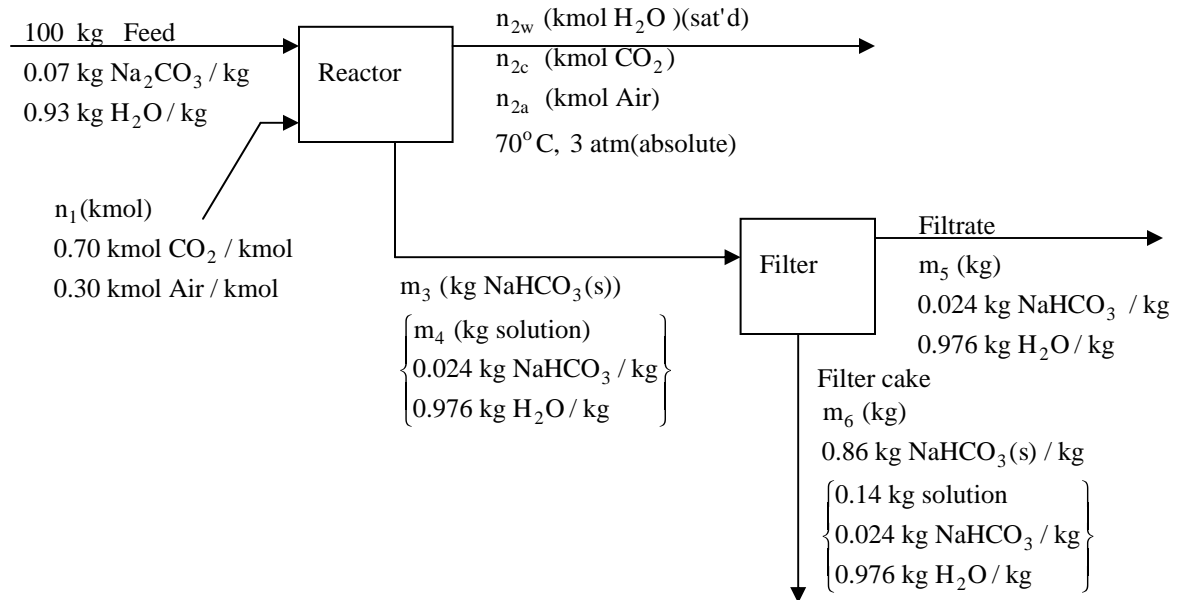
Degree of freedom analysis:

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

Na balance on reactor

$$\frac{100\,kg}{} \left| \frac{0.07\,kg\,Na_2CO_3}{kg} \right| \frac{46\,kg\,Na}{106\,kg\,Na_2CO_3} = \frac{(m_3+0.024m_4)\,kg\,NaHCO_3}{} \left| \frac{23\,kg\,Na}{84\,kg\,NaHCO_3} \right.$$

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

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

C balance on reactor :

$$\frac{n_1\,(kmol)}{} \left| \frac{0.700\,kmol\,CO_2}{kmol} \right| \frac{12\,kg\,C}{1\,kmol\,CO_2} + \frac{100\,kg}{} \left| \frac{0.07\,kg\,Na_2CO_3}{kg} \right| \frac{12\,kg\,C}{106\,kg\,Na_2CO_3}$$

$$= (n_{2c})(12)+(m_3+0.024m_2)(\frac{12}{84}) \Rightarrow 8.40n_1+0.7924 = 12n_{2c}+0.1429\,(m_3+0.024m_4) \qquad (3)$$

H balance :

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

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

6.81(cont'd)

O balance (not counting O in the air):

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

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

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

Raoult's Law :

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

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

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

$n_1 = 0.8086$ kmol, $\quad n_{2a} = 0.2426$ kmol air, $\quad n_{2c} = 0.500$ kmol CO_2,

$n_{2w} = 0.0848$ kmol $H_2O(v)$, $\quad m_3 = 8.874$ kg $NaHCO_3(s)$, $\quad m_4 = 92.50$ kg solution

$NaHCO_3$ balance on filter:

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

$$\underset{m_4=92.50}{\overset{m_3=8.874}{\Longrightarrow}} 11.09 = 0.024m_5 + 0.8634m_6 \qquad (7)$$

Mass Balance on filter: $8.874 + 92.50 = 101.4 = m_5 + m_6 \qquad (8)$

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

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

(a) Gas stream leaving reactor

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

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

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

6.81(cont'd)

**(c)** <u>Liquid feed</u>: $(100)(56.39) = \underline{\underline{5640}}$ kg / h

To calculate $\dot{V}$, we would need to know the density of a 7 wt% aqueous Na_2CO_3 solution.

(d) If T dropped in the filter, more solid $NaHCO_3$ would be recovered and the residual solution would contain less than 2.4% $NaHCO_3$.

(e)

<u>Benefit</u>: Higher pressure $\Rightarrow$ greater p_{CO_2} $\xrightarrow{\text{Henry's law}}$ higher concentration of CO_2 in solution $\Rightarrow$ higher rate of reaction $\Rightarrow$ smaller reactor needed to get the same conversion $\Rightarrow$ lower cost

<u>Penalty</u>: Higher pressure $\Rightarrow$ greater cost of compressing the gas (purchase cost of compressor, power consumption)

6.82
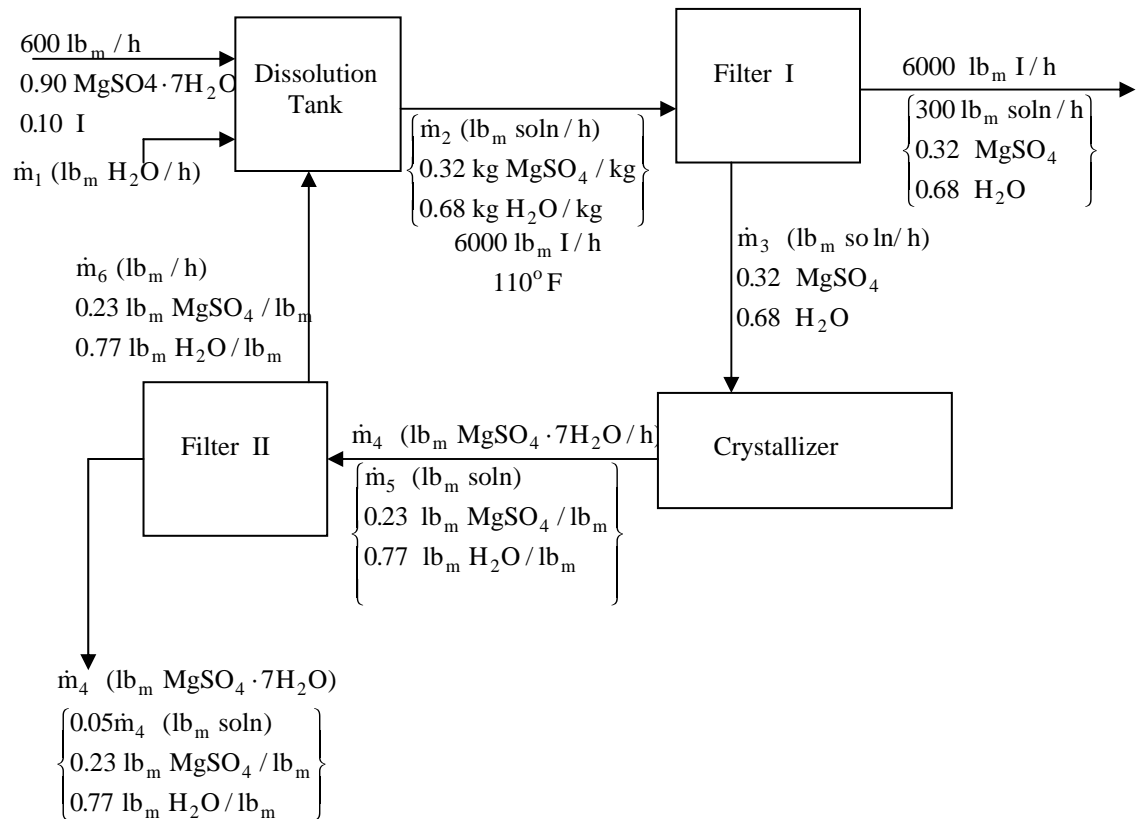
a. Heating the solution dissolves all $MgSO_4$; filtering removes I, and cooling recrystallizes $MgSO_4$ enabling subsequent recovery.

(b) <u>Strategy</u>: Do D.F analysis.

6.82(cont'd)

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

$(MW)_{\text{MgSO}_4} = (24.31 + 32.06 + 64.00) = 120.37, \ (MW)_{\text{MgSO}_4\cdot7\text{H}_2\text{O}} = (120.37 + 7*18.01) = 246.44$

Overall MgSO$_4$ balance:

$$\frac{60,000\,\text{lb}_m}{\text{h}}\left|\frac{0.90\,\text{lb}_m\ \text{MgSO}_4\cdot7\text{H}_2\text{O}}{\text{lb}_m}\right|\frac{120.37\,\text{lb}_m\ \text{MgSO}_4}{246.44\,\text{lb}_m\ \text{MgSO}_4\cdot7\text{H}_2\text{O}}$$

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

$$\Rightarrow \ \dot{m}_4 = 5.257x10^4\ \text{lb}_m\ \text{crystals}\,/\,\text{h}$$

$\underline{\text{Overall mass balance: }} 60,000 + \dot{m}_1 = 6300 + 1.05\dot{m}_4 \xrightarrow{\dot{m}_4 = 5.257x10^4\ \text{lb}_m/h} \dot{m}_1 = \underline{\underline{1494\ \text{lb}_m\ \text{H}_2\text{O}\,/\,\text{h}}}$
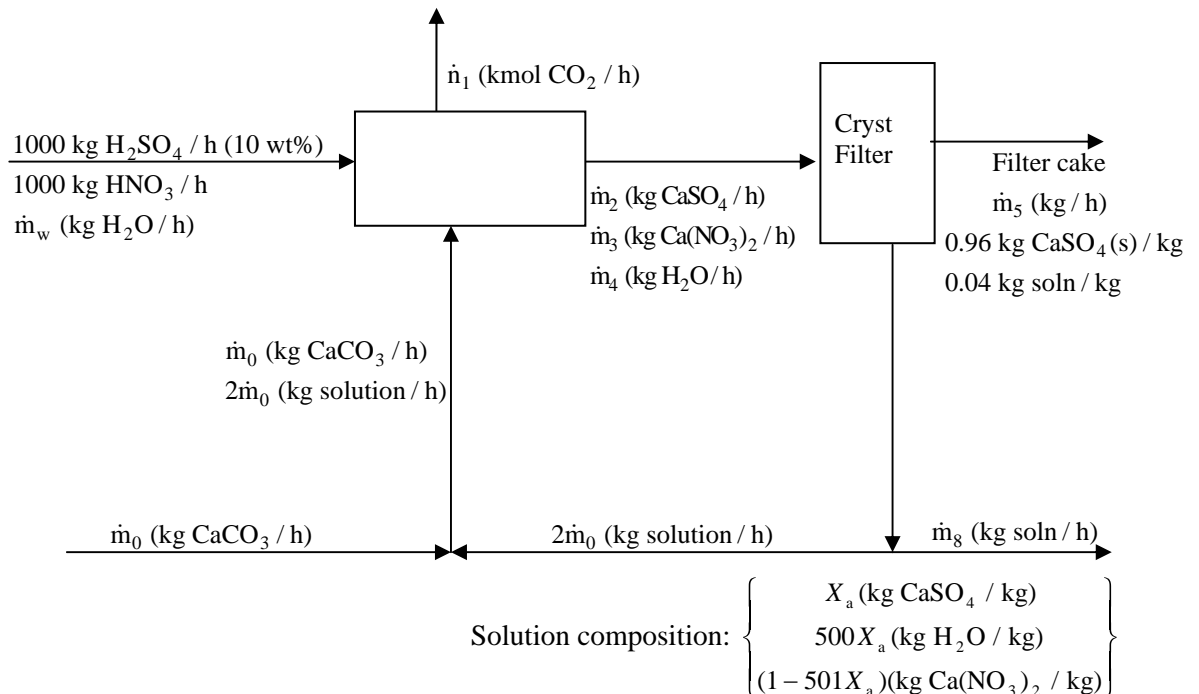
c.

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

$$\Rightarrow \quad \begin{array}{l}\dot{m}_2 = 1.512x10^5\ \text{lb}_m\,/\,\text{h}\\ \dot{m}_6 = 9.575x10^4\ \text{lb}_m\,/\,\text{h}\quad\text{recycle}\end{array}$$

$$\underline{\text{Recycle/fresh feed ratio}} = \frac{9.575x10^4\ \text{lb}_m\,/\,\text{h}}{1494\ \text{lb}_m\,/\,\text{h}} = \underline{\underline{64\quad\text{lb}_m\ \text{recycle}\,/\,\text{lb}_m\ \text{fresh feed}}}$$

6.83 a.

6.83 (cont'd)

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

c. <u>Acid feed</u>: $\dfrac{1000 \text{ kg } H_2SO_4 \,/\, h}{(2000 + \dot{m}_w) \text{ kg} \,/\, h} = 0.10 \Rightarrow \dot{m}_w = 8000 \text{ kg } H_2O \,/\, h$

<u>Overall S balance</u>:

$$\frac{1000 \text{ kg } H_2SO_4}{h} \left|\frac{32 \text{ kg S}}{98 \text{ kg } H_2SO_4}\right. = \frac{\dot{m}_5 \text{ (kg / h)}}{} \left|\frac{(0.96 + 0.04 X_a) \text{ (kg CaSO}_4)}{kg}\right| \frac{32 \text{ kg S}}{136 \text{ kg CaSO}_4}$$

$$+ \frac{\dot{m}_8 \text{ (kg / h)}}{} \left|\frac{X_a \text{ (kg CaSO}_4)}{kg}\right| \frac{32 \text{ kg S}}{136 \text{ kg CaSO}_4}$$

$$\Rightarrow 326.5 = 0.2353\dot{m}_5(0.96 + 0.04 X_a) + 0.2353\dot{m}_8 X_a \tag{1}$$

<u>Overall N balance</u>:

$$\frac{1000 \text{ kg } HNO_3}{h} \left|\frac{14 \text{ kg N}}{63 \text{ kg } HNO_3}\right. = \frac{0.04\dot{m}_5 \text{ (kg / h)}}{} \left|\frac{(1 - 501X_a) \text{ (kg Ca(NO}_3)_2)}{kg}\right| \frac{28 \text{ kg N}}{164 \text{ kg Ca(NO}_3)_2}$$

$$+ \frac{\dot{m}_8 \text{ (kg / h)}}{} \left|\frac{(1 - 501X_a) \text{ (kg Ca(NO}_3)_2)}{kg}\right| \frac{28 \text{ kg N}}{164 \text{ kg Ca(NO}_3)_2}$$

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

<u>Overall Ca balance</u>:

$$\frac{\dot{m}_0 \text{ (kg / h)}}{} \left|\frac{40 \text{ kg Ca}}{100 \text{ kg CaCO}_3}\right. = \frac{\dot{m}_5 \text{ (kg / h)}}{} \left|\frac{(0.96 + 0.04 X_a) \text{ (kg CaSO}_4)}{kg}\right| \frac{40 \text{ kg Ca}}{136 \text{ kg CaSO}_4}$$

$$+ \frac{(1 - 501X_a) \text{ (kg Ca(NO}_3)_2)}{kg} \left|\frac{0.04\dot{m}_5 \text{ (kg / h)}}{}\right| \frac{40 \text{ kg Ca}}{164 \text{ kg Ca(NO}_3)_2}$$

$$+ \frac{\dot{m}_8 \text{ (kg / h)}}{} \left|\frac{X_a \text{ (kg CaSO}_4)}{kg}\right| \frac{40 \text{ kg Ca}}{136 \text{ kg CaSO}_4}$$

$$+ \frac{\dot{m}_8 \text{ (kg / h)}}{} \left|\frac{(1 - 501X_a) \text{ (kg Ca(NO}_3)_2)}{kg}\right| \frac{40 \text{ kg Ca}}{164 \text{ kg Ca(NO}_3)_2}$$

$$\Rightarrow 0.40\dot{m}_0 = 0.294\dot{m}_5(0.96 + 0.04 X_a) + 0.00976\dot{m}_5(1 - 501X_a)$$
$$+ 0.294\dot{m}_8 X_a + 0.244\dot{m}_8(1 - 501X_a) \tag{3}$$

<u>Overall C balance</u> :

$$\frac{\dot{m}_0 \text{ (kg / h)}}{} \left|\frac{12 \text{ kg C}}{100 \text{ kg CaCO}_3}\right. = \frac{\dot{n}_1 \text{ (kmol CO}_2 \text{ / h)}}{} \left|\frac{1 \text{ kmol C}}{1 \text{ kmol CO}_2}\right| \frac{12 \text{ kg C}}{1 \text{ kmol C}}$$

$$\Rightarrow 0.01\dot{m}_0 = \dot{n}_1 \tag{4}$$

6.83 (cont'd)

Overall H balance :

$$\frac{1000\,(kg\,H_2SO_4)}{h}\left|\frac{2\,kg\,H}{98\,kg\,H_2SO_4}+\frac{1000\,kg\,HNO_3}{h}\right|\frac{1\,kg\,H}{63\,kg\,HNO_3}+\frac{\dot{m}_w\,(kg/h)}{}\left|\frac{2\,kg\,H}{18\,kg\,H_2O}\right.$$

$$=\frac{0.04\dot{m}_5\,(kg/h)}{}\left|\frac{500X_a\,(kg\,H_2O)}{kg}\right|\frac{2\,kg\,H}{18\,kg\,H_2O}+\frac{\dot{m}_8\,(kg/h)}{}\left|\frac{500X_a\,(kg\,H_2O)}{kg}\right|\frac{2\,kg\,H}{18\,kg\,H_2O}$$

$$\Rightarrow 925.17 = 2.22\dot{m}_5 X_a + 55.56\dot{m}_8 X_a \qquad (5)$$

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

$$\dot{m}_0 = \underline{\underline{1812.5\,kg\,CaCO_3(s)/h}}, \qquad \dot{m}_5 = \underline{\underline{1428.1\,kg/h}}, \qquad \dot{m}_8 = \underline{\underline{9584.9\,kg\,soln/h}},$$

$$\dot{n}_1 = \underline{\underline{18.1\,kmol\,CO_2/h(v)}}, \qquad X_a = 0.00173\,kg\,CaSO_4/kg$$

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

$$\left\{\begin{array}{c}0.00173(kg\,CaSO_4/kg)\\500*0.00173(kg\,H_2O/kg)\\(1-501*0.00173)(kg\,Ca(NO_3)_2/kg)\end{array}\right\}\Rightarrow\left\{\begin{array}{c}\underline{\underline{0.173\%\ CaSO_4}}\\\underline{\underline{86.5\%\ H_2O}}\\\underline{\underline{13.3\%\ Ca(NO_3)_2}}\end{array}\right\}$$

d. From Table B.1, for CO_2:

$$T_c = 304.2\ K, \qquad P_c = 72.9\ atm$$

$$\Rightarrow T_r = \frac{T}{T_c} = \frac{(40+273.2)\ K}{304.2} = 1.03, \qquad P_r = \frac{30\ atm}{72.9\ atm} = 0.411$$

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

$$z = 0.86 \Rightarrow \hat{V} = \frac{zRT}{P} = \frac{0.86}{}\left|\frac{0.08206\,L\cdot atm}{mol\cdot K}\right|\frac{313.2\ K}{30\ atm} = 0.737\,\frac{L}{mol\,CO_2}$$

Volumetric flow rate of CO_2:

$$\dot{V} = \dot{n}_1 * \hat{V} = \frac{18.1\,kmol\,CO_2}{h}\left|\frac{0.737\,L}{mol\,CO_2}\right|\frac{1000\,mol}{1\,kmol} = \underline{\underline{1.33\text{x}10^4\ L/h}}$$

e. Solution saturated with $Ca(NO_3)_2$:

$$\Rightarrow \frac{1-501X_a\ (kg\,Ca(NO_3)_2/kg)}{500Xa\ (kg\,H_2O/kg)} = 1.526 \Rightarrow X_a = 0.00079\,kg\,CaSO_4/kg$$

Let $\dot{m}_1$ (kg HNO_3/h) = feed rate of nitric acid corresponding to saturation without crystallization.

6.83 (cont'd)

Overall S balance:

$$\frac{1000\,\text{kg}\,H_2SO_4}{h}\left|\frac{32\,\text{kg}\,S}{98\,\text{kg}\,H_2SO_4}\right.=\frac{\dot{m}_5\,(\text{kg}/\text{h})}{}\left|\frac{(0.96+(0.04)(0.00079))\,(\text{kg}\,CaSO_4)}{\text{kg}}\right|\frac{32\,\text{kg}\,S}{136\,\text{kg}\,CaSO_4}$$

$$+\frac{\dot{m}_8\,(\text{kg}/\text{h})}{}\left|\frac{0.00079\,(\text{kg}\,CaSO_4)}{\text{kg}}\right|\frac{32\,\text{kg}\,S}{136\,\text{kg}\,CaSO_4}$$

$$\Rightarrow 326.5=0.226\dot{m}_5+0.000186\dot{m}_8 \qquad\qquad (1')$$

Overall N balance:

$$\frac{\dot{m}_1\,(\text{kg}\,HNO_3)}{h}\left|\frac{14\,\text{kg}\,N}{63\,\text{kg}\,HNO_3}\right.=\frac{0.04\dot{m}_5\,(\text{kg}/\text{h})}{}\left|\frac{(1-(501)(0.00079))\,(\text{kg}\,Ca(NO_3)_2)}{\text{kg}}\right|\frac{28\,\text{kg}\,N}{164\,\text{kg}\,Ca(NO_3)_2}$$

$$+\frac{\dot{m}_8\,(\text{kg}/\text{h})}{}\left|\frac{(1-(501)(0.00079))\,(\text{kg}\,Ca(NO_3)_2)}{\text{kg}}\right|\frac{28\,\text{kg}\,N}{164\,\text{kg}\,Ca(NO_3)_2}$$

$$\Rightarrow 0.222\dot{m}_1=0.00413\dot{m}_5+0.103\dot{m}_8 \qquad\qquad (2')$$

Overall H balance:

$$\frac{1000\,(\text{kg}\,H_2SO_4)}{h}\left|\frac{2\,\text{kg}\,H}{98\,\text{kg}\,H_2SO_4}\right.+\frac{\dot{m}_1\,\text{kg}\,HNO_3}{h}\left|\frac{1\,\text{kg}\,H}{63\,\text{kg}\,HNO_3}\right.$$

$$+\frac{8000\,(\text{kg}/\text{h})}{}\left|\frac{2\,\text{kg}\,H}{18\,\text{kg}\,H_2O}\right.=\frac{0.04\dot{m}_5\,(\text{kg}/\text{h})}{}\left|\frac{500(0.00079)\,(\text{kg}\,H_2O)}{\text{kg}}\right|\frac{2\,\text{kg}\,H}{18\,\text{kg}\,H_2O}$$

$$+\frac{\dot{m}_8\,(\text{kg}/\text{h})}{}\left|\frac{500(0.00079)\,(\text{kg}\,H_2O)}{\text{kg}}\right|\frac{2\,\text{kg}\,H}{18\,\text{kg}\,H_2O}$$

$$\Rightarrow 909.30+0.0159\dot{m}_1=0.00175\dot{m}_5+0.0439\dot{m}_8 \qquad\qquad (3')$$

Solve eqns (1')-(3') simultaneously using E-Z solve:

$$\dot{m}_1=1.155x10^4\ \text{kg}/\text{h};\qquad \dot{m}_5=1.424x10^3\ \text{kg}/\text{h};\qquad \dot{m}_8=2.484x10^4\ \text{kg}/\text{h}$$

Maximum ratio of nitric acid to sulfuric acid in the feed

$$=\frac{1.155x10^4\ \text{kg}/\text{h}}{1000\ \text{kg}/\text{h}}=\underline{\underline{11.5\ \text{kg}\,HNO_3\,/\,\text{kg}\,H_2SO_4}}$$

6.84

$$\underline{\text{Moles of diphenyl (DP):}} \quad \frac{56.0 \text{ g}}{154.2 \text{ g/mol}} = 0.363 \text{ mol}$$

$$\underline{\text{Moles of benzene (B):}} \quad \frac{550.0 \text{ ml}}{} \left| \frac{0.879 \text{ g}}{\text{ml}} \right| \frac{1 \text{ mol}}{78.11 \text{ g}} = 6.19 \text{ mol}$$

$$\Rightarrow x_{\text{DP}} = \frac{0.363}{6.19 + 0.363} = 0.0544 \text{ mol DP/mol}$$

$$p_{\text{B}}^*(T) = (1 - x_{DP}) p_{\text{B}}^*(T) = 0.945(120.67 \text{ mm Hg}) = \underline{\underline{114.0 \text{ mm Hg}}}$$

$$\Delta T_{\text{m}} = \frac{RT_{\text{m0}}^2}{\Delta \hat{H}_{\text{m}}} x_{\text{DP}} = \frac{8.314(273.2 + 5.5)^2}{9837}(0.0554) = 3.6 \text{ K} = 3.6^\circ C \Rightarrow T_{\text{m}} = 5.5 - 3.6 = \underline{\underline{1.9 \ ^\circ C}}$$

$$\Delta T_{\text{bp}} = \frac{RT_{\text{b0}}^2}{\Delta \hat{H}_{\text{v}}} x_{\text{DP}} = \frac{8.314(273.2 + 80.1)^2}{30,765}(0.0554) = 1.85 \text{ K} = 1.85^\circ C$$

$$\Rightarrow T_{\text{b}} = 80.1 + 1.85 = \underline{\underline{82.0 \ ^\circ C}}$$

6.85

$$T_{m0} = 0.0^\circ C, \ \Delta T_m = 4.6^\circ C = 4.6 K$$

$$\xrightarrow[\text{Table B.1}]{\text{Eq. 6.5-5}} x_u = \frac{\Delta T_m \Delta \hat{H}_m}{R(T_{m0})^2} = \frac{(4.6 K)(600.95 \text{ J/mol})}{(8.314 \text{ J/mol} \cdot K)(273.2 K)^2} = 0.0445 \text{ mol urea/mol}$$

$$\text{Eq. (6.5-4)} \Rightarrow \Delta T_b = \frac{RT_{b0}^2}{\Delta \hat{H}_v} x_u = \frac{(8.314)(373.2)^2}{40,656} 0.0445 = 1.3 K = \underline{\underline{1.3^\circ C}}$$

1000 grams of this solution contains m_u (g urea) and $(1000 - m_u)$ (g water)

$$n_{u1}(\text{mol urea}) = \frac{m_{u1}(g)}{60.06 \text{ g/mol}} \qquad n_{w1}(\text{mol water}) = \frac{(1000 - m_{u1})(g)}{18.02 \text{ g/mol}}$$

$$x_{u1} = 0.0445 = \frac{\dfrac{m_{u1}}{60.06}(\text{mol urea})}{\left[\dfrac{m_{u1}}{60.06} + \dfrac{(1000 - m_{u1})}{18.02}\right](\text{mol solution})} \Rightarrow m_{u1} = 134 \text{ g urea}, \ m_{w1} = 866 \text{ g water}$$

$$\Delta T_b = 3.0^\circ C = 3.0 K \Rightarrow x_{u2} = \frac{\Delta T_b \Delta \hat{H}_v}{R(T_{b0})^2} = \frac{(3.0 K)(40,656 \text{ J/mol})}{(8.314 \text{ J/mol} \cdot K)(373.2 K)^2} = 0.105 \text{ mol urea/mol}$$

$$x_{u2} = 0.105 = \frac{\dfrac{m_{u2}}{60.06}(\text{mol urea})}{\left[\dfrac{m_{u2}}{60.06} + \dfrac{866}{18.02}\right](\text{mol solution})} \Rightarrow m_{u2} = 339 \text{ g urea}$$

$$\Rightarrow \text{ Add } (339 - 134) \text{ g urea} = \underline{\underline{205 \text{ g urea}}}$$

6.86 $x_a^I = \dfrac{(0.5150 \text{ g})/(110.1 \text{ g/mol})}{(0.5150 \text{ g})/(110.1 \text{ g/mol}) + (100.0 \text{ g})/(94.10 \text{ g/mol})} = 0.00438 \text{ mol solute/mol}$

$$\Delta T_m = \frac{RT_{m0}^2}{\Delta \hat{H}_m} x_s \Rightarrow \frac{\Delta T_m^I}{\Delta T_m^{II}} = \frac{x_s^I}{x_s^{II}} \Rightarrow x_s^{II} = x_s^I \frac{\Delta T_m^{II}}{\Delta T_m^I} = 0.00438 \frac{0.49°\text{C}}{0.41°\text{C}} = 0.00523 \frac{\text{mol solute}}{\text{mol solution}}$$

$$\Rightarrow \frac{(1 - 0.00523) \text{ mol solvent}}{0.00523 \text{ mol solute}} \left| \frac{94.10 \text{ g solvent}}{1 \text{ mol solvent}} \right| \frac{0.4460 \text{ g solute}}{95.60 \text{ g solvent}} = \underline{\underline{83.50 \text{ g solute/mol}}}$$

$$\Delta \hat{H}_m = \frac{RT_{m0}^2}{\Delta T_m} x_s = \frac{8.314(273.2 - 5.00)^2}{0.49}(0.00523) = 6380 \text{ J/mol} = \underline{\underline{6.38 \text{ kJ / mol}}}$$
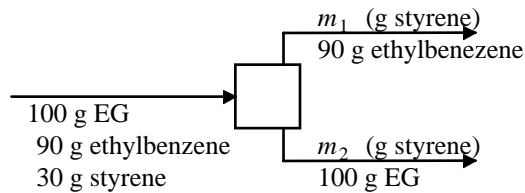
6.87 a. $\ln p_s^*(T_{b0}) = -\dfrac{\Delta H_v^I}{RT_{b0}} + B$, $\ln p_s^*(T_{bs}) = -\dfrac{\Delta H_v^{II}}{RT_{bs}} + B$

Assume $\Delta H_v^I \cong \Delta H_v^{II}$; $T_0 T_s \cong T_0^2$

$$\Rightarrow \ln P_s^*(T_{b0}) - \ln P_0^*(T_{bs}) = -\frac{\Delta H_v}{R}\left(\frac{1}{T_{b0}} - \frac{1}{T_{bs}}\right) \cong \frac{\Delta H_v}{R}\frac{T_{bs} - T_{b0}}{T_{b0}^2}$$

b. <u>Raoult's Law</u>: $p_s^*(T_{b0}) = (1-x)p_0^*(T_{bs}) \Rightarrow \ln(1-x) \approx -x = -\dfrac{\Delta H_v \Delta T_b}{RT_{b0}^2} \Rightarrow \underline{\underline{\Delta T_b = \dfrac{RT_{b0}^2}{\Delta H_v}x}}$

6.88

<u>Styrene balance:</u> $m_1 + m_2 = 30$ g styrene

<u>Equilibrium relation:</u> $\dfrac{m_2}{100 + m_2} = 0.19\left(\dfrac{m_1}{90 + m_1}\right)$

$\Big\Downarrow$ solve simultaneously

$m_1 = 25.6$ g styrene in ethylbenzene phase

$m_2 = 4.4$ g styrene in ethylene glycol phase

6.89 <u>Basis</u>: 100 kg/h.   A=oleic acid; C=condensed oil; P=propane
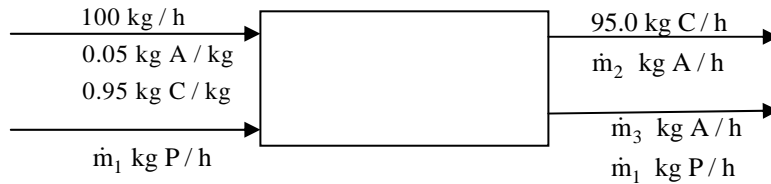
a. <u>90% extraction</u>: $\dot{m}_3 = (0.09)(0.05)(100 \text{ kg / h}) = 4.5 \text{ kg A / h}$

   <u>Balance on oleic acid</u>: $(0.05)(100) = \dot{m}_2 + 4.5 \text{ kg A / h} \Rightarrow \dot{m}_2 = 0.5 \text{ kg A / h}$

   <u>Equilibrium condition</u>: $0.15 = \dfrac{0.5 / (\dot{n}_1 + 0.5)}{4.5 / (4.5 + 95)} \Rightarrow \dot{n}_1 = 73.2 \text{ kg P / h}$

**b.** Operating pressure must be above the vapor pressure of propane at T=85°C=185°F
   Figure 6.1-4 $\Rightarrow p_{\text{propane}}^{*} = 500 \text{ psi} = 34 \text{ atm}$

c. Other less volatile hydrocarbons cost more and/or impose greater health or environmental
   hazards.

6.90 a. Benzene is the solvent of choice. It holds a greater amount of acetic acid for a given mass
   fraction of acetic acid in water.

   <u>Basis</u>: 100 kg feed.   A=Acetic acid, W=H_2O, H=Hexane, B=Benzene
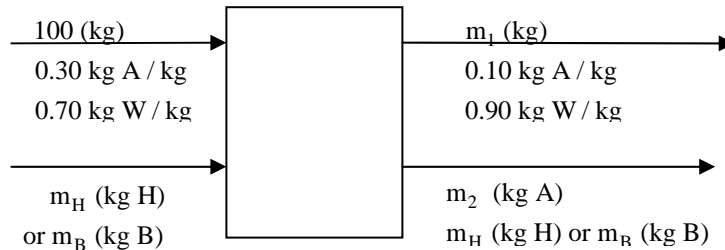
   <u>Balance on W</u>: $100 * 0.70 = m_1 * 0.90 \Rightarrow m_1 = 77.8 \text{ kg}$

   <u>Balance on A</u>: $100 * 0.30 = m_2 + 77.8 * 0.10 \Rightarrow m_2 = 22.2 \text{ kg}$

   <u>Equilibrium for H</u>:

   $$K_H = \frac{m_2 / (m_2 + m_H)}{x_A} = \frac{22.2 / (22.2 + m_H)}{0.10} = 0.017 \Rightarrow m_H = 1.30x10^4 \text{ kg H}$$

   <u>Equilibrium for B</u>:

   $$K_B = \frac{m_2 / (m_2 + m_B)}{x_A} = \frac{22.2 / (22.2 + m_B)}{0.10} = 0.098 \Rightarrow m_B = 2.20x10^3 \text{ kg B}$$

(b) Other factors in picking solvent include cost, solvent volatility, and health, safety, and
   environmental considerations.

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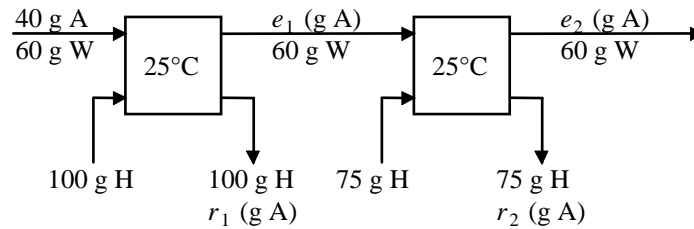

$$x_{A\,\text{in H phase}} \,/\, x_{A\,\text{in W phase}} = 0.343 \;(x = \text{mass fraction})$$

<u>Balance on A – stage 1:</u> $40 = e_1 + r_1$

<u>Equilibrium condition – stage 1:</u> $\dfrac{r_1/(100 + r_1)}{e_1/(60 + e_1)} = 0.343$ $\left.\begin{array}{l}\\ \\\end{array}\right\} \Rightarrow \begin{array}{l} e_1 = 27.8 \text{ g acetone} \\ r_1 = 12.2 \text{ g acetone}\end{array}$

<u>Balance on A – stage 2:</u> $27.8 = e_2 + r_2$

<u>Equilibrium condition – stage 2:</u> $\dfrac{r_2/(75 + r_2)}{e_2/(60 + e_2)} = 0.343$ $\left.\begin{array}{l}\\ \\\end{array}\right\} \Rightarrow \begin{array}{l} r_2 = 7.2 \text{ g acetone} \\ e_2 = 20.6 \text{ g acetone}\end{array}$

<u>% acetone not extracted</u> $= \dfrac{20.6 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{51.5\%}}$

b.
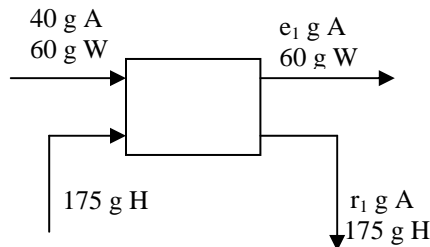
<u>Balance on A – stage 1:</u> $40.0 = e_1 + r_1$

<u>Equilibrium condition – stage 1:</u> $\dfrac{r_1/(175 + r_1)}{e_1/(60 + e_1)} = 0.343$ $\left.\begin{array}{l}\\ \\\end{array}\right\} \Rightarrow \begin{array}{l} r_1 = 17.8 \text{ g acetone} \\ e_1 = 22.2\text{g acetone}\end{array}$

<u>% acetone not extracted</u> $= \dfrac{22.2 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{55.5\%}}$

c.
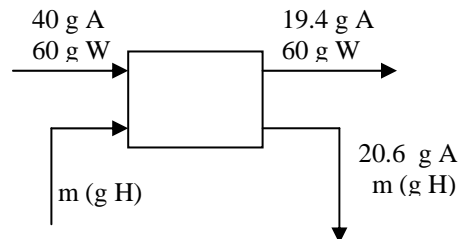
<u>Equilibrium condition:</u> $\dfrac{20.6/(m + 20.6)}{19.4/(60 + 19.4)} = 0.343 \Rightarrow m = \underline{\underline{225 \text{ g hexane}}}$

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.

6.92 **a.** P--penicillin; Ac--acid solution; BA--butyl acetate; Alk--alkaline solution

D.F. analysis:

Extraction Unit I
3 unknown (m_1, m_{2p}, m_{3p})
−1 balance (P)
−1 distribution coefficient
−1 (90% transfer)
0 DF

Extraction Unit II (consider m_1, m_{3p})
3 unknowns
−1 balance (P)
−1 distribution coefficient
−1 (90% transfer)
0 DF

b. In Unit I, 90% transfer $\Rightarrow$ $m_{3P} = 0.90(1.5) = 1.35\ \text{kg P}$

P balance: $1.5 = m_{2P} + 1.35 \Rightarrow m_{2P} = 0.15\ \text{kg P}$
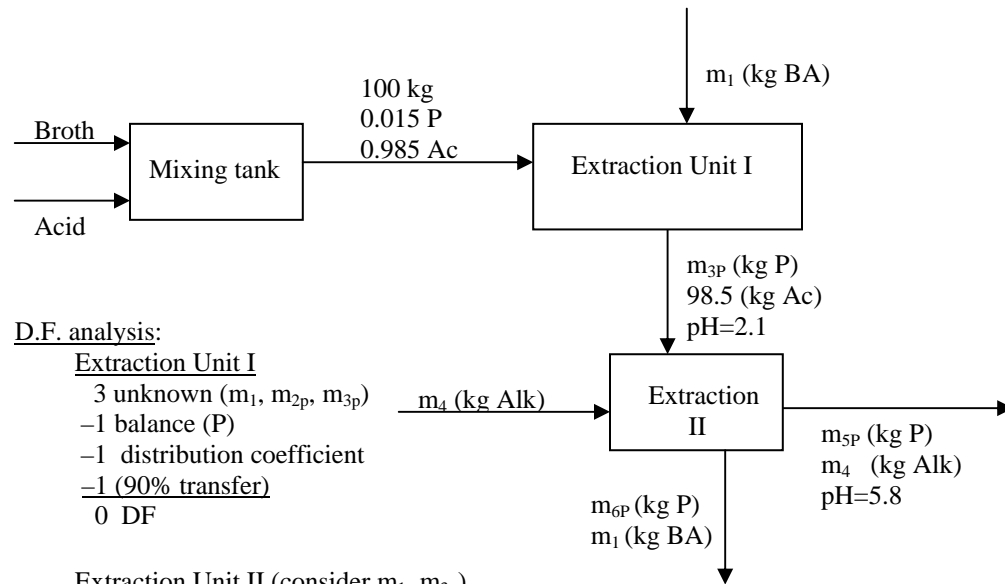
pH=2.1 $\Rightarrow K = 25.0 = \dfrac{1.35/(1.35 + m_1)}{0.15/(0.15 + 98.5)} \Rightarrow m_1 = 34.16\ \text{kg BA}$

In Unit II, 90% transfer: $m_{5P} = 0.90(m_{3P}) = 1.215\ kg\ P$

P balance: $m_{3P} = 1.215 + m_{6P} \Rightarrow m_{6P} = 0.135\ kg\ P$

pH=5.8 $\Rightarrow K = 0.10 = \dfrac{m_{6P}/(m_{6P} + 34.16)}{1.215/(1.215 + m_4)} \Rightarrow m_4 = 29.65\ \text{kg Alk}$

$\dfrac{m_1}{100} = \dfrac{34.16\ \text{kg BA}}{100\ \text{kg broth}} = \underline{\underline{0.3416\ \text{kg butyl acetate / kg acidified broth}}}$

$\dfrac{m_4}{100} = \dfrac{29.65\ \text{kg Alk}}{100\ \text{kg broth}} = \underline{\underline{0.2965\ \text{kg alkaline solution / kg acidified broth}}}$

Mass fraction of P in the product solution:

$$x_P = \frac{m_{5P}}{m_4 + m_{5P}} = \frac{1.215\ \text{P}}{(29.65 + 1.215)\ \text{kg}} = \underline{\underline{0.394\ \text{kg P / kg}}}$$

c. (i). The first transfer (low pH) separates most of the P from the other broth constituents, which are not soluble in butyl acetate. The second transfer (high pH) moves the penicillin back into an aqueous phase without the broth impurities.

(ii). Low pH favors transfer to the organic phase, and high pH favors transfer back to the aqueous phase.

(iii).The penicillin always moves from the raffinate solvent to the extract solvent.

6.93   W = water, A = acetone, M = methyl isobutyl ketone

$$\left.\begin{array}{l} x_W = 0.20 \\ x_A = 0.33 \\ x_M = 0.47 \end{array}\right\} \xrightarrow{\text{\textit{Figure 6.6-1}}} \begin{array}{l} \underline{\text{Phase 1: } x_W = 0.07, \ x_A = 0.35, \ x_M = 0.58} \\ \underline{\text{Phase 2: } x_W = 0.71, \ x_A = 0.25, \ x_M = 0.04} \end{array}$$

Basis: 1.2 kg of original mixture, m_1=total mass in phase 1, m_2=total mass in phase 2.

$$\begin{array}{ll} \underline{\text{H}_2\text{O Balance:}} & 1.2*0.20 = 0.07m_1 + 0.71m_2 \\ \underline{\text{Acetone balance:}} & 1.2*0.33 = 0.35m_1 + 0.25m_2 \end{array} \Rightarrow \left\{\begin{array}{l} m_1 = \underline{\underline{0.95 \text{ kg in MIBK - rich phase}}} \\ m_2 = \underline{\underline{0.24 \text{ kg in water - rich phase}}} \end{array}\right.$$

6.94 Basis: Given feeds: A = acetone, W = H_2O, M=MIBK

Overall system composition:

$$\left.\begin{array}{l} 5000 \text{ g } (30 \text{ wt\% A, } 70 \text{ wt\% W}) \Rightarrow 1500 \text{ g A, } 3500 \text{ g W} \\ 3500 \text{ g } (20 \text{ wt\% A, } 80 \text{ wt\% M}) \Rightarrow 700 \text{ g A, } 2800 \text{ g M} \end{array}\right\}$$

$$\left.\begin{array}{l} 2200 \text{ g A} \\ \Rightarrow 3500 \text{ g W} \\ 2800 \text{ g M} \end{array}\right\} \Rightarrow 25.9\% \text{ A, } 41.2\% \text{ W, } 32.9\% \text{ M} \xrightarrow{\text{Fig. 6.6-1}} \begin{array}{l} \underline{\underline{\text{Phase 1: 31\% A, 63\% M, 6\% W}}} \\ \underline{\underline{\text{Phase 2: 21\% A, 3\% M, 76\% W}}} \end{array}$$

Let m_1=total mass in phase 1, m_2=total mass in phase 2.

$$\begin{array}{ll} \underline{\text{H}_2\text{O Balance:}} & 3500 = 0.06m_1 + 0.76m_2 \\ \underline{\text{Acetone balance:}} & 2200 = 0.31m_1 + 0.21m_2 \end{array} \Rightarrow \left\{\begin{array}{l} m_1 = \underline{\underline{4200 \text{ g in MIBK - rich phase}}} \\ m_2 = \underline{\underline{4270 \text{ g in water - rich phase}}} \end{array}\right.$$

6.95   A=acetone, W = H_2O, M=MIBK
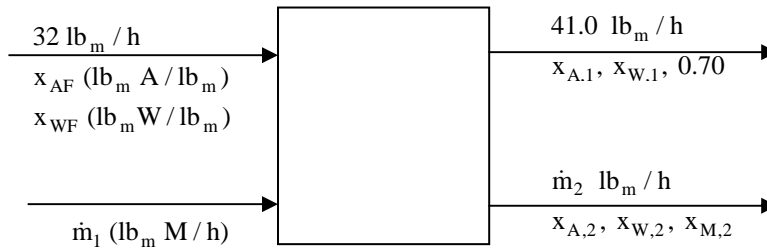
Figure 6.6-1$\Rightarrow$ Phase 1: $x_M = 0.700 \Rightarrow x_{w,1} = 0.05; \ x_{A,1} = 0.25$;

Phase 2: $x_{w,2} = 0.81; \ x_{A,2} = 0.81; \ x_{M,2} = 0.03$

$$\left.\begin{array}{ll} \underline{\text{Overall mass balance:}} & 32.0 \text{ lb}_m / h + \dot{m}_1 = 41.0 \text{ lb}_m / h + \dot{m}_2 \\ \underline{\text{MIBK balance:}} & \dot{m}_1 = 41.0*0.7 + \dot{m}_2 * 0.03 \end{array}\right\} \Rightarrow \begin{array}{l} \dot{m}_1 = \underline{\underline{28.1 \text{ lb}_m \text{ MIBK } / h}} \\ \dot{m}_2 = \underline{\underline{19.1 \text{ lb}_m / h}} \end{array}$$

6.96 a. <u>Basis</u>: 100 kg; A=acetone, W=water, M=MIBK

<u>System 1</u>: $x_{a,org} = 0.375$ mol A, $x_{m,org} = 0.550$ mol M, $x_{w,org} = 0.075$ mol W

$x_{a,aq} = 0.275$ mol A, $x_{m,aq} = 0.050$ mol M, $x_{w,aq} = 0.675$ mol W

<u>Mass balance</u>: $m_{aq,1} + m_{org,1} = 100$

<u>Acetone balance</u>: $m_{aq,1} * 0.275 + m_{org,1} * 0.375 = 33.33$ $\Bigg\} \Rightarrow$ $m_{aq,1} = \underline{\underline{41.7 \text{ kg}}}$

$m_{org,1} = \underline{\underline{58.3 \text{ kg}}}$

<u>System 2</u>: $x_{a,org} = 0.100$ mol A, $x_{m,org} = 0.870$ mol M, $x_{w,org} = 0.030$ mol W

$x_{a,aq} = 0.055$ mol A, $x_{m,aq} = 0.020$ mol M, $x_{w,aq} = 0.925$ mol W

<u>Mass balance</u>: $m_{aq,2} + m_{org,2} = 100$

<u>Acetone balance</u>: $m_{aq,2} * 0.055 + m_{org,2} * 0.100 = 9$ $\Bigg\} \Rightarrow$ $m_{aq,2} = \underline{\underline{22.2 \text{ kg}}}$

$m_{org,2} = \underline{\underline{77.8 \text{ kg}}}$

b. $K_{a,1} = \dfrac{x_{a,org,1}}{x_{a,aq,1}} = \dfrac{0.375}{0.275} = \underline{\underline{1.36}}$; $K_{a,2} = \dfrac{x_{a,org,2}}{x_{a,aq,2}} = \dfrac{0.100}{0.055} = \underline{\underline{1.82}}$

High K_a to extract acetone from water into MIBK; low K_a to extract acetone from MIBK into water.

c. $\beta_{aw,1} = \dfrac{x_{a,org} / x_{w,org}}{x_{a,aq} / x_{w,aq}} = \dfrac{0.375 / 0.075}{0.275 / 0.675} = \underline{\underline{12.3}}$; $\beta_{aw,2} = \dfrac{0.100 / 0.040}{0.055 / 0.920} = \underline{\underline{41.8}}$

If water and MIBK were immiscible, $x_{w,org} = 0 \Rightarrow \underline{\underline{\beta_{aw} \to \infty}}$

d. Organic phase= extract phase; aqueous phase= raffinate phase

$$\beta_{a,w} = \frac{(x_a / x_w)_{org}}{(x_a / x_w)_{aq}} = \frac{(x_a)_{org} / (x_a)_{aq}}{(x_w)_{org} / (x_w)_{aq}} = \frac{K_a}{K_w}$$

When it is critically important for the raffinate to be as pure (acetone-free) as possible.

6.97 <u>Basis</u>: Given feed rates: A = acetone, W = water, M=MIBK
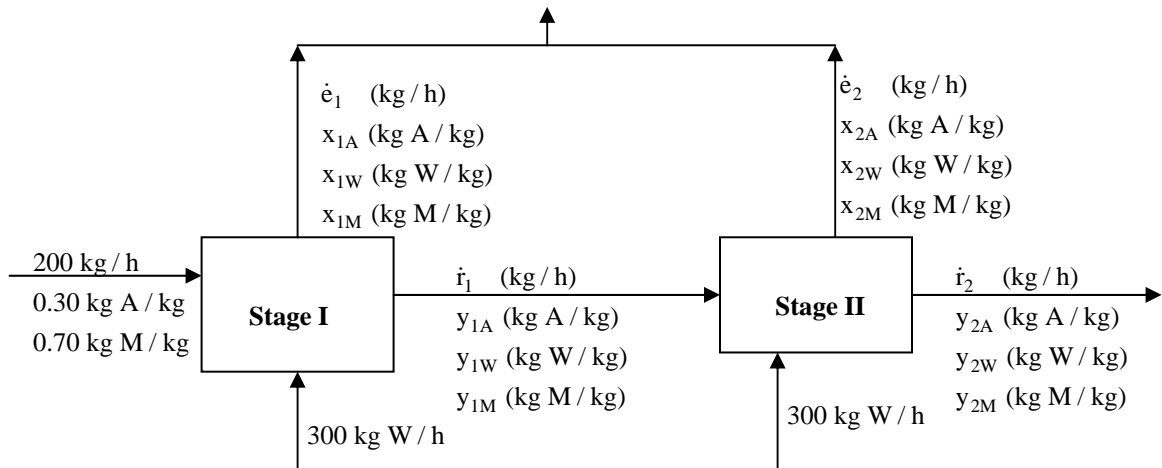
6.97(cont'd)

Overall composition of feed to Stage 1:

$$\left.\begin{array}{l}(200)(0.30) = 60 \ \text{kg A/h} \\ 200 - 60 = 140 \ \text{kg M/h} \\ 300 \ \text{kg W/h}\end{array}\right\} \Rightarrow \begin{array}{l}500 \ \text{kg/h} \\ 12\% \ \text{A}, \ 28\% \ \text{M}, \ 60\% \ \text{W}\end{array}$$

Figure 6.6-1 $\Rightarrow$ $\dfrac{\text{Extract: } x_{1A} = 0.095, \ x_{1W} = 0.880, \ x_{1M} = 0.025}{\text{Raffinate: } y_{1A} = 0.15, \ y_{1W} = 0.035, \ y_{1M} = 0.815}$

Mass balance $\quad 500 = \dot{e}_1 + \dot{r}_1$

Acetone balance: $\quad 60 = 0.095\dot{e}_1 + 0.15\dot{r}_1 \quad \Rightarrow \begin{cases} \dot{e}_1 = \underline{\underline{273 \ \text{kg / h}}} \\ \dot{r}_1 = \underline{\underline{227 \ \text{kg / h}}} \end{cases}$

Overall composition of feed to Stage 2:

$$\left.\begin{array}{l}(227)(0.15) = 34 \ \text{kg A/h} \\ (227)(0.815) = 185 \ \text{kg M/h} \\ (227)(0.035) + 300 = 308 \ \text{kg W/h}\end{array}\right\} \Rightarrow \begin{array}{l}527 \ \text{kg/h} \\ 6.5\% \ \text{A}, \ 35.1\% \ \text{MIBK}, \ 58.4\% \ \text{W}\end{array}$$

Figure 6.6-1 $\Rightarrow$ $\dfrac{\text{Extract: } x_{2A} = 0.04, \ x_{2W} = 0.94, \ x_{2M} = 0.02}{\text{Raffinate: } y_{2A} = 0.085, \ y_{2W} = 0.025, \ y_{2M} = 0.89}$

Mass balance: $\quad 527 = \dot{e}_2 + \dot{r}_2$

Acetone balance: $\quad 34 = 0.04e_2 + 0.085r_2 \quad \Rightarrow \begin{cases} \dot{e}_2 = \underline{\underline{240 \ \text{kg / h}}} \\ \dot{r}_2 = \underline{\underline{287 \ \text{kg / h}}} \end{cases}$

Acetone removed:

$$\frac{[60 - (0.085)(287)] \ \text{kg A removed / h}}{60 \ \text{kg A / h in feed}} = \underline{\underline{0.59 \ \text{kg acetone removed / kg fed}}}$$

Combined extract:

Overall flow rate $= \dot{e}_1 + \dot{e}_2 = 273 + 240 = 513 \ \text{kg / h}$

Acetone: $\dfrac{(x_{1A}\dot{e}_1 + x_{2A}\dot{e}_2) \ \text{kg A}}{} = \dfrac{0.095 * 273 + 0.04 * 240}{513} = \underline{\underline{0.069 \ \text{kg A / kg}}}$

Water: $\dfrac{(x_{1w}\dot{e}_1 + x_{2w}\dot{e}_2) \ \text{kg W}}{\dot{e}_1 + \dot{e}_2} = \dfrac{0.88 * 273 + 0.94 * 240}{513} = \underline{\underline{0.908 \ \text{kg W / kg}}}$

MIBK: $\dfrac{(x_{1M}\dot{e}_1 + x_{2M}\dot{e}_2) \ \text{kg M}}{(\dot{e}_1 + \dot{e}_2) \text{kg}} = \dfrac{0.025 * 273 + 0.02 * 240}{513} = \underline{\underline{0.023 \ \text{kg M / kg}}}$

6.98. a.

1.50 L / min

25°C, 1atm, rh $=25\%$

$\dot{n}_0$ (mol / min)

y_0 (mol H_2O / mol)

$(1 - y_0)$ (mol dry air / mol)

M (g gel)
M_a (g H_2O)
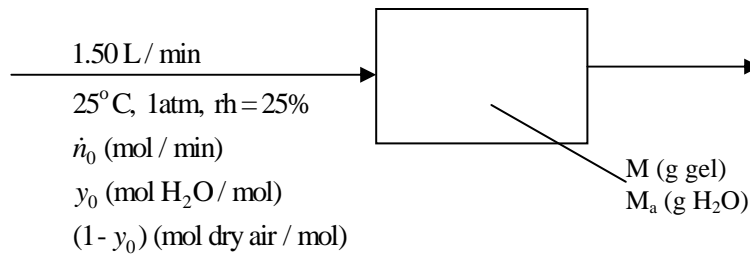
$$\dot{n}_0 = \frac{P\dot{V}}{RT} = \frac{(1\,\text{atm})(1.50\,\text{L / min})}{(0.08206\,\text{L} \cdot \text{atm / mol} \cdot \text{K})(298\,\text{K})} = 0.06134 \text{ mol / min}$$

$\underline{\text{r.h.}=25\%} \Rightarrow \dfrac{p_{H_2O}}{p^*_{H_2O}(25^\circ\text{C})} = 0.25$

$\underline{\text{Silica gel saturation condition:}} \quad X^* = 12.5 \dfrac{p_{H_2O}}{p^*_{H_2O}} = 12.5 * 0.25 = 3.125 \dfrac{\text{g } H_2O \text{ ads}}{100 \text{ g silica gel}}$

$\underline{\text{Water feed rate:}} \quad y_0 = \dfrac{0.25 p^*_{H_2O}(25^\circ C)}{p} = \dfrac{0.25(23.756 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.00781 \dfrac{\text{mol } H_2O}{\text{mol}}$

$$\Rightarrow \dot{m}_{H_2O} = \frac{0.06134 \text{ mol}}{\text{min}} \left| \frac{0.00781 \text{ mol } H_2O}{\text{mol}} \right| \frac{18.01 \text{ g } H_2O}{\text{mol } H_2O} = 0.00863 \text{ g } H_2O \text{ / min}$$

$\underline{\text{Adsorption in 2 hours}} = (0.00863 \text{ g } H_2O \text{ / min})(120\text{min}) = 1.035 \text{ g } H_2O$

$\underline{\text{Saturation condition:}} \quad \dfrac{1.035 \text{ g } H_2O}{M \text{ (g silica gel)}} = \dfrac{3.125 \text{ g } H_2O}{100 \text{ g silica gel}} \Rightarrow \underline{\underline{M = 33.1 \text{ g silica gel}}}$

Assume that all entering water vapor is adsorbed throughout the 2 hours and that P and T are constant.

b. Humid air is dehumidified by being passed through a column of silica gel, which absorbs a significant fraction of the water in the entering air and relatively little oxygen and nitrogen. The capacity of the gel to absorb water, while large, is not infinite, and eventually the gel reaches its capacity. If air were still fed to the column past this point, no further dehumidification would take place. To keep this situation from occurring, the gel is replaced at or (preferably) before the time when it becomes saturated.

6.99 a. Let c = CCl_4

$\underline{\text{Relative saturation} = 0.30} \Rightarrow \dfrac{p_c}{p^*_c(34^\circ\text{C})} \Rightarrow \underline{\underline{p_c = 0.30 * (169 \text{ mm Hg}) = 50.7 \text{ mm Hg}}}$

b. $\underline{\text{Initial moles of gas in tank:}}$

$$n_0 = \frac{P_0 V_0}{RT_0} = \frac{1 \text{ atm}}{0.08206 \text{ L} \cdot \text{atm / mol} \cdot \text{K}} \left| \frac{50.0 \text{ L}}{307 \text{ K}} \right. = 1.985 \text{ mol}$$

$\underline{\text{Initial moles of } CCl_4 \text{ in tank:}}$

$$n_{c0} = y_{c0} n_0 = \frac{p_{c0}}{P_0} n_0 = \frac{50.7 \text{ mm Hg}}{760 \text{ mm Hg}} \times 1.985 \text{ mol} = 0.1324 \text{ mol } CCl_4$$

6.99 (cont'd)

50% CCl_4 adsorbed $\Rightarrow n_c = 0.500 n_{c0} = 0662$ mol CCl_4 $(= n_{ads})$

Total moles in tank: $n_{tot} = n_0 - n_{ads} = (1.985 - 0.0662)$ mol $= 1.919$ mol

Pressure in tank. Assume $T = T_0$ and $V = V_0$.

$$P = \frac{n_{tot} R T_0}{V_0} = \left(\frac{(1.919)(0.08206)(307)}{50.0} \text{ atm} \right) \left(\frac{760 \text{ mm Hg}}{\text{atm}} \right) = \underline{\underline{735 \text{ mm Hg}}}$$

$$y_C = \frac{n_c}{n_{tot}} = \frac{0.0662 \text{ mol } CCl_4}{1.919 \text{ mol}} = 0.0345 \frac{\text{mol } CCl_4}{\text{mol}}$$

$$\Rightarrow p_c = 0.0345(760 \text{ mm Hg}) = \underline{\underline{26.2 \text{ mm Hg}}}$$

c. Moles of air in tank: $n_a = n_0 - n_{c0} = (1.985 - 0.1324)$ mol air $= 1.853$ mol air

$$y_c = \frac{n_c}{n_c + 1.853} = 0.001 \frac{\text{mol } CCl_4}{\text{mol}} \Rightarrow n_c = 1.854 \times 10^{-3} \text{ mol } CCl_4$$

$$\Rightarrow n_{tot} = n_c + n_{air} = 1.854 \text{ mol}$$

$$p_c = y_c P = 0.001 \left[\frac{n_{tot} R T_0}{V_0} \right] = \frac{1.854 \times 10^{-3} \text{ mol}}{50.0 \text{ L}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \frac{307 \text{ K}}{} \left| \frac{760 \text{ mm}}{1 \text{ atm}} \right.$$

$$= 0.710 \text{ mm Hg}$$

$$X^* \left(\frac{\text{g } CCl_4}{\text{g carbon}} \right) = \frac{0.0762 p_c}{1 + 0.096 p_c} \Rightarrow X^* = \frac{0.0762(0.710)}{1 + 0.096(0.710)} = 0.0506 \frac{\text{g } CCl_4 \text{ adsorbed}}{\text{g carbon}}$$

Mass of CCl_4 adsorbed

$$m_{ads} = (n_{c0} - n_c)(MW)_c = \frac{(0.1324 - 0.001854) \text{ mol } CCl_4}{} \left| \frac{153.85 \text{ g}}{1 \text{ mol } CCl_4} \right.$$

$$= 20.3 \text{ mol } CCl_4 \text{ adsorbed}$$

Mass of carbon required: $m_c = \dfrac{20.3 \text{ g } CCl_4 \text{ ads}}{0.0506 \dfrac{\text{g } CCl_4 \text{ ads}}{\text{g carbon}}} = \underline{\underline{400 \text{ g carbon}}}$

6.100   a. $X^* = K_F p_{NO_2}^\beta \Rightarrow \ln X^* = \ln K_F + \beta \ln p_{NO_2}^\beta$
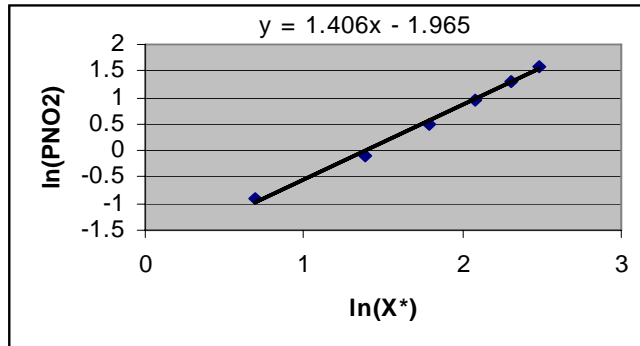
6.100 (cont'd)

$$\ln X^* = 1.406 \ln p_{NO_2} - 1.965 \Rightarrow X^* = e^{-1.965} p_{NO_2}^{1.406} = 0.140 p_{NO_2}^{1.406}$$

$$\underline{\underline{K_F = 0.140 \text{ (kg NO}_2 \text{ / 100 kg gel)(mm Hg)}^{-1.406}}}; \quad \underline{\underline{\beta = 1.406}}$$

b. Mass of silica gel : $m_g = \dfrac{\pi * (0.05\,\text{m})^2 (1\,\text{m})}{\left|\, 1\,\text{m}^3 \,\right.} \left|\, \dfrac{10^3\,\text{L}}{} \,\right| \dfrac{0.75\,\text{kg gel}}{\text{L}} = 5.89 \text{ kg gel}$

Maximum NO_2 adsorbed :

$$p_{NO_2} \text{ in feed} = 0.010(760 \text{ mm Hg}) = 7.60 \text{ mm Hg}$$

$$m_{ads} = \dfrac{0.140(7.60)^{1.406} \text{ kg NO}_2}{100 \text{ kg gel}} \left|\, \dfrac{5.89 \text{ kg gel}}{} \right. = 0.143 \text{ kg NO}_2$$

Average molecular weight of feed :

$$\overline{MW} = 0.01(MW)_{NO_2} + 0.99(MW)_{air} = (0.01)(46.01) + (0.99)(29.0) = 29.17 \dfrac{\text{kg}}{\text{kmol}}$$

Mass feed rate of NO_2:

$$\dot{m} = \dfrac{8.00 \text{ kg}}{\text{h}} \left|\, \dfrac{1 \text{ kmol}}{29.17 \text{ kg}} \,\right| \dfrac{0.01 \text{ kmol NO}_2}{\text{kmol}} \left|\, \dfrac{46.01 \text{ kg NO}_2}{\text{kmol NO}_2} \right. = 0.126 \dfrac{\text{kg NO}_2}{\text{h}}$$

Breakthrough time: $\quad t_b = \dfrac{0.143 \text{ kg NO}_2}{0.126 \text{ kg NO}_2 \text{ / h}} = 1.13 \text{ h} = \underline{\underline{68 \text{ min}}}$

c. The first column would start at time 0 and finish at 1.13 h, and would not be available for another run until $(1.13+1.50) = 2.63$ h. The second column could start at 1.13 h and finish at 2.26 h. Since the first column would still be in the regeneration stage, a third column would be needed to start at 2.26 h. It would run until 3.39 h, at which time the first column would be available for another run. The first few cycles are shown below on a Gantt chart.

———— Run ·············· Regenerate

Column 1						
0	1.13	2.63	3.39	4.52	6.02	

Column 2					
1.13	2.26	3.76	4.52	5.65	

Column 3					
2.26	3.39	4.89	5.65	6.78	
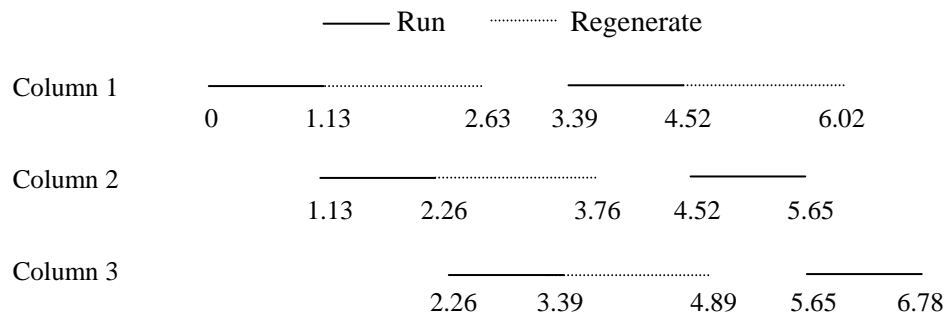
6.101 Let S=sucrose, I=trace impurities, A=activated carbon

Add m_A (kg A)

Come to equilibrium

m_A (kg A)
m_{IA} (kg I adsorbed)
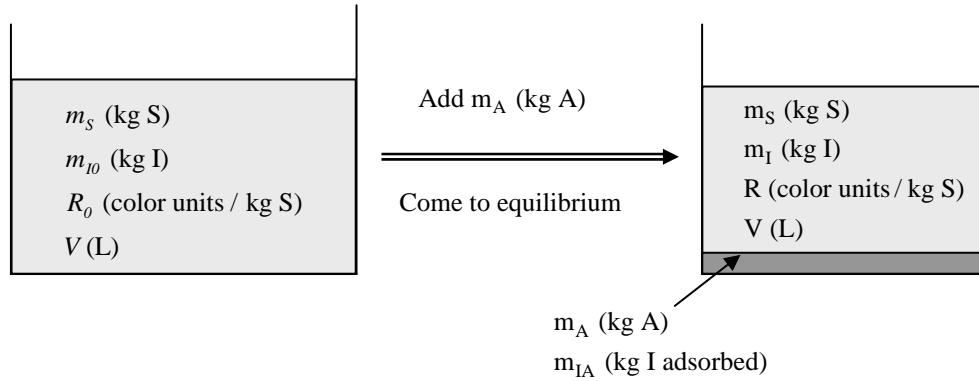
<u>Assume</u> • no sucrose is adsorbed

• solution volume (V) is not affected by addition of the carbon

a. $R(\text{color units/kg S}) = kC_i \text{ (kg I / L)} = k\dfrac{m_I}{V}$ (1)

$$\Rightarrow \ \Delta R = k(C_{i0} - C_i) = \dfrac{k}{V}(m_{I0} - m_I) \xrightarrow{m_{IA} = m_{I0} - m_I} \Delta R = \dfrac{km_{IA}}{V} \quad (2)$$

$\underline{\% \text{ removal of color}} = \dfrac{\Delta R}{R_0}\, x100\% = \dfrac{km_{IA}/V}{km_{I0}/V}\, x100 = 100\dfrac{m_{IA}}{m_{I0}}$ (3)

<u>Equilibrium adsorption ratio:</u> $X_i^* = \dfrac{m_{IA}}{m_A}$ (4)

<u>Normalized percentage color removal:</u>

$$v = \dfrac{\% \text{ removal}}{m_A / m_S} \overset{(3)}{=} \dfrac{100\, m_{IA}/m_{I0}}{m_A/m_S} = 100\dfrac{m_{IA}}{m_A}\dfrac{m_S}{m_{I0}}$$

$$\Rightarrow \ v = 100 X_i^* \dfrac{m_S}{m_{I0}} \Rightarrow X_i^* = \dfrac{m_{I0}}{100 m_S}v \quad (5)$$

<u>Freundlich isotherm</u> $X_i^* = K_F C_i^{\beta} \qquad \overset{(1),(5)}{\Longrightarrow} \qquad \dfrac{m_{I0}}{100 m_S}v = K_F(\dfrac{R}{k})^{\beta}$

$$\Rightarrow \ v = \dfrac{100 m_S K_F}{m_{I0}k^{\beta}} R^{\beta} = K_F' R^{\beta}$$

A plot of $\ln v$ vs. $\ln R$ should be linear: slope $= \beta$; intercept $= \ln K_F'$

6-78
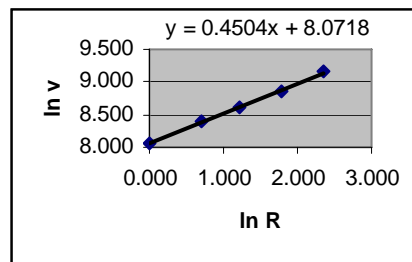
6.101 (cont'd)

$$\ln \upsilon = 0.4504 \ln p_{NO_2} + 8.0718 \Rightarrow \upsilon = e^{8.0718} R^{0.4504} = 3203 R^{0.4504}$$

$$\Rightarrow K_F^{'} = \underline{3203}, \quad \beta = \underline{0.4504}$$

b. <u>100 kg 48% sucrose solution</u> $\Rightarrow$ $m_S = 480$ kg

$\quad$ <u>95% reduction in color</u> $\quad \Rightarrow$ $R = 0.025(20.0) = 0.50$ color units / kg sucrose

$$\upsilon = K_F^{'} R^{\beta} = 3203(0.50)^{0.4504} = 2344$$

$$\Rightarrow 2344 = \frac{\% \text{ color reduction}}{m_A / m_S} = \frac{97.5}{m_A / 480} \Rightarrow m_A = \underline{\underline{20.0 \text{ kg carbon}}}$$

CHAPTER SEVEN

7.1 $\dfrac{0.80\ \text{L}}{\text{h}}\left|\dfrac{3.5\times10^{4}\ \text{kJ}}{\text{L}}\right|\dfrac{0.30\ \text{kJ work}}{1\ \text{kJ heat}}\left|\dfrac{1\ \text{h}}{3600\ \text{s}}\right|\dfrac{1\ \text{kW}}{1\ \text{k J/s}}=2.33\ \text{kW}\Rightarrow \underline{\underline{2.3\ \text{kW}}}$

$\dfrac{2.33\ \text{kW}}{}\left|\dfrac{10^{3}\ \text{W}}{1\ \text{kW}}\right|\dfrac{1.341\times10^{-3}\ \text{hp}}{1\ \text{W}}=3.12\ \text{hp}\Rightarrow \underline{\underline{3.1\ \text{hp}}}$

7.2 All kinetic energy dissipated by friction

(a) $E_k=\dfrac{mu^2}{2}$

$=\dfrac{5500\ \text{lb}_\text{m}}{2}\left|\dfrac{55^2\ \text{miles}^2}{\text{h}^2}\right|\dfrac{5280^2\ \text{ft}^2}{1^2\ \text{mile}^2}\left|\dfrac{1^2\quad \text{h}^2}{3600^2\ \text{s}^2}\right|\dfrac{1\ \text{lb}_\text{f}}{32.174\ \text{lb}_\text{m}\cdot\text{ft}\,/\,\text{s}^2}\left|\dfrac{9.486\times10^{-4}\ \text{Btu}}{0.7376\ \text{ft}\cdot\ \text{lb}_\text{f}}\right.$

$= \underline{\underline{715\ \text{Btu}}}$

(b)

$\dfrac{3\times10^{8}\ \text{brakings}}{\text{day}}\left|\dfrac{715\ \text{Btu}}{\text{braking}}\right|\dfrac{1\ \text{day}}{24\ \text{h}}\left|\dfrac{1\ \text{h}}{3600\ \text{s}}\right|\dfrac{1\ \text{W}}{9.486\times10^{-4}\ \text{Btu/s}}\left|\dfrac{1\ \text{MW}}{10^{6}\text{W}}\right.=2617\ \text{MW}$

$\Rightarrow \underline{\underline{3000\ \text{MW}}}$

7.3 **(a)** <u>Emissions:</u>

$\text{Paper}\Rightarrow \dfrac{1000\ \text{sacks}}{}\left|\dfrac{(0.0510+0.0516)\ \text{oz}}{\text{sack}}\right|\dfrac{1\ \text{lb}_\text{m}}{16\ \text{oz}}=\underline{\underline{6.41\ \text{lb}_\text{m}}}$

$\text{Plastic}\Rightarrow \dfrac{2000\ \text{sacks}}{}\left|\dfrac{(0.0045+0.0146)\ \text{oz}}{\text{sack}}\right|\dfrac{1\ \text{lb}_\text{m}}{16\ \text{oz}}=\underline{\underline{2.39\ \text{lb}_\text{m}}}$

<u>Energy:</u>

$\text{Paper}\Rightarrow \dfrac{1000\ \text{sacks}}{}\left|\dfrac{(724+905)\ \text{Btu}}{\text{sack}}\right.=\underline{\underline{1.63\times10^{6}\ \text{Btu}}}$

$\text{Plastic}\Rightarrow \dfrac{2000\ \text{sacks}}{}\left|\dfrac{(185+464)\ \text{Btu}}{\text{sack}}\right.=\underline{\underline{1.30\times10^{6}\ \text{Btu}}}$

(b) For paper (double for plastic)
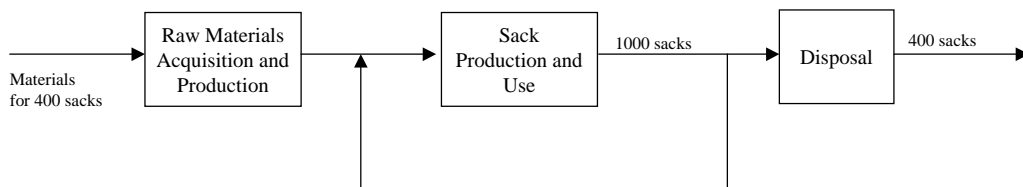
7.3 (cont'd)

Emissions:

$$\text{Paper} \Rightarrow \frac{400 \text{ sacks}}{} \left| \frac{0.0510 \text{ oz}}{\text{sack}} \right| \frac{1 \text{ lb}_m}{16 \text{ oz}} + \frac{1000 \text{ sacks}}{} \left| \frac{0.0516 \text{ oz}}{\text{sack}} \right| \frac{1 \text{ lb}_m}{16 \text{ oz}} = \underline{\underline{4.5 \text{ lb}_m}}$$

$$\Rightarrow \underline{30\% \text{ reduction}}$$

$$\text{Plastic} \Rightarrow \frac{800 \text{ sacks}}{} \left| \frac{0.0045 \text{ oz}}{\text{sack}} \right| \frac{1 \text{ lb}_m}{16 \text{ oz}} + \frac{2000 \text{ sacks}}{} \left| \frac{0.0146 \text{ oz}}{\text{sack}} \right| \frac{1 \text{ lb}_m}{16 \text{ oz}} = \underline{\underline{2.05 \text{ lb}_m}}$$

$$\Rightarrow \underline{14\% \text{ reduction}}$$

Energy:

$$\text{Paper} \Rightarrow \frac{400 \text{ sacks}}{} \left| \frac{724 \text{ Btu}}{\text{sack}} \right. + \frac{1000 \text{ sacks}}{} \left| \frac{905 \text{ Btu}}{\text{sack}} \right. = \underline{\underline{1.19 \times 10^6 \text{ Btu}; \ 27\% \text{ reduction}}}$$

$$\text{Plastic} \Rightarrow \frac{800 \text{ sacks}}{} \left| \frac{185 \text{ Btu}}{\text{sack}} \right. + \frac{2000 \text{ sacks}}{} \left| \frac{464 \text{ Btu}}{\text{sack}} \right. = \underline{\underline{1.08 \times 10^6 \text{ Btu}; \ 17\% \text{ reduction}}}$$

(c) $\frac{3 \times 10^8 \text{ persons}}{} \left| \frac{1 \text{ sack}}{\text{person - day}} \right| \frac{1 \text{ day}}{24 \text{ h}} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \frac{649 \text{ Btu}}{1 \text{ sack}} \left| \frac{1 \text{ J}}{9.486 \times 10^{-4} \text{ Btu}} \right| \frac{1 \text{ MW}}{10^6 \text{ J / s}}$

$$= \underline{\underline{2,375 \text{ MW}}}$$

Savings for recycling: $0.17(2,375 \text{ MW}) = \underline{404 \text{ MW}}$

(d) Cost, toxicity, biodegradability, depletion of nonrenewable resources.

7.4 **(a)** Mass flow rate: $\dot{m} = \frac{3.00 \text{ gal}}{\text{min}} \left| \frac{1 \text{ ft}^3}{7.4805 \text{ gal}} \right| \frac{(0.792)(62.43) \text{ lb}_m}{1 \text{ ft}^3} \left| \frac{1 \text{ min}}{60 \text{ s}} \right. = 0.330 \text{ lb}_m/\text{s}$

Stream velocity: $u = \frac{3.00 \text{ gal}}{\text{min}} \left| \frac{1728 \text{ in}^3}{7.4805 \text{ gal}} \right| \frac{1}{\Pi(0.5)^2 \text{ in}^2} \left| \frac{1 \text{ ft}}{12 \text{ in}} \right| \frac{1 \text{ min}}{60 \text{ s}} = 1.225 \text{ ft}/\text{s}$

Kinetic energy: $E_k = \frac{mu^2}{2} = \frac{0.330 \text{ lb}_m}{\text{s}} \left| \frac{(1.225)^2 \text{ ft}^2}{\text{s}^2} \right| \frac{1}{2} \left| \frac{1}{32.174 \text{ lb}_m \cdot \text{ft / s}^2} \right| \frac{\text{lb}_f}{} = \underline{\underline{7.70 \times 10^{-3} \frac{\text{ft} \cdot \text{lb}_f}{\text{s}}}}$

$$= \left(7.70 \times 10^{-3} \text{ ft} \cdot \text{lb}_f \text{ / s}\right) \left(\frac{1.341 \times 10^{-3} \text{ hp}}{0.7376 \text{ ft} \cdot \text{lb}_f \text{ / s}} \right) = \underline{\underline{1.40 \times 10^{-5} \text{ hp}}}$$

(b) Heat losses in electrical circuits, friction in pump bearings.

7.5 **(a)** <u>Mass flow rate:</u>

$$\dot{m} = \frac{42.0 \text{ m}}{\text{s}} \left| \frac{\pi(0.07 \text{ m})^2}{4} \right| \frac{10^3 \text{ L}}{1 \text{ m}^3} \left| \frac{273 \text{ K}}{573 \text{ K}} \right| \frac{130 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right| \frac{29 \text{ g}}{\text{mol}} = 127.9 \text{ g/s}$$

$$\dot{E}_k = \frac{\dot{m}u^2}{2} = \frac{127.9 \text{ g}}{2} \left| \frac{1 \text{ kg}}{\text{s}} \right| \frac{42.0^2 \text{ m}^2}{1000 \text{ g}} \left| \frac{1 \text{ N}}{\text{s}^2} \right| \frac{1 \text{ J}}{1 \text{ kg} \cdot \text{m} / \text{s}^2} \left| \frac{}{\text{N} \cdot \text{m}} \right| = \underline{\underline{113 \text{ J/s}}}$$

(b)

$$\frac{127.9 \text{ g}}{\text{s}} \left| \frac{1 \text{ mol}}{29 \text{ g}} \right| \frac{673 \text{ K}}{273 \text{ K}} \left| \frac{101.3 \text{ kPa}}{130 \text{ kPa}} \right| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \left| \frac{1 \text{ m}^3}{10^3 \text{ L}} \right| \frac{4}{\pi(0.07)^2 \text{ m}^2} = 49.32 \text{ m/s}$$

$$\dot{E}_k = \frac{\dot{m}u^2}{2} = \frac{127.9 \text{ g}}{2} \left| \frac{1 \text{ kg}}{\text{s}} \right| \frac{49.32^2 \text{ m}^2}{1000 \text{ g}} \left| \frac{1 \text{ N}}{\text{s}^2} \right| \frac{1 \text{ J}}{1 \text{ kg} \cdot \text{m} / \text{s}^2} \left| \frac{}{\text{N} \cdot \text{m}} \right| = 155.8 \text{ J / s}$$

$$\Delta\dot{E}_k = \dot{E}_k(400\,°\text{C}) - \dot{E}_k(300\,°\text{C}) = (155.8 - 113) \text{ J / s} = 42.8 \text{ J / s} \Rightarrow \underline{\underline{43 \text{ J / s}}}$$

(c) Some of the heat added goes to raise T (and hence U) of the air

7.6 **(a)**

$$\Delta E_p = mg\Delta z = \frac{1 \text{ gal}}{7.4805 \text{ gal}} \left| \frac{1 \text{ ft}^3}{1 \text{ ft}^3} \right| \frac{62.43 \text{ lb}_m}{\text{s}^2} \left| \frac{32.174 \text{ ft}}{\text{s}^2} \right| \frac{-10 \text{ ft}}{} \left| \frac{1 \text{ lb}_f}{32.174 \text{ lb}_m \cdot \text{ft} / \text{s}^2} \right| = \underline{\underline{-83.4 \text{ ft} \cdot \text{lb}_f}}$$

(b) $E_k = -\Delta E_p \Rightarrow \dfrac{mu^2}{2} = mg(-\Delta z) \Rightarrow u = \left[2g(-\Delta z)\right]^{1/2} = \left[2\left(32.174 \dfrac{\text{ft}}{\text{s}^2}\right)(10 \text{ ft})\right]^{1/2} = \underline{\underline{25.4 \dfrac{\text{ft}}{\text{s}}}}$

(c) <u>False</u>

7.7 **(a)** $\underline{\underline{\Delta\dot{E}_k \Rightarrow \mathit{positive}}}$ When the pressure decreases, the volumetric flow rate increases, and hence the velocity increases.

$\underline{\underline{\Delta\dot{E}_p \Rightarrow \mathit{negative}}}$ The gas exits at a level below the entrance level.

(b) $\dot{m} = \dfrac{5 \text{ m}}{\text{s}} \left| \dfrac{\pi(1.5)^2 \text{cm}^2}{} \right| \dfrac{1 \text{ m}^3}{10^4 \text{ cm}^2} \left| \dfrac{273 \text{ K}}{303 \text{ K}} \right| \dfrac{10 \text{ bars}}{1.01325 \text{ bars}} \left| \dfrac{1 \text{ kmol}}{22.4 \text{ m}^3 \text{ (STP)}} \right| \dfrac{16.0 \text{ kg CH}_4}{1 \text{ kmol}}$

$= 0.0225 \text{ kg/s}$

$$\frac{P_{out}\dot{V}_{out}}{P_{in}\dot{V}_{in}} = \frac{\dot{n}RT}{\dot{n}RT} \Rightarrow \frac{\dot{V}_{out}}{\dot{V}_{in}} = \frac{P_{in}}{P_{out}} \Rightarrow \frac{u_{out}(\text{m/s}) \cdot A(\text{m}^2)}{u_{in}(\text{m/s}) \cdot A(\text{m}^2)} = \frac{P_{in}}{P_{out}}$$

$$\Rightarrow u_{out} = u_{in}\frac{P_{in}}{P_{out}} = 5(\text{m/s})\frac{10 \text{ bar}}{9 \text{ bar}} = 5.555 \text{ m/s}$$

$$\Delta\dot{E}_k = \frac{1}{2}\dot{m}(u_{out}^2 - u_{in}^2) = \frac{0.5(0.0225) \text{ kg}}{\text{s}} \left| \frac{(5.555^2 - 5.000^2)\text{m}^2}{\text{s}^2} \right| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \left| \frac{1 \text{ W}}{1 \text{ N} \cdot \text{m/s}} \right|$$

$= \underline{\underline{0.0659 \text{ W}}}$

$$\Delta\dot{E}_p = \dot{m}g(z_{out} - z_{in}) = \frac{0.0225 \text{ kg}}{\text{s}} \left| \frac{9.8066 \text{ m}}{\text{s}} \right| \frac{-200 \text{ m}}{} \left| \frac{1 \text{ N}}{\text{kg} \cdot \text{m/s}^2} \right| \frac{1 \text{ W}}{1 \text{ N} \cdot \text{m/s}}$$

$= \underline{\underline{-44.1 \text{ W}}}$

7.8
$$\Delta \dot{E}_p = \dot{m}g\Delta z = \frac{10^5 \text{ m}^3}{\text{h}} \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \frac{1 \text{ kg H}_2\text{O}}{1 \text{ L}} \left| \frac{9.81 \text{ m}}{\text{s}^2} \right| \frac{-75 \text{ m}}{} \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m}/\text{s}^2} \right| \frac{1 \text{ J}}{1 \text{ N} \cdot \text{m}} \left| \frac{2.778 \times 10^{-7} \text{ kW} \cdot \text{h}}{1 \text{ J}} \right.$$

$$= -2.04 \times 10^4 \text{ kW} \cdot \text{h}/\text{h}$$

The maximum energy to be gained equals the potential energy lost by the water, or

$$\frac{2.04 \times 10^4 \text{ kW} \cdot \text{h}}{\text{h}} \left| \frac{24 \text{ h}}{1 \text{ day}} \right| \frac{7 \text{ days}}{1 \text{ week}} = 3.43 \times 10^6 \text{ kW} \cdot \text{h}/\text{week} \quad \text{(more than sufficient)}$$

7.9 **(b)** $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$\Delta E_k = 0$ (system is stationary)

$\Delta E_p = 0$ (no height change)

$\underline{\underline{Q - W = \Delta U, Q < 0, W > 0}}$

(c) $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$Q = 0$ (adiabatic), $W = 0$ (no moving parts or generated currents)

$\Delta E_k = 0$ (system is stationary)

$\Delta E_p = 0$ (no height change)

$\underline{\underline{\Delta U = 0}}$

(d). $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$W = 0$ (no moving parts or generated currents)

$\Delta E_k = 0$ (system is stationary)

$\Delta E_p = 0$ (no height change)

$\underline{\underline{Q = \Delta U, Q < 0}}$ Even though the system is isothermal, the occurrence of a chemical reaction assures that $\Delta U \neq 0$ in a non-adiabatic reactor. If the temperature went up in the adiabatic reactor, heat must be transferred from the system to keep T constant, hence $Q < 0$.

7.10 4.00 L, 30 °C, 5.00 bar $\Rightarrow$ V (L), T (°C), 8.00 bar

(a). Closed system: $\Delta U + \Delta E_k + \Delta E_p = Q - W$

$\begin{cases} \Delta E_k = 0 \text{ (initial / final states stationary)} \\ \Delta E_p = 0 \text{ (by assumption)} \end{cases}$

$\underline{\underline{\Delta U = Q - W}}$

(b) Constant $T \Rightarrow \Delta U = 0 \Rightarrow Q = W = \dfrac{-7.65 \text{ L} \cdot \text{bar}}{} \left| \dfrac{8.314 \text{ J}}{0.08314 \text{ L} \cdot \text{bar}} \right. = \underline{\underline{-765 \text{ J}}}$ transferred from gas to surroundings

(c) Adiabatic $\Rightarrow Q = 0 \Rightarrow \Delta U = -W = 7.65 \text{ L} \cdot \text{bar} > 0, \ \underline{\underline{T_{\text{final}} > 30° \text{C}}}$

7.11 $A = \dfrac{\pi(3)^2 \text{ cm}^2}{} \left| \dfrac{1 \text{ m}^2}{10^4 \text{ cm}^2} \right. = 2.83 \times 10^{-3} \text{ m}^2$

(a) Downward force on piston:

$F_d = P_{atm} A + m_{piston+weight}\, g$

$= \dfrac{1 \text{ atm}}{} \left| \dfrac{1.01325 \times 10^5 \text{ N}/\text{m}^2}{\text{atm}} \right| \dfrac{2.83 \times 10^{-3} \text{ m}^2}{} + \dfrac{24.50 \text{ kg}}{} \left| \dfrac{9.81 \text{ m}}{\text{s}^2} \right| \dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m}/\text{s}^2} = 527 \text{ N}$

Upward force on piston: $F_u = A P_{gas} = \left(2.83 \times 10^{-3} \text{ m}^2\right)\left[P_g\left(\text{N}/\text{m}^2\right)\right]$

Equilibrium condition:

$F_u = F_d \Rightarrow 2.83 \times 10^{-3} \text{ m}^2 \cdot P_0 = 527 \Rightarrow \underline{\underline{P_0 = 1.86 \times 10^5 \text{ N}/\text{m}^2 = 1.86 \times 10^5 \text{ Pa}}}$

$V_0 = \dfrac{nRT}{P_0} = \dfrac{1.40 \text{ g N}_2}{} \left| \dfrac{1 \text{ mol N}_2}{28.02 \text{ g}} \right| \dfrac{303 \text{ K}}{1.86 \times 10^5 \text{ Pa}} \left| \dfrac{1.01325 \times 10^5 \text{ Pa}}{1 \text{ atm}} \right| \dfrac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} = \underline{\underline{0.677 \text{ L}}}$

(b) For any step, $\Delta U + \Delta E_k + \Delta E_p = Q - W \underset{\substack{\Delta E_k = 0 \\ \Delta E_p = 0}}{\Rightarrow} \Delta U = Q - W$

Step 1: $Q \approx 0 \Rightarrow \underline{\underline{\Delta U = -W}}$

Step 2: $\underline{\underline{\Delta U = Q - W}}$ As the gas temperature changes, the pressure remains constant, so
that $V = nRT/P_g$ must vary. This implies that the piston moves, so that W is not zero.

Overall: $T_{initial} = T_{final} \Rightarrow \Delta U = 0 \Rightarrow \underline{\underline{Q - W = 0}}$

In step 1, the gas expands $\Rightarrow W > 0 \Rightarrow \Delta U < 0 \Rightarrow \underline{\underline{T \text{ decreases}}}$

(c) Downward force $F_d = \left(1.00\right)\left(1.01325 \times 10^5\right)\left(2.83 \times 10^{-3}\right) + \left(4.50\right)\left(9.81\right)\left(1\right) = 331 \text{ N}$ (units
as in Part (a))

Final gas pressure $P_f = \dfrac{F}{A} = \dfrac{331 \text{ N}}{2.83 \times 10^{-3} \text{ m}^2} = 1.16 \times 10^5 \text{ N}/\text{m}^2$

Since $T_0 = T_f = 30°\text{C}$, $P_f V_f = P_0 V_0 \Rightarrow V_f = V_0 \dfrac{P_0}{P_f} = \left(0.677 \text{ L}\right) \dfrac{1.86 \times 10^5 \text{ Pa}}{1.16 \times 10^5 \text{ Pa}} = 1.08 \text{ L}$

Distance traversed by piston $= \dfrac{\Delta V}{A} = \dfrac{\left(1.08 - 0.677\right) \text{ L}}{2.83 \times 10^{-3} \text{ m}^2} \left| \dfrac{1 \text{ m}^3}{10^3 \text{ L}} \right. = 0.142 \text{ m}$

$\Rightarrow W = Fd = \left(331 \text{ N}\right)\left(0.142 \text{ m}\right) = 47 \text{ N} \cdot \text{m} = 47 \text{ J}$

Since work is done by the gas on its surroundings, $W = +47 \text{ J} \underset{Q-W=0}{\Rightarrow} \underline{\underline{Q = +47 \text{ J}}}$

(heat transferred to gas)

7.12 $\hat{V} = \dfrac{32.00 \text{ g}}{\text{mol}} \left| \dfrac{4.684 \text{ cm}^3}{\text{g}} \right| \dfrac{10^3 \text{ L}}{10^6 \text{ cm}^3} = 0.1499 \text{ L}/\text{mol}$

$\hat{H} = \hat{U} + P\hat{V} = 1706 \text{ J}/\text{mol} + \dfrac{41.64 \text{ atm}}{} \left| \dfrac{0.1499 \text{ L}}{\text{mol}} \right| \dfrac{8.314}{0.08206 \text{ L} \cdot \text{atm}/(\text{mol} \cdot \text{K})} \dfrac{\text{J}/(\text{mol} \cdot \text{K})}{} = \underline{\underline{2338 \text{ J}/\text{mol}}}$

7.13 **(a)** Ref state $\left(\hat{U}=0\right)\Rightarrow$ liquid Bromine @ 300 K, 0.310 bar

(b) $\Delta\hat{U}=\hat{U}_{final}-\hat{U}_{initial}=0.000-28.24=-28.24$ kJ/mol

$\Delta\hat{H}=\Delta\hat{U}+\Delta\left(P\hat{V}\right)=\Delta\hat{U}+P\Delta\hat{V}$ (Pressure Constant)

$\Delta\hat{H}=-28.24 \text{ kJ/mol}+\dfrac{0.310 \text{ bar}}{}\left|\dfrac{(0.0516-79.94) \text{ L}}{\text{mol}}\right|\dfrac{8.314 \text{ J}}{0.08314 \text{ L}\cdot\text{bar}}\left|\dfrac{1 \text{ kJ}}{10^3 \text{ J}}\right.=-30.7 \text{ kJ/mol}$

$\Delta H=n\Delta\hat{H}=\left(5.00 \text{ mol}\right)\left(-30.7 \text{ kJ / mol}\right)=-153.58 \text{ kJ}\Rightarrow\underline{-154 \text{ kJ}}$

(c) $\hat{U}$ independent of $P\Rightarrow\hat{U}\left(300 \text{ K, } 0.205 \text{ bar}\right)=\hat{U}\left(300 \text{ K, } 0.310 \text{ bar}\right)=28.24$ kJ/mol
$$\hat{U}\left(340 \text{ K, } P_f\right)=\hat{U}\left(340 \text{ K, } 1.33 \text{ bar}\right)=29.62 \text{ kJ/mol}$$

$\Delta\hat{U}=\hat{U}_{final}-\hat{U}_{initial}$

$\Delta\hat{U}=29.62-28.24=\underline{1.380 \text{ kJ/mol}}$

$\hat{V}$ changes with pressure. At constant temperature $\Rightarrow P\hat{V}=P'\hat{V}'\Rightarrow\hat{V}'=P\hat{V}/P'$

$\hat{V}'(T=300K, \ P=0.205 \text{ bar})=\dfrac{(0.310 \text{ bar})(79.94 \text{ L / mol})}{0.205 \text{ bar}}=120.88 \text{ L / mol}$

$n=\dfrac{5.00 \text{ L}}{}\left|\dfrac{1 \text{ mol}}{120.88 \text{ L}}\right.=0.0414 \text{ mol}$

$\Delta U=n\Delta\hat{U}=\left(0.0414 \text{ mol}\right)\left(1.38 \text{ kJ / mol}\right)=\underline{0.0571 \text{ kJ}}$

$\Delta U+\cancel{\Delta E_k}+\cancel{\Delta E_p}=Q-\cancel{W}\Rightarrow\underline{\underline{Q=0.0571 \text{ kJ}}}$
$\quad\quad\quad 0 \quad\quad 0 \quad\quad\quad 0$

(d) Some heat is lost to the surroundings; the energy needed to heat the wall of the container is being neglected; internal energy is not completely independent of pressure.

7.14 **(a)** By definition $\hat{H}=\hat{U}+P\hat{V}$; ideal gas $P\hat{V}=RT\Rightarrow\hat{H}=\hat{U}+RT$

$\hat{U}\left(T,P\right)=\hat{U}\left(T\right)\Rightarrow\hat{H}\left(T,P\right)=\hat{U}\left(T\right)+RT=\hat{H}\left(T\right)$ independent of P

(b) $\Delta\hat{H}=\Delta\hat{U}+R\Delta T=3500\dfrac{\text{cal}}{\text{mol}}+\dfrac{1.987 \text{ cal}}{\text{mol}\cdot\text{K}}\left|\dfrac{50 \text{ K}}{}\right.=3599$ cal/mol

$\Delta H=n\Delta\hat{H}=\left(2.5 \text{ mol}\right)\left(3599 \text{ cal / mol}\right)=8998 \text{ cal}\Rightarrow\underline{9.0\times10^3 \text{ cal}}$

7.15 $\Delta U+\Delta E_k+\Delta E_p=Q-Ws$

$\quad\quad\quad\quad\quad\quad\quad\Delta E_k=0$ (no change in m and u)
$\quad\quad\quad\quad\quad\quad\quad\Delta E_p=0$ (no elevation change)
$\quad\quad\quad\quad\quad\quad\quad W_s=P\Delta V$ (since energy is transferred from the system to the surroundings)

$\Delta U=Q-W\Rightarrow\Delta U=Q-P\Delta V\Rightarrow Q=\Delta U+P\Delta V=\Delta(U+PV)=\Delta H$

7.16. **(a)** $\Delta E_k = 0 \; (u_1 = u_2 = 0)$

$\Delta E_p = 0 \; (\text{no elevation change})$

$\Delta P = 0$ (the pressure is constant since restraining force is constant, and area is constrant)

$W_s = P\Delta V$ (the only work done is expansion work)

$\hat{H} = 34980 + 35.5T$ (J / mol), $V_1 = 785$ cm^3, $T_1 = 400$ K, P = 125 kPa, Q = 83.8 J

$$n = \frac{PV}{RT} = \frac{125 \times 10^3 \text{ Pa}}{8.314 \text{ m}^3 \cdot \text{Pa / mol} \cdot \text{K}} \left| \frac{785 \text{ cm}^3}{400 \text{ K}} \right| \frac{1 \text{ m}^3}{10^6 \text{ cm}^3} = 0.0295 \text{ mol}$$

$Q = \Delta H = n(\hat{H}_2 - \hat{H}_1) = 0.0295 \text{ mol}\left[34980 + 35.5T_2 - 34980 - 35.5(400K)\right]$ (J / mol)

$83.8 \text{ J} = 0.0295\left[35.5T_2 - 35.5(400)\right] \Rightarrow \underline{\underline{T_2 = 480 \text{ K}}}$

$i) \; V = \dfrac{nRT}{P} = \dfrac{0.0295 \text{ mol}}{125 \times 10^5 \text{ Pa}} \left| \dfrac{8.314 \text{ m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}} \right| \dfrac{10^6 \text{ cm}^3}{1 \quad \text{m}^3} \left| 480 \text{ K} \right. = \underline{\underline{941 \text{ cm}^3}}$

$ii) \; W = P\Delta V = \dfrac{125 \times 10^5 \text{ N}}{\text{m}^2} \left| \dfrac{(941 - 785)\text{cm}^3}{} \right| \dfrac{1 \quad \text{m}^3}{10^6 \text{ cm}^3} = \underline{\underline{19.5 \text{ J}}}$

$iii) \; Q = \Delta U + P\Delta V \Rightarrow \Delta U = Q - \Delta PV = 83.8 \text{ J} - 19.5 \text{ J} = \underline{\underline{64.3 \text{ J}}}$

(b) $\underline{\underline{\Delta E_p = 0}}$

7.17 **(a)** "The gas temperature remains constant while the circuit is open." (If heat losses could occur, the temperature would drop during these periods.)

(b) $\Delta U + \Delta E_p + \Delta E_R = \dot{Q}\Delta t - \dot{W}\Delta t$

$\left\| \begin{array}{l} \Delta E_p = 0, \; \Delta E_k = 0, \; \dot{W} = 0, \; \hat{U}(t = 0) = 0 \\[4pt] \dot{Q} = \dfrac{0.90 \times 1.4 \text{ W}}{} \left| \dfrac{1 \text{ J/s}}{1 \text{ W}} \right. = 1.26 \text{ J/s} \end{array} \right.$

$U \text{ (J)} = 1.26 \, t$

$\underline{\text{Moles in tank: }} n = PV/RT = \dfrac{1 \text{ atm}}{} \left| \dfrac{2.10 \text{ L}}{(25 + 273)\text{K}} \right| \dfrac{1}{0.08206 \text{ L} \cdot \text{atm}} \dfrac{\text{mol} \cdot \text{K}}{} = 0.0859 \text{ mol}$

$\hat{U} = \dfrac{U}{n} = \dfrac{1.26t \text{ (J)}}{0.0859 \text{ mol}} = 14.67t$

$\underline{\text{Thermocouple calibration: }} T = aE + b \implies T(^\circ\text{C}) = 18.1E(\text{mV}) + 4.51$

$\substack{T=0, \, E=-0.249 \\ T=100, \, E=5.27}$

$\hat{U} = 14.67t$	0	440	880	1320
$T = 18.1E + 4.51$	25	45	65	85

(c) To keep the temperature uniform throughout the chamber.

(d) Power losses in electrical lines, heat absorbed by chamber walls.

(e) In a closed container, the pressure will increase with increasing temperature. However, at the low pressures of the experiment, the gas is probably close to ideal $\Rightarrow \hat{U} = f(T)$ only.

Ideality could be tested by repeating experiment at several initial pressures $\Rightarrow$ same results.

7.18 (b) $\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$ (The system is the liquid stream.)

$\quad\quad\quad\quad\quad\quad\quad\quad\Delta \dot{E}_k = 0$ (no change in m and u)
$\quad\quad\quad\quad\quad\quad\quad\quad\Delta \dot{E}_p = 0$ (no elevation change)
$\quad\quad\quad\quad\quad\quad\quad\quad\dot{W}_s = 0$ (no moving parts or generated currents)

$\quad\quad\quad\quad\quad \underline{\underline{\Delta \dot{H} = \dot{Q}, \ \dot{Q} > 0}}$

(c) $\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$ (The system is the water)

$\quad\quad\quad\quad\quad\quad\quad\quad\Delta \dot{H} = 0$ (T and $P \sim$ constant)
$\quad\quad\quad\quad\quad\quad\quad\quad\Delta \dot{E}_k = 0$ (no change in m and u)
$\quad\quad\quad\quad\quad\quad\quad\quad\dot{Q} = 0$ (no ΔT between system and surroundings)

$\quad\quad\quad\quad\quad \underline{\underline{\Delta \dot{E}_p = -\dot{W}_s, \ \dot{W}_s > 0 \ \left(\text{for water system}\right)}}$

(d) $\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$ (The system is the oil)

$\quad\quad\quad\quad\quad\quad\Delta \dot{E}_k = 0$ (no velocity change)

$\quad\quad \underline{\underline{\Delta \dot{H} + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s \ \ \dot{Q} < 0}}$ (friction loss); $\dot{W}_s < 0$ (pump work).

(e) $\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$ (The system is the reaction mixture)

$\quad\quad\quad\quad\quad\quad\quad\Delta \dot{E}_k = \Delta \dot{E}_p = 0$ (given)
$\quad\quad\quad\quad\quad\quad\quad\Delta \dot{W}_s = 0$ (no moving parts or generated current)

$\quad \underline{\underline{\Delta \dot{H} = \dot{Q}, \ \dot{Q} \text{ pos. or neg. depends on reaction}}}$

7.19 (a) $\underline{\text{molar flow:}}$

$$\frac{1.25 \text{ m}^3}{\text{min}} \left| \frac{273 \text{ K}}{423 \text{ K}} \right| \frac{122 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| \frac{10^3 \text{ L}}{1 \text{ m}^3} = 43.4 \text{ mol/min}$$

$$\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

$\quad\quad\quad\quad\quad\quad\Delta \dot{E}_k = \Delta \dot{E}_p = 0$ (given)
$\quad\quad\quad\quad\quad\quad\dot{W}_s = 0$ (no moving parts)

$$\dot{Q} = \Delta \dot{H} = \dot{n}\Delta \hat{H} = \frac{43.37 \text{ mol}}{\text{min}} \left| \frac{1 \text{ min}}{60\text{s}} \right| \frac{3640 \text{ J}}{\text{mol}} \left| \frac{\text{kW}}{10^3 \text{ J / s}} \right| = \underline{\underline{2.63 \text{ kW}}}$$

(b) More information would be needed. The change in kinetic energy would depend on the cross-sectional area of the inlet and outlet pipes, hence the internal diameter of the inlet and outlet pipes would be needed to answer this question.

7.20 **(a)** $\hat{H} = 1.04[T(°C) - 25]$ $\hat{H}$ in kJ/kg

$\hat{H}_{out} = 1.04[34.0 - 25] = 9.36$ kJ/kg

$\hat{H}_{in} = 1.04[30.0 - 25] = 5.20$ kJ/kg

$\Delta\hat{H} = 9.36 - 5.20 = 4.16$ kJ/kg
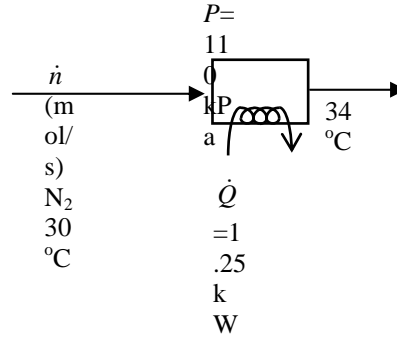
$\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$

$\quad\quad \Delta\dot{E}_k = \Delta\dot{E}_p = 0$ (assumed)

$\quad\quad \dot{W}_s = 0$ (no moving parts)

$\dot{Q} = \Delta\dot{H} = \dot{n}\Delta\hat{H}$

$\dot{n}$ (mol/s) N_2 30 °C

P= 110 kPa   34 °C

$\dot{Q} = 1.25$ kW

$$\Rightarrow \dot{n} = \frac{\dot{Q}}{\Delta\hat{H}} = \frac{1.25 \text{ kW}}{} \left|\frac{\text{kg}}{4.16 \text{ kJ}}\right| \frac{1 \text{ kJ/s}}{\text{kW}} \left|\frac{10^3 \text{ g}}{1 \text{ kg}}\right| \frac{1 \text{ mol}}{28.02 \text{ g}} = 10.7 \text{ mol/s}$$

$$\Rightarrow \dot{V} = \frac{10.7 \text{ mol}}{\text{s}} \left|\frac{22.4 \text{ L(STP)}}{\text{mol}}\right| \frac{303 \text{ K}}{273 \text{ K}} \left|\frac{101.3 \text{ kPa}}{110 \text{ kPa}}\right| = 245.5 \text{ L/s} \Rightarrow \underline{\underline{246 \text{ L/s}}}$$

(b) Some heat is lost to the surroundings, some heat is needed to heat the coil, enthalpy is assumed to depend linearly on temperature and to be independent of pressure, errors in measured temperature and in wattmeter reading.

7.21 **(a)** $\hat{H} = aT + b$ $a = \dfrac{\hat{H}_2 - \hat{H}_1}{T_2 - T_1} = \dfrac{129.8 - 25.8}{50 - 30} = 5.2$

$b = \hat{H}_1 - aT_1 = 25.8 - (5.2)(30) = -130.2$

$\Rightarrow \underline{\underline{\hat{H}(\text{kJ/kg}) = 5.2T(°C) - 130.2}}$

$\hat{H} = 0 \Rightarrow T_{ref} = \dfrac{130.2}{5.2} = \underline{\underline{25°C}}$

Table B.1 $\Rightarrow (S.G.)_{C_6H_{14}(l)} = 0.659 \Rightarrow \hat{V} = \dfrac{1 \text{ m}^3}{659 \text{ kg}} = 1.52 \times 10^{-3} \text{ m}^3/\text{kg}$

$\hat{U}(\text{kJ/kg}) = \hat{H} - P\hat{V} = (5.2T - 130.2)\text{kJ/kg}$

$$- \frac{1 \text{ atm}}{} \left|\frac{1.0132 \times 10^5 \text{ N/m}^2}{1}\right| \frac{1.52 \times 10^{-3} \text{ m}^3}{\text{atm}} \left|\frac{1 \text{ J}}{1 \text{ N}\cdot\text{m}}\right| \frac{1 \text{ kJ}}{10^3 \text{ J}}$$

$\Rightarrow \underline{\underline{\hat{U}(\text{kJ/kg}) = 5.2T - 130.4}}$

(b) Energy balance: $Q = \Delta U = \dfrac{20 \text{ kg}}{} \left|\dfrac{[(5.2 \times 20 - 130.4) - (5.2 \times 80 - 130.4)] \text{ kJ}}{1}\right| \dfrac{}{\text{kg}} = -6240 \text{ kJ}$

$\overline{\Delta E_k, \Delta E_p, W = 0}$

Average rate of heat removal $= \dfrac{6240 \text{ kJ}}{5 \text{ min}} \left|\dfrac{1 \text{ min}}{60 \text{ s}}\right| = \underline{\underline{20.8 \text{ kW}}}$
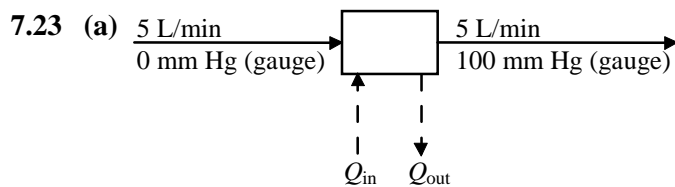
7.22

$$\underset{\text{260°C, 7 bars}}{\overset{\dot{m}\,(\text{kg/s})}{\longrightarrow}}\boxed{}\underset{\text{200°C, 4 bars}}{\overset{\dot{m}\,(\text{kg/s})}{\longrightarrow}}$$

$\hat{H}$ = 2974 kJ/kg $\hat{H}$ = 2860 kJ/kg

$u_0 = 0$ u (m/s)

$$\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$$

$$\Big\Downarrow \quad \Delta\dot{E}_p = \dot{Q} = \dot{W}_s = 0$$

$$\Delta\dot{E}_k = -\Delta\dot{H} \ \Rightarrow\ \frac{\dot{m}u^2}{2} = -\dot{m}\big(\hat{H}_{\text{out}} - \hat{H}_{\text{in}}\big)$$

$$u^2 = 2\big(\hat{H}_{\text{in}} - \hat{H}_{\text{out}}\big) = \frac{(2)(2974-2860)\text{kJ}}{\text{kg}}\left|\frac{10^3\,\text{N}\cdot\text{m}}{1\,\text{kJ}}\right|\frac{1\,\text{kg}\cdot\text{m}/\text{s}^2}{1\,\text{N}} = 2.28\times10^5\,\frac{\text{m}^2}{\text{s}^2} \Rightarrow \underline{\underline{u = 477\ \text{m/s}}}$$

7.23 **(a)**

$$\underset{\text{0 mm Hg (gauge)}}{\overset{\text{5 L/min}}{\longrightarrow}}\boxed{}\underset{\text{100 mm Hg (gauge)}}{\overset{\text{5 L/min}}{\longrightarrow}}$$

$$\dot{Q}_{\text{in}} \quad \dot{Q}_{\text{out}}$$

Since there is only one inlet stream and one outlet stream, and $\dot{m}_{\text{in}} = \dot{m}_{\text{out}} \equiv \dot{m}$,
Eq. (7.4-12) may be written

$$\dot{m}\Delta\hat{U} + \dot{m}\Delta\big(P\hat{V}\big) + \frac{\dot{m}}{2}\Delta\big(u^2\big) + \dot{m}g\Delta z = \dot{Q} - \dot{W}_s$$

$$\Bigg\Downarrow
\begin{aligned}
&\Delta\hat{U} = 0 \ (\text{given})\\
&\dot{m}\Delta P\hat{V} = \dot{m}\hat{V}\big(P_{\text{out}} - P_{\text{in}}\big) = \dot{V}\Delta P\\
&\Delta u^2 = 0 \ (\text{assume for incompressible fluid})\\
&\Delta z = 0\\
&\dot{W}_s = 0 \ (\text{all energy other than flow work included in heat terms})\\
&\dot{Q} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}
\end{aligned}$$

$$\underline{\underline{\dot{V}\Delta P = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}}}$$

(b) <u>Flow work:</u> $\dot{V}\Delta P = \dfrac{5\,\text{L}}{\text{min}}\left|\dfrac{(100-0)\text{mm Hg}}{}\right|\dfrac{1\,\text{atm}}{760\,\text{mm Hg}}\left|\dfrac{8.314\ \text{J}}{0.08206\,\text{liter}\cdot\text{atm}}\right. = 66.7\ \text{J/min}$
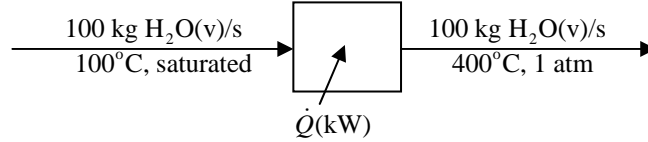
<u>Heat input:</u> $\dot{Q}_{\text{in}} = \dfrac{5\,\text{ml O}_2}{\text{min}}\left|\dfrac{20.2\,\text{J}}{1\,\text{ml O}_2}\right. = 101\ \text{J/min}$

<u>Efficiency:</u> $\dfrac{\dot{V}\Delta P}{\dot{Q}_{\text{in}}} = \dfrac{66.7\ \text{J/min}}{101\ \text{J/min}}\times100\% = \underline{\underline{66\%}}$

7.24 (a) $\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$; $\Delta\dot{E}_k$, $\Delta\dot{E}_p$, $\dot{W}_s = 0 \Rightarrow \Delta\dot{H} = \dot{Q}$

$\hat{H}(400°\text{C}, 1\text{ atm}) = 3278$ kJ/kg (Table B.7)

$\hat{H}(100°\text{C}, \text{sat'd} \Rightarrow 1\text{ atm}) = 2676$ kJ/kg (Table B.5)

$$\dot{Q} = \frac{100\text{ kg}}{\text{s}} \left| \frac{(3278 - 2676.0)\text{kJ}}{\text{kg}} \right| \frac{10^3\text{ J}}{1\text{ kJ}} = \underline{\underline{6.02 \times 10^7 \text{ J/s}}}$$

(b) $\Delta U + \Delta E_k + \Delta E_p = Q - W$; ΔE_k, ΔE_p, $W = 0 \Rightarrow \Delta U = Q$

Table B.5 $\Rightarrow$ $\hat{U}(100°\text{C}, 1\text{ atm}) = 2507 \dfrac{\text{kJ}}{\text{kg}}$, $\hat{V}(100°\text{C}, 1\text{ atm}) = 1.673 \dfrac{\text{m}^3}{\text{kg}} = \hat{V}(400°\text{C}, P_{\text{final}})$

Interpolate in Table B.7 to find P at which $\hat{V} = 1.673$ at 400°C, and then interpolate again to find $\hat{U}$ at 400°C and that pressure:
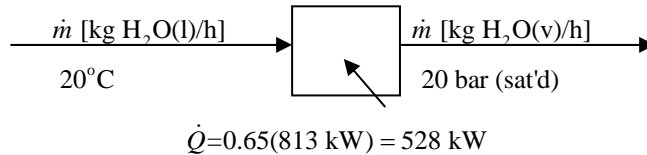
$\hat{V} = 1.673$ m³/g $\Rightarrow P_{\text{final}} = 1.0 + 4.0\left(\dfrac{3.11 - 1.673}{3.11 - 0.617}\right) = 3.3$ bar, $\hat{U}(400°\text{C}, 3.3\text{ bar}) = 2966$ kJ/kg

$\Rightarrow Q = \Delta U = m\Delta\hat{U} = 100\text{ kg}\left[(2966 - 2507)\text{kJ/kg}\right](10^3 \text{ J/kJ}) = \underline{4.59 \times 10^7 \text{ J}}$

The difference is the net energy needed to move the fluid through the system (flow work). (The energy change associated with the pressure change in Part (b) is insignificant.)

7.25 $\hat{H}(\text{H}_2\text{O}(l), 20°\text{C}) = 83.9$ kJ/kg (Table B.5)

$\hat{H}(\text{steam}, 20\text{ bars}, \text{sat'd}) = 2797.2$ kJ/kg (Table B.6)

$\dot{Q} = 0.65(813\text{ kW}) = 528$ kW

(a) $\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$; $\Delta\dot{E}_k$, $\Delta\dot{E}_p$, $\dot{W}_s = 0 \Rightarrow \Delta\dot{H} = \dot{Q}$

$\Delta\dot{H} = \dot{m}\Delta\hat{H}$

$$\dot{m} = \frac{\dot{Q}}{\Delta\hat{H}} = \frac{528\text{ kW}}{(2797.2 - 83.9)\text{kJ}} \left| \frac{\text{kg}}{} \right| \frac{1\text{ kJ / s}}{1\text{ kW}} \left| \frac{3600\text{ s}}{1\text{ h}} \right| = \underline{\underline{701 \text{ kg/h}}}$$

(b) $\dot{V} = (701\text{ kg/h})(0.0995\text{ m}^3/\text{kg}) = \underline{\underline{69.7 \text{ m}^3/\text{h}}}$ sat'd steam @ 20 bar

↑
Table B.6

(c) $\dot{V} = \dfrac{\dot{n}RT}{P} = \dfrac{701\text{ kg / h}}{18.02\text{ g / mol}} \left| \dfrac{10^3\text{ g / kg}}{20\text{ bar}} \right| 485.4\text{ K} \left| \dfrac{0.08314\text{ L}\cdot\text{bar}}{\text{mol}\cdot\text{K}} \right| \dfrac{1\text{ m}^3}{10^3\text{ L}} = \underline{\underline{78.5\text{ m}^3 / \text{h}}}$

The calculation in (b) is more accurate because the steam tables account for the effect of pressure on specific enthalpy (nonideal gas behavior).

(d) Most energy released goes to raise the temperature of the combustion products, some is transferred to the boiler tubes and walls, and some is lost to the surroundings.

7.26 $\hat{H}(H_2O(l),\ 24°C,\ 10\ \text{bar}) = 100.6\ \text{kJ/kg}$ (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) $\Rightarrow \Delta\hat{H} = 2776.2 - 100.6 = \underline{\underline{2675.6\ \text{kJ/kg}}}$

$$\underset{\text{24°C, 10 bar}}{\overset{\dot{m}\ [\text{kg}\ H_2O(l)/\text{h}]}{\longrightarrow}} \boxed{} \underset{\substack{15{,}000\ \text{m}^3/\text{h @10 bar (sat'd)}}}{\overset{\dot{m}\ [\text{kg}\ H_2O(v)/\text{h}]}{\longrightarrow}}$$

$$\dot{Q}(\text{kW})$$
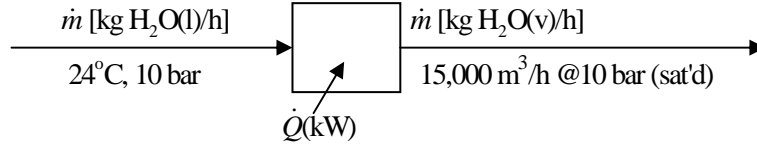
$$\dot{m} = \frac{15000\ \text{m}^3}{\text{h}}\ \left|\ \frac{\text{kg}}{0.1943\ \underset{\substack{\uparrow \\ (\text{Table 8.6})}}{\text{m}^3}}\ = 7.72 \times 10^4\ \text{kg/h}\right.$$

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

$$\Delta\dot{E}_k = \dot{E}_{k_{final}} - \dot{E}_{k_{initial}} \overset{\dot{E}_{k_{initial}} \approx 0}{\Longrightarrow} \Delta\dot{E}_k = \dot{E}_{k_{final}}$$

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

$$\dot{Q} = \dot{m}\Delta\hat{H} + \Delta\dot{E}_k = \frac{7.72 \times 10^4\ \text{kg}}{\text{h}}\ \left|\ \frac{2675.6\ \text{kJ}}{\text{kg}}\ \right|\ \frac{1\ \text{h}}{3600\ \text{s}}\ + \frac{5.96 \times 10^5\ \text{J}}{\text{s}}\ \left|\ \frac{1\ \text{kJ}}{10^3\ \text{J}}\right.$$

$$= 57973\ \text{kJ/s} = \underline{\underline{5.80 \times 10^4\ \text{kW}}}$$

7.27 (a)

$$\underset{25°C}{\overset{228\ \text{g/min}}{\longrightarrow}} \boxed{} \underset{T(°C)}{\overset{228\ \text{g/min}}{\longrightarrow}}$$

$$\dot{Q}(\text{kW})$$

Energy balance: $\underset{\Delta\dot{E}_x,\ \Delta\dot{E}_p,\ \dot{W}_s=0}{\dot{Q} = \Delta\dot{H}} \Rightarrow \dot{Q}(\text{W}) = \frac{228\ \text{g}}{\text{min}}\ \left|\ \frac{1\ \text{min}}{60\ \text{s}}\ \right|\ \frac{(\hat{H}_{out} - \overset{=0}{\cancel{\hat{H}_{in}}})\ \text{J}}{\text{g}}$

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

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

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

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

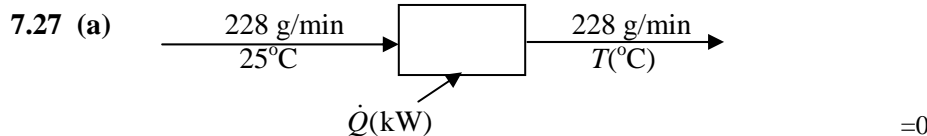**(c)** $\dot{Q} = \Delta\dot{H} = \dfrac{350\ \text{kg}}{\text{min}}\ \left|\ \dfrac{10^3\ \text{g}}{\text{kg}}\ \right|\ \dfrac{1\ \text{min}}{60\ \text{s}}\ \left|\ \dfrac{3.34(40 - 20)\text{J}}{\text{g}}\ \right|\ \dfrac{\text{kW}\cdot\text{s}}{10^3\ \text{J}} = \underline{\underline{390\ \text{kW}}}$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

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

7.28

$\dot{m}_w$ [kg H$_2$O(v) / min]
3 bar, sat'd → $\dot{Q}$(kW) → $\dot{m}_w$ [kg H$_2$O(l) / min]
27°C

$\dot{m}_e$ [kg C$_2$H$_6$ / min]
16°C, 2.5 bar →   ↓   → $\dot{m}_e$ [kg C$_2$H$_6$ / min]
93°C, 2.5 bar
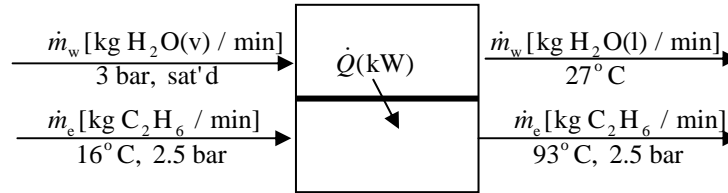
(a) $\underline{C_2H_6 \text{ mass flow:}}$ $\dot{m}_e = \dfrac{795 \text{ m}^3}{\text{min}} \left| \dfrac{10^3 \text{ L}}{\text{m}^3} \right| \dfrac{2.50 \text{ bar}}{289 \text{ K}} \left| \dfrac{1}{0.08314 \text{ L - bar}} \right| \dfrac{\text{K - mol}}{} \left| \dfrac{30.01 \text{ g}}{\text{mol}} \right| \dfrac{1 \text{ kg}}{1000 \text{ g}}$

$= 2.487 \times 10^3 \text{ kg/min}$

$\hat{H}_{ei} = 941 \text{ kJ/kg}, \hat{H}_{ef} = 1073 \text{ kJ/kg}$

$\underline{\text{Energy Balance on } C_2H_6}: \Delta \dot{E}_p, \dot{W}_s = 0, \Delta \dot{E}_k \cong 0 \Rightarrow \dot{Q} = \Delta \dot{H}$

$\dot{Q} = 2.487 \times 10^3 \dfrac{\text{kg}}{\text{min}} \left[(1073 - 941) \dfrac{\text{kJ}}{\text{kg}} \right] = \dfrac{2.487 \times 10^3 \text{ kJ}}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} \right| = \underline{\underline{5.47 \times 10^3 \text{ kW}}}$

(b) $\hat{H}_{s_1} (3.00 \text{ bar, sat'd vapor}) = 2724.7 \text{ kJ/kg}$ (Table B.6)

$\hat{H}_{s_2} (\text{liquid, } 27°C) = 113.1 \text{ kJ/kg}$ (Table B.5)

Assume that heat losses to the surroundings are negligible, so that the heat given up by the condensing steam equals the heat transferred to the ethane $\left(5.47 \times 10^3 \text{ kW} \right)$

$\underline{\text{Energy balance on } H_2O}: \dot{Q} = \Delta \dot{H} = \dot{m} \left(\hat{H}_{s_2} - \hat{H}_{s_1} \right)$

$\Rightarrow \dot{m} = \dfrac{\dot{Q}}{\hat{H}_{s_2} - \hat{H}_{s_1}} = \dfrac{-5.47 \times 10^3 \text{ kJ}}{\text{s}} \left| \dfrac{\text{kg}}{(113.1 - 2724.7)\text{kJ}} \right| = 2.09 \text{ kg/s steam}$

$\Rightarrow \dot{V}_s = (2.09 \text{ kg / s}) \underset{\underset{\text{Table B.6}}{\uparrow}}{(0.606 \text{ m}^3/\text{kg})} = \underline{\underline{1.27 \text{ m}^3/\text{s}}}$

Too low. Extra flow would make up for the heat losses to surroundings.

(c) $\underline{\text{Countercurrent flow}}$ Cocurrent (as depicted on the flowchart) would not work, since it would require heat flow from the ethane to the steam over some portion of the exchanger. (Observe the two outlet temperatures)

7.29

$$\underset{\substack{\text{250 kg } H_2O(v)/\text{min} \\ \text{40 bar, 500°C} \\ H_1 \text{ (kJ/kg)}}}{\longrightarrow} \boxed{\text{Turbine}} \underset{\substack{\text{250 kg/min} \\ \text{5 bar, } T_2(\text{°C}), H_2(\text{kJ/kg})}}{\longrightarrow} \boxed{\substack{\text{Heat} \\ \text{exchanger}}} \underset{\substack{\text{250 kg/min} \\ \text{5 bar, 500°C} \\ H_3 \text{ (kJ/kg)}}}{\longrightarrow}$$

$\downarrow \dot{W}_s = 1500 \text{ kW}$ $\uparrow \dot{Q}(\text{kW})$
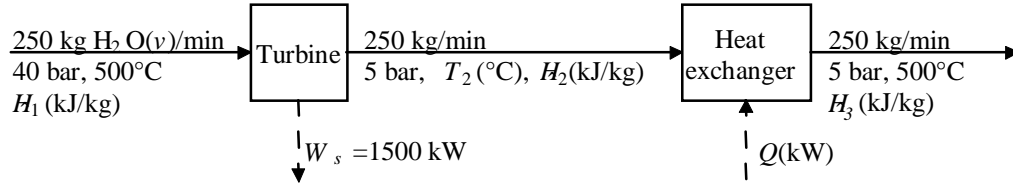
$H_2O(v, \text{ 40 bar, } 500°C): \hat{H}_1 = 3445 \text{ kJ/kg}$ (Table B.7)

$H_2O(v, \text{ 5 bar, } 500°C): \hat{H}_3 = 3484 \text{ kJ/kg}$ (Table B.7)

(a) Energy balance on turbine: $\Delta \dot{E}_p = 0, \ \dot{Q} = 0, \ \Delta \dot{E}_k \cong 0$

$$\Delta \dot{H} = -\dot{W}_s \Rightarrow \dot{m}\left(\hat{H}_2 - \hat{H}_1\right) = -\dot{W}_s \Rightarrow \hat{H}_2 = \hat{H}_1 - \dot{W}_s / \dot{m}$$

$$= \frac{3445 \text{ kJ}}{\text{kg}} - \frac{1500 \text{ kJ}}{\text{s}} \left| \frac{\text{min}}{250 \text{ kg}} \right| \frac{60 \text{ s}}{1 \text{ min}} = 3085 \text{ kJ/kg}$$

$\hat{H} = 3085 \text{ kJ/kg}$ and $P = 5$ bars $\Rightarrow \underline{T = 310°C}$ (Table B.7)

(b) Energy balance on heat exchanger: $\Delta \dot{E}_p = 0, \ \dot{W}_s = 0, \ \Delta \dot{E}_k \cong 0$

$$\dot{Q} = \Delta \dot{H} = \dot{m}\left(\hat{H}_3 - \hat{H}_2\right) = \frac{250 \text{ kg}}{\text{min}} \left| \frac{(3484 - 3085)\text{kJ}}{\text{kg}} \right| \frac{1 \text{ min}}{60 \text{ s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ} / \text{s}} \right. = \underline{\underline{1663 \text{ kW}}}$$

(c) Overall energy balance: $\Delta \dot{E}_p = 0, \Delta \dot{E}_k \cong 0$

$$\Delta \dot{H} = \dot{Q} - \dot{W}_s \Rightarrow \dot{m}_s \left(\hat{H}_3 - \hat{H}_1\right) = \dot{Q} - \dot{W}_s$$

$$\dot{Q} = \Delta \dot{H} + \Delta \dot{W}_s = \frac{250 \text{ kg}}{\text{min}} \left| \frac{(3484 - 3445)\text{kJ}}{\text{kg}} \right| \frac{1 \text{ min}}{60 \text{ s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ} / \text{s}} \right. + \frac{1500 \text{ kJ}}{\text{s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ} / \text{s}} \right.$$

$$= \underline{\underline{1663 \text{ kW}}} \ \sqrt{}$$

(d) $H_2O(v, \text{ 40 bar, } 500°C): \hat{V}_1 = 0.0864 \text{ m}^3/\text{kg}$ (Table B.7)

$H_2O(v, \text{ 5 bar, } 310°C): \hat{V}_2 = 0.5318 \text{ m}^3/\text{kg}$ (Table B.7)

$$u_1 = \frac{250 \text{ kg}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{0.0864 \text{ m}^3}{\text{kg}} \left| \frac{1}{0.5^2 \ \pi/4 \text{ m}^2} \right. = 1.83 \text{ m/s}$$

$$u_2 = \frac{250 \text{ kg}}{\text{min}} \left| \frac{\text{min}}{60 \text{ s}} \right| \frac{0.5318 \text{ m}^3}{\text{kg}} \left| \frac{1}{0.5^2 \ \pi/4 \text{ m}^2} \right. = 11.3 \text{ m/s}$$

$$\Delta \dot{E}_k = \frac{\dot{m}}{2}\left[u_2^2 - u_1^2\right] = \frac{250 \text{ kg}}{\text{min}} \left| \frac{1}{2} \right| \frac{1 \text{ min}}{60 \text{ s}} \left| \frac{\left[(11.3)^2 - (1.83)^2\right]\text{m}^2}{\text{s}^2} \right| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m} / \text{s}^2} \left| \frac{1 \text{ kW} \cdot \text{s}}{10^3 \text{N} \cdot \text{m}} \right.$$

$$= 0.26 \text{ kW} << 1500 \text{ kW}$$

7.30 **(a)** $\Delta \dot{E}_p$, $\Delta \dot{E}_k$, $\dot{W}_s = 0 \Rightarrow \dot{Q} = \Delta \dot{H} \Rightarrow -hA(T_s - T_o) = -300$ kJ/h $\Rightarrow 1.8h\ (T_s - T_o) = 300\dfrac{\text{kJ}}{\text{h}}$

(b) Clothed: $h = 8 \Rightarrow \underline{\underline{T_o = 13.4°\,C}}$
$\phantom{\text{(b) Clothed:} } T_s = 34.2$

Nude, immersed: $h = 64 \Rightarrow \underline{\underline{T_o = 31.6°\,C}}$ (Assuming T_s remains 34.2°C)
$\phantom{\text{Nude, immersed: } } T_s = 34.2$

(c) *The wind raises the effective heat transfer coefficient.* (Stagnant air acts as a thermal insulator —i.e., in the absence of wind, h is low.) For a given T_o , the skin temperature must drop to satisfy the energy balance equation: when T_s drops, you feel cold.

7.31 Basis: 1 kg of 30°C stream
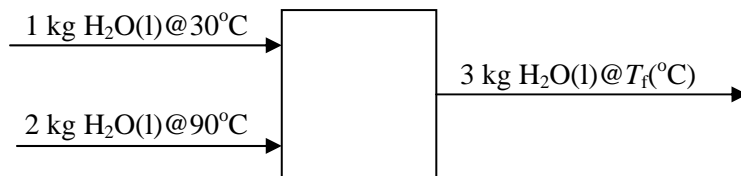
(a) $T_f = \dfrac{1}{3}(30°\,\text{C}) + \dfrac{2}{3}(90°\,\text{C}) = \underline{\underline{70°\,\text{C}}}$

(b) Internal Energy of feeds: $\left.\begin{array}{l} \hat{U}(30°\,\text{C, liq.}) = 125.7\ \text{kJ/kg} \\ \hat{U}(90°\,\text{C, liq.}) = 376.9\ \text{kJ/kg} \end{array}\right\}$

(Table B.5 - neglecting effect of P on $\hat{H}$)

Energy Balance: $Q - W = \Delta U + \Delta E_p + \Delta E_k \xrightarrow{Q = W = \Delta E_p = \Delta E_k = 0} \Delta U = 0$

$\Rightarrow 3\hat{U}_f - (1\ \text{kg})(125.7\ \text{kJ / kg}) - (2\ \text{kg})(376.9\ \text{kJ / kg}) = 0$

$\Rightarrow \underline{\underline{\hat{U}_f = 293.2\ \text{kJ/kg}}} \Rightarrow \underline{\underline{T_f = 70.05°\,\text{C}}}$ (Table B.5)

Diff. $= \dfrac{70.05 - 70.00}{70.05} \times 100\% = \underline{\underline{0.07\%}}$ (Any answer of this magnitude is acceptable).

7.32
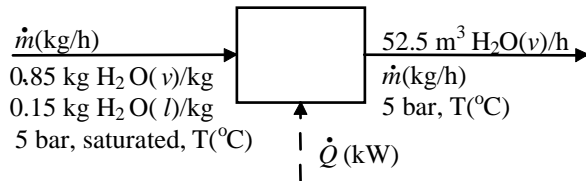
(a) Table B.6 $\xRightarrow{P = 5\ \text{bars}}$ $\underline{\underline{T = 151.8°\,\text{C}}}$, $\hat{H}_\text{L} = 640.1\ \text{kJ/kg}$, $\hat{H}_\text{V} = 2747.5\ \text{kJ/kg}$

$\hat{V}(5\ \text{bar, sat'd}) = 0.375\ \text{m}^3 / \text{kg} \Rightarrow \dot{m} = \dfrac{52.5\ \text{m}^3}{\text{h}} \left| \dfrac{1\ \ \text{kg}}{0.375\ \text{m}^3} \right. = \underline{\underline{140\ \text{kg/h}}}$

(b) H$_2$O evaporated $= (0.15)(140\ \text{kg/h}) = 21\ \text{kg/h}$

Energy balance: $\dot{Q} = \Delta \dot{H} = \dfrac{21\ \text{kg}}{\text{h}} \left| \dfrac{(2747.5 - 640.1)\text{kJ}}{\text{kg}} \right| \dfrac{1\ \text{h}}{3600\ \text{s}} \left| \dfrac{1\ \text{kW}}{1\ \text{kJ/s}} \right. = \underline{\underline{12\ \text{kW}}}$

7.33 **(a)** $P = 5$ bar $\xrightarrow{\text{Table B.6}}$ $T_{\text{saturation}} = 151.8^o\,C$. At 75°C the discharge is all liquid

(b) Inlet: T=350°C, P=40 bar $\xrightarrow{\text{Table B.7}}$ $\hat{H}_{\text{in}} = 3095$ kJ / kg, $\hat{V}_{\text{in}} = 0.0665$ m^3 / kg

Outlet: T=75°C, P=5 bar $\xrightarrow{\text{Table B.7}}$ $\hat{H}_{\text{out}} = 314.3$ kJ / kg, $\hat{V}_{\text{out}} = 1.03 \times 10^{-3}$ m^3 / kg

$$u_{\text{in}} = \frac{\dot{V}_{\text{in}}}{A_{\text{in}}} = \frac{200\text{ kg}}{\text{min}} \left| \frac{1\text{ min}}{60\text{ s}} \right| \frac{0.0665\text{ m}^3\text{ / kg}}{\left[\pi(0.075)^2 / 4 \right]\text{m}^2} = 50.18\text{ m / s}$$
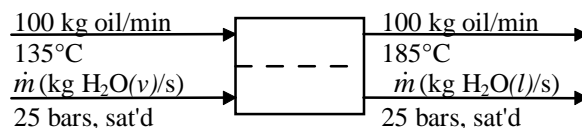
$$u_{\text{out}} = \frac{\dot{V}_{\text{out}}}{A_{\text{out}}} = \frac{200\text{ kg}}{\text{min}} \left| \frac{1\text{ min}}{60\text{ s}} \right| \frac{0.00103\text{ m}^3\text{ / kg}}{\left[\pi(0.05)^2 / 4 \right]\text{m}^2} = 1.75\text{ m / s}$$

Energy balance: $\dot{Q} - \dot{W}_s \approx \Delta\dot{H} + \Delta\dot{E}_k = \dot{m}(\hat{H}_2 - \hat{H}_1) + \dfrac{\dot{m}}{2}(u_2^2 - u_1^2)$

$$\dot{Q} - \dot{W}_s = \frac{200\text{ kg}}{\text{min}} \left| \frac{1\text{ min}}{60\text{ s}} \right| \frac{(314\text{-}3095)\text{ kJ}}{\text{kg}} + \frac{200\text{ kg}}{2\text{ min}} \left| \frac{1\text{ min}}{60\text{ s}} \right| \frac{(1.75^2\text{-}50.18^2)\text{ m}^2}{\text{s}^2}$$

$$= -13,460\text{ kW} \; (\Rightarrow \; 13,460\text{ kW transferred from the turbine})$$

7.34 **(a)** Assume all heat from stream transferred to oil

$$\dot{Q} = \frac{1.00 \times 10^4\text{ kJ}}{\text{min}} \left| \frac{1\text{ min}}{60\text{ s}} \right. = 167\text{ kJ/s}$$

100 kg oil/min   100 kg oil/min
135°C   185°C
$\dot{m}$ (kg H$_2$O(v)/s) $\dot{m}$ (kg H$_2$O(l)/s)
25 bars, sat'd   25 bars, sat'd

Energy balance on H$_2$O: $\dot{Q} = \Delta\dot{H} = \dot{m}\left(\hat{H}_{\text{out}} - \hat{H}_{\text{in}} \right)$

$\Delta\dot{E}_p$, $\Delta\dot{E}_k$, $\dot{W}_s = 0$

$\hat{H}(l,\ 25\text{ bar, sat'd}) = 962.0$ kJ/kg, $\hat{H}(v,\ 25\text{ bar, sat'd}) = 2800.9$ kJ/kg (Table B.6)

$$\dot{m} = \frac{\dot{Q}}{\hat{H}_{\text{out}} - \hat{H}_{\text{in}}} = \frac{-167\text{ kJ}}{\text{s}} \left| \frac{\text{kg}}{(962.0 - 2800.9)\text{kJ}} \right. = 0.091\text{ kg/s}$$

Time between discharges: $\dfrac{1200\text{ g}}{\text{discharge}} \left| \dfrac{1\text{ s}}{0.091\text{ kg}} \right| \dfrac{1\text{ kg}}{10^3\text{ g}} = 13$ s/discharge

(b) Unit Cost of Steam: $\dfrac{\$1}{10^6\text{ Btu}} \left| \dfrac{(2800.9 - 83.9)\text{ kJ}}{\text{kg}} \right| \dfrac{0.9486\text{ Btu}}{\text{kJ}} = \$2.6 \times 10^{-3}$ / kg

Yearly cost:

$\dfrac{1000\text{ traps}}{} \left| \dfrac{0.091\text{ kg stream}}{\text{trap}\cdot\text{s}} \right| \dfrac{0.10\text{ kg last}}{\text{kg stream}} \left| \dfrac{2.6\times10^{-3}\$}{\text{kg lost}} \right| \dfrac{3600\text{ s}}{\text{h}} \left| \dfrac{24\text{ h}}{\text{day}} \right| \dfrac{360\text{ day}}{\text{year}}$

$= \$7.4 \times 10^5$ / year

7.35 Basis: Given feed rate
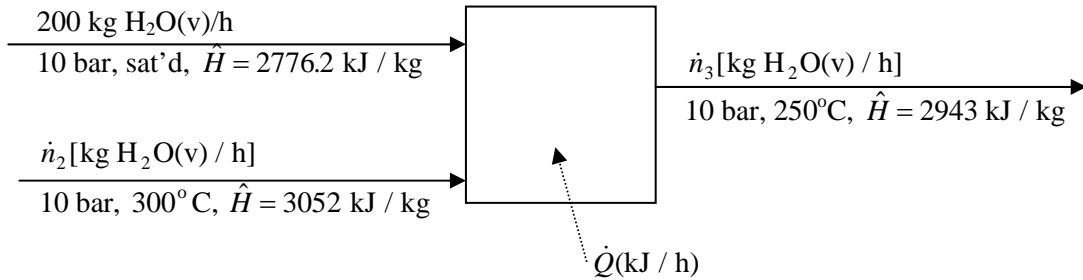
$\hat{H}$ from Table B.6 (saturated steam) or Table B.7 (superheated steam)

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

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

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

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

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

    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)

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

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

    $\overset{(1,2)}{\Longrightarrow}$ $m_l = 70.4$ kg, $m_v = 29.6$ kg $\Rightarrow y_v = \dfrac{29.6\ \text{kg vapor}}{100\ \text{kg}} = \underline{\underline{0.296\dfrac{\text{kg vapor}}{\text{kg}}}}$

(b) $\underline{\underline{T}}$ 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, $\Delta\dot{E}_k > 0$.
    $\underline{y_v\ \text{would be less (less water evaporates)}}$ 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.

7.36 (cont'd)
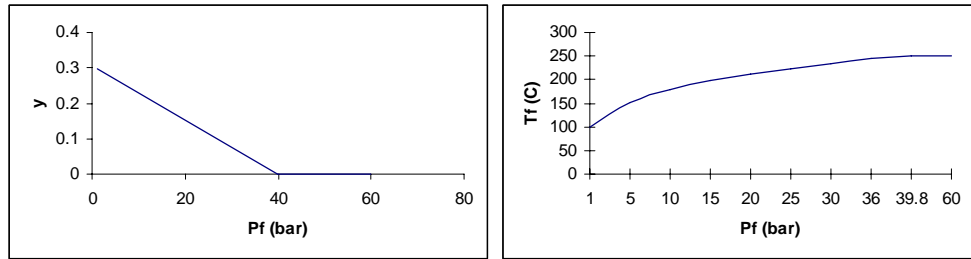
7.37 | 10 m^3, n moles of steam(v), 275°C, 15 bar $\Rightarrow 10 \text{ m}^3$, n moles of water (v+l), 1.2 bar |

```
10.0 m³ H₂O (v)          ┌──────┐    10.0 m³
────────────────────────►│      │───────────────────►
m_in (kg)                │      │    m_v [kg H₂O (v)]
275°C  , 15 bar          │      │    m_l [kg H₂O (l)]
                         └──▲───┘
                            │ Q    1.2 bar, saturated
                            │
```

(a) P=1.2 bar, saturated, $\xrightarrow{\text{Table B.6}}$ $T_2 = \underline{\underline{104.8°C}}$

(b) Total mass of water: $m_{in} = \dfrac{10 \text{ m}^3}{} \left| \dfrac{1 \text{ kg}}{0.1818 \text{ m}^3} = 55 \text{ kg}\right.$

Mass Balance: $m_v + m_l = 55.0$

Volume additivity: $V_v + V_l = 10.0 \text{ m}^3 = m_v (1.428 \text{ m}^3 / \text{kg}) + m_l (0.001048 \text{ m}^3 / \text{kg})$
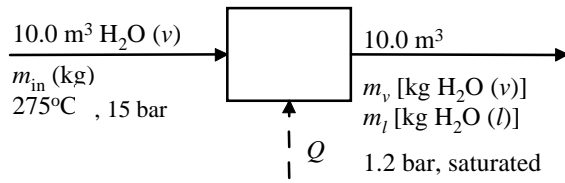
$\Rightarrow m_v = 7.0 \text{ kg}, \; m_l = \underline{\underline{48.0 \text{ kg condensed}}}$

(c) Table B.7 $\Rightarrow \hat{U}_{in} = 2739.2 \text{ kJ / kg}; \; \hat{V}_{in} = 0.1818 \text{ m}^3 / \text{kg}$

Table B.6 $\Rightarrow \begin{cases} \hat{U}_l = 439.2 \text{ kJ / kg}; \quad \hat{V}_l = 0.001048 \text{ m}^3 / \text{kg} \\ \hat{U}_v = 2512.1 \text{ kJ / kg}; \qquad \hat{V}_v = 1.428 \text{ m}^3 / \text{kg} \end{cases}$

Energy balance: $Q = \Delta U = m_v \hat{U}_v + m_l \hat{U}_l - m_{in} \hat{U}_{in}$
$\underset{\Delta E_p, \Delta E_k \; , \; W=0}{}$

$= [(7.0)(2512.1 \text{ kJ / kg}) + (48.0)(439.2) - 55 \text{ kg} (2739.2)] \text{ kJ}$

$= \underline{\underline{-1.12 \times 10^5 \text{ kJ}}}$

7.38 (a) Assume both liquid and vapor are present in the valve effluent.

```
1 kg H₂O(v) / s          ┌──────┐
────────────────────────►│      │──────────────────────►
15 bar, T_sat +150°C     │      │    ṁ_l [kg H₂O(l) / s]
                         └──────┘    ṁ_v [kg H₂O(v) / s]
                                     1.0 bar,  saturated
```
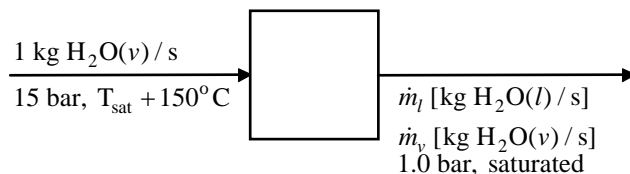
(b) Table B.6 $\Rightarrow T_{sat'n} (15 \text{ bar}) = 198.3°C \Rightarrow T_{in} = 348.3°C$

Table B.7 $\Rightarrow \hat{H}_{in} = \hat{H}(348.3°C, \; 15 \text{ bar}) \approx 3149 \text{ kJ / kg}$

Table B.6 $\Rightarrow \hat{H}_l (1.0 \text{ bar, sat'd}) = 417.5 \text{ kJ / kg}; \quad \hat{H}_v (1.0 \text{ bar, sat'd}) = 2675.4 \text{ kJ / kg}$

7.38 (cont'd)

Energy balance: $\Delta\dot{H} = 0 \Rightarrow \dot{m}_l\hat{H}_l + \dot{m}_v\hat{H}_v - \dot{m}_{in}\hat{H}_{in} = 0$

$\overline{\Delta\dot{E}_p,\Delta\dot{E}_k,\dot{Q},\dot{W}_s=0}$

$\Rightarrow \dot{m}_{in}\hat{H}_{in} = \dot{m}_l\hat{H}_l + \dot{m}_v\hat{H}_v \xrightarrow{\dot{m}_v + \dot{m}_l} \underline{\underline{3149 \text{ kJ / kg}}} = \dot{m}_l(417.5) + (1-\dot{m}_l)(2675.4)$

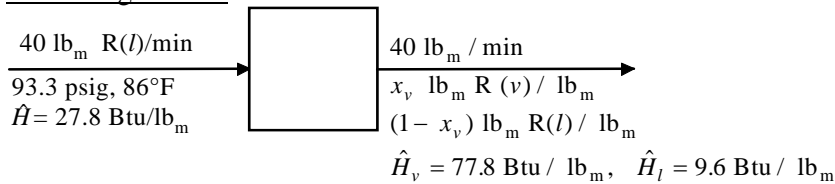There is no value of $\dot{m}_l$ between 0 and 1 that would satisfy this equation. (For any value in this range, the right-hand side would be between 417.5 and 2675.4). The two-phase assumption is therefore incorrect; the effluent must be pure vapor.

(c) Energy balance $\Rightarrow \dot{m}_{out}\hat{H}_{out} = \dot{m}_{in}\hat{H}_{in} \xrightarrow{\dot{m}_{in} = \dot{m}_{out} = 1} 3149 \text{ kJ / kg} = \hat{H}(1 \text{ bar, } T_{out})$

$\xrightarrow{\text{Table B.7}} T_{out} \approx \underline{\underline{337°C}}$

(This answer is only approximate, since $\Delta\dot{E}_k$ is not zero in this process).

7.39   Basis: 40 lb_m/min circulation

(a) Expansion valve
R = Refrigerant 12

40 lb_m R(l)/min

93.3 psig, 86°F
$\hat{H} = 27.8$ Btu/lb_m

40 lb_m / min

x_v lb_m R (v) / lb_m

$(1-x_v)$ lb_m R(l) / lb_m

$\hat{H}_v = 77.8$ Btu / lb_m, $\hat{H}_l = 9.6$ Btu / lb_m

Energy balance: $\Delta\dot{E}_p$, $\dot{W}_s$, $\dot{Q} = 0$, neglect $\Delta\dot{E}_k \Rightarrow \Delta\dot{H} = \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i = 0$

$\dfrac{40X_v \text{ lb}_m R(v)}{\text{min}} \Bigg| \dfrac{77.8 \text{ Btu}}{\text{lb}_m} + \dfrac{40(1-X_v)\text{lb}_m R(l)}{\text{min}} \Bigg| \dfrac{9.6 \text{ Btu}}{\text{lb}_m} - \dfrac{40 \text{ lb}_m}{\text{min}} \Bigg| \dfrac{27.8 \text{ Btu}}{\text{lb}_m} = 0$

$\Downarrow$

$X_v = \underline{\underline{0.267}}$ (26.7% evaporates)

(b) Evaporator coil

40 lb_m/min
0.267 R(v)
0.733 R(l)
11.8 psig, 5°F
$H_v = 77.8$ Btu/lb_m , $H_l = 9.6$ Btu/lb_m

40 lb_m R(v)/min
11.8 psig, 5°F
$H = 77.8$ Btu/lb_m
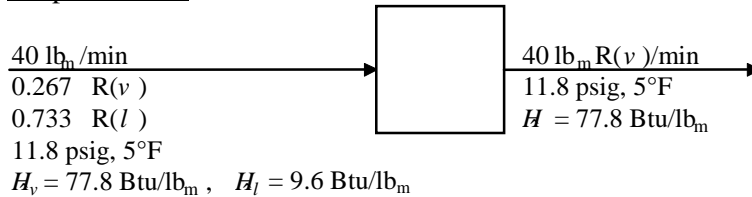
Energy balance: $\Delta\dot{E}_p$, $\dot{W}_s = 0$, neglect $\Delta\dot{E}_k \Rightarrow \dot{Q} = \Delta\dot{H}$

$\dot{Q} = \dfrac{40 \text{ lb}_m}{\text{min}} \Bigg| \dfrac{77.8 \text{ Btu}}{\text{lb}_m} - \dfrac{(40)(0.267)\text{lb}_m R(v)}{\text{min}} \Bigg| \dfrac{77.8 \text{ Btu}}{\text{lb}_m} - \dfrac{(40)(0.733)\text{lb}_m R(l)}{\text{min}} \Bigg| \dfrac{9.6 \text{ Btu}}{\text{lb}_m}$

$= \underline{\underline{2000 \text{ Btu/min}}}$

7.39 (cont'd)

(c) We may analyze the overall process in several ways, each of which leads to the same result. Let us first note that the net rate of heat input to the system is

$$\dot{Q} = \dot{Q}_{evaporator} - \dot{Q}_{condenser} = 2000 - 2500 = -500 \ \text{Btu/min}$$

and the compressor work W_c represents the total work done on the system. The system is closed (no mass flow in or out). Consider a time interval $\Delta t \ (\text{min})$. Since the system is at steady state, the changes ΔU, ΔE_k and ΔE_p over this time interval all equal zero. The total heat input is $\dot{Q}\Delta t$, the work input is $\dot{W}_c \Delta t$, and (Eq. 8.3-4) yields

$$\dot{Q}\Delta t - \dot{W}_c \Delta t = 0 \Rightarrow \dot{W}_c = \dot{Q} = \frac{-500 \ \text{Btu}}{\text{min}} \left| \frac{1 \ \text{min}}{60 \ \text{s}} \right| \frac{1.341 \times 10^{-3} \ \text{hp}}{9.486 \times 10^{-4} \ \text{Btu/s}} = \underline{\underline{11.8 \ \text{hp}}}$$

7.40 Basis: Given feed rates

Molar flow rates of feed streams:

$$\dot{n}_1 = \frac{300 \ \text{L}}{\text{hr}} \left| \frac{1.1 \ \text{atm}}{1 \ \text{atm}} \right| \frac{1 \ \text{mol}}{22.4 \ \text{L(STP)}} = 14.7 \ \text{mol/h}$$

$$\dot{n}_2 = \frac{200 \ \text{L}}{\text{hr}} \left| \frac{273 \ \text{K}}{298 \ \text{K}} \right| \frac{1.1 \ \text{atm}}{1 \ \text{atm}} \left| \frac{1 \ \text{mol}}{22.4 \ \text{L(STP)}} \right. = 9.00 \ \text{mol/h}$$

Propane balance $\Rightarrow \dot{n}_{C_3H_8} = \frac{14.7 \ \text{mol}}{\text{h}} \left| \frac{0.20 \ \text{mol C}_3\text{H}_8}{\text{mol}} \right. + \frac{9.00 \ \text{mol}}{\text{h}} \left| \frac{0.40 \ \text{mol C}_3\text{H}_8}{\text{mol}} \right.$

$$= 6.54 \ \text{mol C}_3\text{H}_8/\text{h}$$

Total mole balance: $\dot{n}_{C_4H_{10}} = (14.7 + 9.00 - 6.54) \ \text{mol C}_4\text{H}_{20}/\text{h} = 17.16 \ \text{mol C}_4\text{H}_{20}/\text{h}$
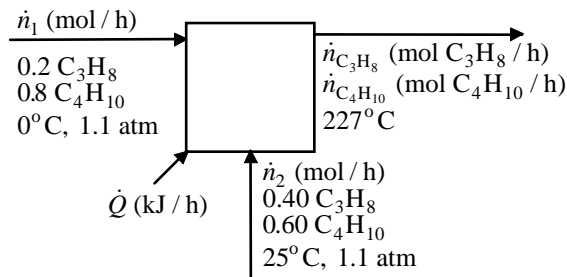
Energy balance: $\Delta \dot{E}_p$, $\dot{W}_s = 0$, neglect $\Delta \dot{E}_k \Rightarrow \dot{Q} = \Delta \dot{H}$

$$\dot{Q} = \Delta \dot{H} = \sum_{out} \dot{N}_i \hat{H}_i - \sum_{in} \dot{N}_i \hat{H}_i = \frac{6.54 \ \text{mol C}_3\text{H}_8}{\text{h}} \left| \frac{20.685 \ \text{kJ}}{\text{mol}} \right. + \frac{17.16 \ \text{mol C}_4\text{H}_{10}}{\text{h}} \left| \frac{27.442 \ \text{kJ}}{\text{mol}} \right.$$

$$-\frac{(0.40 \times 9.00) \ \text{mol C}_3\text{H}_8}{\text{h}} \left| \frac{1.772 \ \text{kJ}}{\text{mol}} \right. - \frac{(0.60 \times 9.00) \ \text{mol C}_4\text{H}_{10}}{\text{h}} \left| \frac{2.394 \ \text{kJ}}{\text{mol}} \right. = \underline{\underline{587 \ \text{kJ/h}}}$$

($\hat{H}_i = 0$ for components of 1st feed stream)

7.41 Basis: $\dfrac{510 \text{ m}^3}{\text{min}} \left| \dfrac{273 \text{ K}}{291 \text{ K}} \right| \dfrac{10^3 \text{L}}{\text{m}^3} \left| \dfrac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| \dfrac{1 \text{ kmol}}{10^3 \text{ mol}} = 21.4 \text{ kmol/min}$

(a)

$\dot{n}_0$ (kmol/min)
38°C, h_r = 97%
y_0 (mol H_2O/mol)
$(1 - y_0)$ mol dry air/mol)

$\dot{Q}$ (kJ/min)

21.4 kmol/min
18°C, sat'd
y_1 (mol H_2O/mol)
$(1 - y_1)$(mol dry air)

$\dot{n}_2$ (kmol $H_2O(l)$)/mol)
18°C
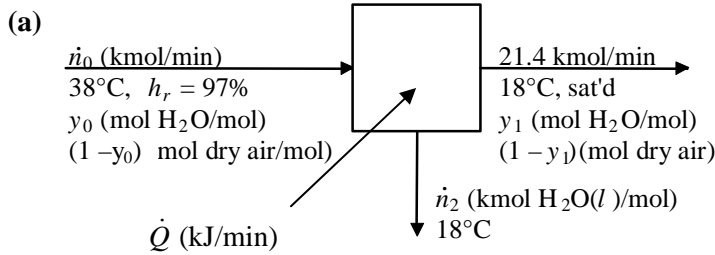
Inlet condition: $y_o = \dfrac{h_r P^*_{H_2O}(38°C)}{P} = \dfrac{0.97(49.692 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.0634 \text{ mol } H_2O/\text{mol}$

Outlet condition: $y_1 = \dfrac{P^*_{H_2O}(18°C)}{P} = \dfrac{15.477 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0204 \text{ mol } H_2O/\text{mol}$

Dry air balance: $(1 - 0.0634)\dot{n}_o = (1 - 0.0204)21.4 \Rightarrow \dot{n}_o = 22.4 \text{ kmol/min}$

Water balance: $(0.0634)22.4 = \dot{n}_2 + (0.0204)21.4 \Rightarrow \dot{n}_2 = 0.98 \text{ kmol/min}$

$\dfrac{0.98 \text{ kmol}}{\text{min}} \left| \dfrac{18.02 \text{ kg}}{\text{kmol}} = 18 \text{ kg / min } H_2O \text{ condenses}$

(b). Enthaphies: $\hat{H}_{air}(38°C) = 0.0291(38 - 25) = 0.3783 \text{ kJ/mol}$

$\hat{H}_{air}(18°C) = 0.0291(18 - 25) = -0.204 \text{ kJ/mol}$

$\hat{H}_{H_2O}(v,\ 38°C) = \dfrac{2570.8 \text{ kJ}}{\text{kg}} \left| \dfrac{1 \text{ kg}}{10^3 \text{ g}} \right| \dfrac{18.02 \text{ g}}{\text{mol}} = 46.33 \text{ kJ/mol}$

$\hat{H}_{H_2O}(v,\ 18°C) = \dfrac{2534.5 \text{ kJ}}{\text{kg}} \left| \dfrac{1 \text{ kg}}{10^3 \text{ g}} \right| \dfrac{18.02 \text{ g}}{\text{mol}} = 45.67 \text{ kJ/mol}$ Table B.5

$\hat{H}_{H_2O}(l,\ 18°C) = \dfrac{75.5 \text{ kJ}}{\text{kg}} \left| \dfrac{1 \text{ kg}}{10^3 \text{ g}} \right| \dfrac{18.02 \text{ g}}{\text{mol}} = 1.36 \text{ kJ/mol}$

Energy balance:

$\Delta\dot{E}_p,\ \dot{W}_s = 0,\ \Delta\dot{E}_k = 0$

$\dot{Q} = \Delta\dot{H} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i \Rightarrow \dot{Q} = (1 - 0.0204)(21.4 \times 10^3)(-0.204)$

$+ (0.0204)(21.4 \times 10^3)(45.67) + (0.98 \times 10^3)(1.36) - (1 - 0.0634)(22.4 \times 10^3)(0.3783)$

$- (0.0634)(22.4 \times 10^3)(46.33) = -5.67 \times 10^4 \text{ kJ/min}$

$\Rightarrow \dfrac{5.67 \times 10^4 \text{ kJ}}{\text{min}} \left| \dfrac{60 \text{ min}}{\text{h}} \right| \dfrac{0.9486 \text{ Btu}}{\text{kJ}} \left| \dfrac{1 \text{ ton cooling}}{12000 \text{ Btu}} = 270 \text{ tons of cooling}$

7.42 Basis: 100 mol feed

n_2 (mol), 63.0°C

A - Acetone
B - Acetic Acid

0.98 A(v)
0.02 B(v)

Q_c (cal)

100 mol, 67.5°C
0.65 A(l)
0.35 B(l)

0.5n_2 (mol)
0.98 A(l)
0.02 B(l)

56.8°C

0.5n_2 (mol)
0.98 A(l)
0.02 B(l)

n_5 (mol), 98.7°C
0.544 A(v)
0.456 B(v)

n_5 (mol), 98.7°C
0.155 A(l)
0.845 B(l)

Q_r (cal)
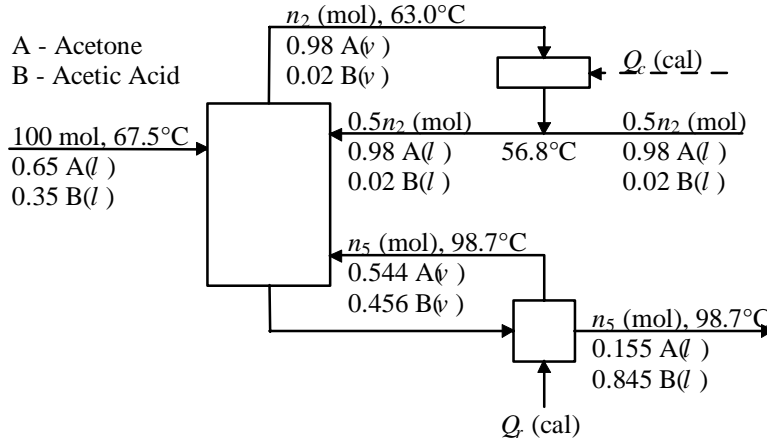
(a) Overall balances:

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

Product flow rates: Overhead $0.5(120)0.98 = 58.8$ mol A
$0.5(120)0.02 = 1.2$ mol B

Bottoms $0.155(40) = 6.2$ mol A
$0.845(40) = 33.8$ mol B

Overall energy balance: $Q = \Delta H = \sum\limits_{out} n_i \hat{H}_i - \sum\limits_{in} n_i \hat{H}_i$
$\scriptstyle \Delta E_p,\, W_s=0,\, \Delta E_k=0$

interpolate in table   interpolate in table
↓   ↓

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

(b) Flow through condenser: $2(58.8) = 117.6$ mols A

$2(1.2) = 2.4$ mols B

Energy balance on condenser: $Q_c = \Delta H$
$\scriptstyle \Delta E_p,\, W_s=0,\, \Delta E_k=0$

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

1.96 kg, P_1= 10.0 bar, T_1

2.96 kg, P_3= 7.0 bar, T_3=250°C

1.00 kg, P_2= 7.0 bar, T_2

$Q= 0$
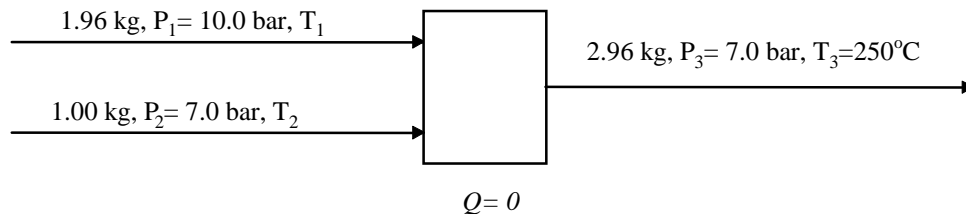
7.43 (cont'd)

(a) $T_2 = T(P = 7.0 \text{ bar, sat'd steam}) = \underline{165.0 \ ^\circ\text{C}}$

$\hat{H}_3 (\text{H}_2\text{O}(v), \ P = 7.0 \text{ bar}, \ T = 250 \ ^\circ\text{C}) = 2954 \text{ kJ/kg} \quad (\text{Table B.7})$
$\hat{H}_2 (\text{H}_2\text{O}(v), \ P = 7.0 \text{ bar}, \ \text{sat'd}) = 2760 \text{ kJ/kg} \quad (\text{Table B.6})$

Energy balance
$\overline{\Delta E_p, \ Q, \ W_s, \ \Delta E_k \equiv 0}$

$\Delta H = 0 = 2.96\hat{H}_3 - 1.96\hat{H}_1 - 1.0\hat{H}_2 \Rightarrow 1.96\hat{H}_1 = 2.96 \text{ kg}(2954 \text{ kJ/kg}) - 1.0 \text{ kg}(2760 \text{ kJ/kg})$

$\Rightarrow \hat{H}_1(10.0 \text{ bar}, \ T_1) = 3053 \text{ kJ/kg} \Rightarrow \underline{\underline{T_1 \cong 300^\circ\text{C}}}$

(b) The estimate is <u>too low</u>. If heat is being lost the entering steam temperature would have to be higher for the exiting steam to be at the given temperature.

7.44 (a) $T_1 = T(P = 3.0 \text{ bar}, \ \text{sat'd.}) = \underline{133.5^\circ\text{C}}$

Vapor
P=3 bar
Liquid
m=165.0 kg

V=200.0 L
P_{max}=20 bar

$\hat{V}_l (P = 3.0 \text{ bar}, \ \text{sat'd.}) = 0.001074 \text{ m}^3/\text{kg}$

$\hat{V}_v (P = 3.0 \text{ bar}, \ \text{sat'd.}) = 0.606 \text{ m}^3/\text{kg}$

$V_l = \dfrac{0.001074 \text{ m}^3}{\text{kg}} \left|\dfrac{1000 \text{ L}}{\text{m}^3}\right| 165 \text{ kg} = \underline{\underline{177.2 \text{ L}}}$

$V_{space} = 200.0 \text{ L} - 177.2 \text{ L} = \underline{22.8 \text{ L}}$

$m_v = \dfrac{22.8 \text{ L}}{} \left|\dfrac{1 \text{ m}^3}{1000 \text{ L}}\right| \dfrac{1 \text{ kg}}{0.606 \text{ m}^3} = \underline{\underline{0.0376 \text{ kg}}}$

(b) $P = P_{max} = 20.0 \text{ bar}; \qquad m_{total} = 165.0 + 0.0376 = 165.04 \text{ kg}$

$T_1 = T(P = 20.0 \text{ bar}, \ \text{sat'd.}) = \underline{212.4^\circ\text{C}}$

$\hat{V}_l (P = 20.0 \text{ bar}, \ \text{sat'd.}) = 0.001177 \text{ m}^3/\text{kg}; \ \hat{V}_v (P = 20.0 \text{ bar}, \ \text{sat'd.}) = 0.0995 \text{ m}^3/\text{kg}$

$V_{total} = m_l\hat{V}_l + m_v\hat{V}_v \Rightarrow m_l\hat{V}_l + (m_{total} - m_l)\hat{V}_v$

$\Rightarrow \dfrac{200.0 \text{ L}}{} \left|\dfrac{1 \text{ m}^3}{1000 \text{ L}}\right| = m_l \text{ kg}(0.001177 \text{ m}^3/\text{kg}) + (165.04 - m_l)\text{kg}(0.0995 \text{ m}^3/\text{kg})$

$\Rightarrow m_l = 164.98 \text{ kg}; \ m_v = 0.06 \text{ kg}$

$V_l = \dfrac{0.001177 \text{ m}^3}{\text{kg}} \left|\dfrac{1000 \text{ L}}{\text{m}^3}\right| 164.98 \text{ kg} = \underline{\underline{194.2 \text{ L}}}; \quad V_{space} = 200.0 \text{ L} - 194.2 \text{ L} = \underline{\underline{5.8 \text{ L}}}$

$m_{evaporated} = \dfrac{(0.06 - 0.04) \text{ kg}}{} \left|\dfrac{1000 \text{ g}}{\text{kg}}\right| = \underline{\underline{20 \text{ g}}}$

(c) Energy balance $\quad Q = \Delta U = U(P = 20.0 \text{ bar}, \ \text{sat'd}) - U(P = 3.0 \text{ bar}, \ \text{sat'd})$
$\overline{\Delta E_p, \ W_s, \ \Delta E_k \equiv 0}$

$\hat{U}_l (P = 20.0 \text{ bar}, \ \text{sat'd.}) = 906.2 \text{ kJ/kg}; \ \hat{U}_v (P = 20.0 \text{ bar}, \ \text{sat'd.}) = 2598.2 \text{ kJ/kg}$

$\hat{U}_l (P = 3.0 \text{ bar}, \ \text{sat'd.}) = 561.1 \text{ kJ/kg}; \ \hat{U}_v (P = 3.0 \text{ bar}, \ \text{sat'd.}) = 2543 \text{ kJ/kg}$

$Q = 0.06 \text{ kg}(2598.2 \text{ kJ/kg}) + 164.98 \text{ kg}(906.2 \text{ kJ/kg}) - 0.04 \text{ kg}(2543 \text{ kJ/kg})$

$\qquad - 165.0 \text{ kg}(561.1 \text{ kJ/kg}) = \underline{\underline{5.70 \times 10^4 \text{ kJ}}}$

Heat lost to the surroundings, energy needed to heat the walls of the tank

7.44 (cont'd)

(d) (i) The specific volume of liquid increases with the temperature, hence the same mass of liquid water will occupy more space; (ii) some liquid water vaporizes, and the lower density of vapor leads to a pressure increase; (iii) the head space is smaller as a result of the changes mentioned above.

(e) – Using an automatic control system that interrupts the heating at a set value of pressure
– A safety valve for pressure overload.
– Never leaving a tank under pressure unattended during operations that involve temperature and pressure changes.

7.45 Basis: 1 kg wet steam

(a)
```
1 kg H₂O  20 bars  ┌──────┐  1 kg H₂O,(v) 1 atm  ┌──────┐  1 kg H₂O
0.97 kg H₂O(v)     │      │                      │      │  T_amb, 1 atm
0.03 kg H₂O(l)     └──────┘  Ĥ₂ (kJ/kg)          └──────┘
Ĥ₁ (kJ/kg)           Q=0                            ↑ Q
```

Enthalpies: $\hat{H}(v,\ 20\ \text{bars, sat'd}) = 2797.2\ \text{kJ/kg}$ ⎫ (Table B.7)
$\hat{H}(l,\ 20\ \text{bars, sat'd}) = 908.6\ \text{kJ/kg}$ ⎭

Energy balance on condenser: $\Delta H = 0 \Rightarrow \hat{H}_2 = \hat{H}_1 = 0.97(2797.2) + 0.03(908.6)$
(underneath: $\Delta E_p, \Delta E_k, Q, W_s = 0$)

$\Rightarrow \hat{H}_2 = 2740\ \text{kJ / kg} \xRightarrow{\text{Table B.7}} \underline{\underline{T \approx 132\,°\text{C}}}$

(b) As the steam (which is transparent) moves away from the trap, it cools. When it reaches its saturation temperature at 1 atm, it begins to condense, so that $\underline{\underline{T = 100\,°\text{C}}}$. The white plume is a mist formed by liquid droplets.

7.46 Basis: $\dfrac{8\ \text{oz H}_2\text{O}(l)}{} \left|\ \dfrac{1\ \text{quart}}{32\ \text{oz}}\ \right|\ \dfrac{1\ \text{m}^3}{1057\ \text{quarts}}\ \left|\ \dfrac{1000\ \text{kg}}{\text{m}^3}\right. = 0.2365\ \text{kg H}_2\text{O}(l)$

(For simplicity, we assume the beverage is water)

```
0.2365 kg H₂O (l)  ┌──────┐  (m + 0.2365) (kg H₂O (l))
18°C               │      │
m (kg H₂O (s))     │      │  4°C
32°F (0°C)         └──────┘              Assume P = 1 atm
```
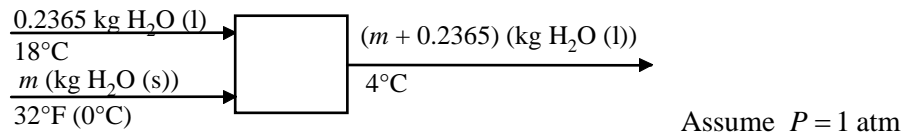
Enthalpies (from Table B.5):
$\hat{H}(\text{H}_2\text{O}(l),\ 18\,°\text{C}) = 75.5\ \text{kJ/kg};\quad \hat{H}(\text{H}_2\text{O}(l),\ 4\,°\text{C}) = 16.8\ \text{kJ/kg};\quad \hat{H}(\text{H}_2\text{O}(s),\ 0\,°\text{C}) = -348\ \text{kJ/kg}$

Energy balance (closed isobaric system): $\Rightarrow \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0$
(underneath: $\Delta E_p,\ \Delta E_k,\ Q,\ W = 0$)

$\Rightarrow (m + 0.2365)\text{kg}(16.8\ \text{kJ / kg}) = 0.2365\ \text{kg}(75.5\ \text{kJ / kg}) + m\ \text{kg}\ (-348\ \text{kJ / kg})$
$\Rightarrow m = 0.038\ \text{kg} = \underline{\underline{38\ \text{g ice}}}$

7.47 **(a)** When $T = 0°C$, $\hat{H} = 0$, $\Rightarrow \underline{\underline{T_{ref} = 0°C}}$

(b) <u>Energy Balance-Closed System:</u> $\Delta U = 0$

$$\Delta E_k, \Delta E_p, Q, W = 0$$

25 g Fe, 175°C

1000 g H₂O(l)

20°C

25 g Fe

1000 g H₂O

T_f (°C)
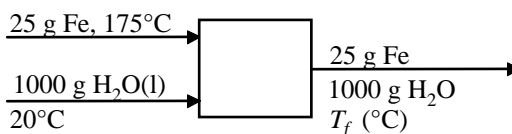
$$U_{Fe}(T_f) + U_{H_2O}(T_f) - U_{Fe}(175°C) - U_{H_2O}(20°\ C,\ 1\ atm) = 0 \ \text{ or } \ \Delta U_{Fe} + \Delta U_{H_2O} = 0$$

$$\Delta U_{Fe} = \frac{25.0\ g\ \left|\ 4.13(T_f - 175)cal\ \right|\ 4.184\ \ J}{|\ \ \ \ \ \ \ \ \ \ g\ \ \ \ \ \ \ \ \ |\ \ \ \ cal} = 432\left[T_f - 175\right]J$$

Table B.5 $\Rightarrow \Delta U_{H_2O} = \dfrac{1.0\ \ L\ \left|\ 10^3\ g\ \right|\ \left(\hat{U}_{H_2O}(T_f) - 83.9\right) J}{|\ \ 1\ \ L\ \ |\ \ \ \ \ \ \ \ \ \ g} = 1000\left(\hat{U}_{H_2O}(T_f) - 83.9\right)J$

$$\Rightarrow 432T_f + 1000\hat{U}_{H_2O}(T_f) - 1.60 \times 10^5 = f(T_f) = 0$$

$T_f\ °C$	30	40	35	34
$f(T_f)$	-2.1×10^4	$+2.5 \times 10^4$	1670	-2612

$\Rightarrow$ $\xrightarrow{\text{Interpolate}}$ $\underline{\underline{T_f = 34.6°C}}$

7-25

7.48
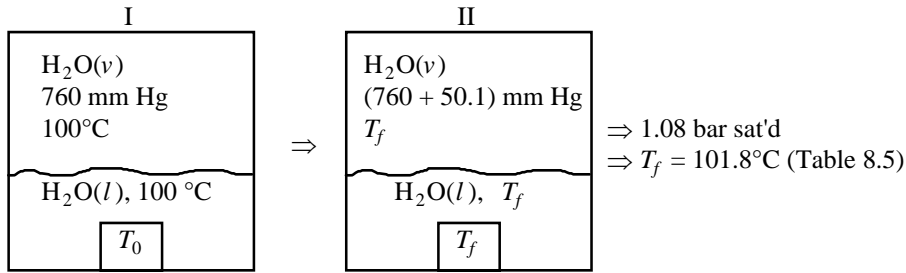
Energy balance - closed system:

$$\Delta E_p,\ \Delta E_K,\ W,\ Q = 0$$

$$\Delta U = 0 = m_v^{II}\hat{U}_v^{II} + m_l^{II}\hat{U}_l^{II} + m_b^{II}\hat{U}_b^{II} - m_v^{I}\hat{U}_v^{I} - m_l^{I}\hat{U}_l^{I} - m_b^{I}\hat{U}_b^{I}$$

v-vapor
l-liquid
b-block

	$I(1.01\ \text{bar},\ 100°\text{C})$	$II(1.08\ \text{bar},\ 101.8°\text{C})$
$\hat{V}_l\,(\text{L/kg})$	1.044	1.046
$\hat{V}_v\,(\text{L/kg})$	1673	1576
$\hat{U}_l\,(\text{L/kg})$	419.0	426.6
$\hat{U}_v\,(\text{L/kg})$	2506.5	2508.6

Initial vapor volume: $V_v^{I} = 20.0\ \text{L} - 5.0\ \text{L} - \dfrac{50\ \text{kg}}{8.92\ \text{kg}}\bigg|\dfrac{1\ \text{L}}{} = 14.4\ \text{L H}_2\text{O}(v)$

Initial vapor mass: $m_v^{I} = 14.4\ \text{L}/(1673\ \text{L/kg}) = 8.61 \times 10^{-3}\ \text{kg H}_2\text{O}(v)$

Initial liquid mass: $m_l^{I} = 5.0\ \text{L}/(1.044\ \text{L/kg}) = 4.79\ \text{kg H}_2\text{O}(l)$

Final energy of bar: $\hat{U}_b^{II} = 0.36(101.8) = 36.6\ \text{kJ/kg}$

Assume negligible change in volume & liquid $\Rightarrow V_v^{II} = 14.4\ \text{L}$

Final vapor mass: $m_v^{II} = 14.4\ \text{L}/(1576\ \text{L/kg}) = 9.14 \times 10^{-3}\ \text{kg H}_2\text{O}(v)$

Initial energy of the bar:

$$\hat{U}_b^{I} = \frac{1}{5.0\ \text{kg}}\left(9.14 \times 10^{-3}(2508.6) + 4.79(426.6) + 5.0(36.6) - 8.61 \times 10^{-3}(2506.5) - 4.79(419.0)\right)$$

$$= 44.1\ \text{kJ/kg}$$

(a) Oven Temperature: $T_o = \dfrac{44.1\ \text{kJ / kg}}{0.36\ \text{kJ / kg} \cdot°\ \text{C}} = \underline{\underline{122.5°\,\text{C}}}$

$\text{H}_2\text{O}_{\text{evaporated}} = m_v^{II} - m_v^{I} = 9.14 \times 10^{-3}\ \text{kg} - 8.61 \times 10^{-3}\ \text{kg} = 5.30 \times 10^{-4}\ \text{kg} = \underline{\underline{0.53\ \text{g}}}$

(b) $\hat{U}_b^{I} = 44.1 + 8.3/5.0 = 45.8\ \text{kJ/kg}$

$T_o = 45.8/0.36 = \underline{127.2°\,\text{C}}$

(c) Meshuggeneh forgot to turn the oven on ($T_o < 100°\text{C}$)

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

$$P = \frac{30.0 \text{ kg}}{400.0 \text{ cm}^2} \left| \frac{9.807 \text{ N}}{\text{kg}} \right| \frac{(100 \text{ cm})^2}{1^2 (\text{m})^2} \left| \frac{1.0 \text{ bar}}{10^5 \text{ N/m}^2} + \frac{1 \text{ atm}}{} \right| \frac{1.013 \text{ bar}}{\text{atm}} = \underline{\underline{1.08 \text{ bar}}}$$
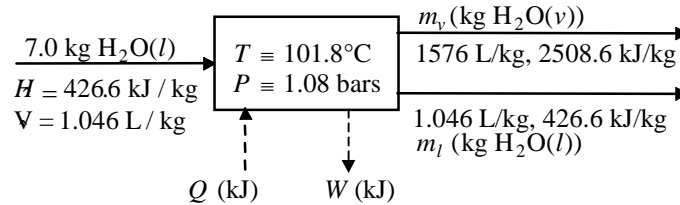
$\Rightarrow T_{sat} = 101.8°\text{C}$

<u>Heat required to bring the water and block to the boiling point</u>

$$Q = \Delta U = m_w \left(\hat{U}_{wl}(1.08 \text{ bar, sat'd}) - \hat{U}_{wl}(1, \; 20°\text{C}) \right) + m_{Al}\left(\hat{U}_{Al}(T_{sat}) - \hat{U}_{Al}(20°\text{C}) \right)$$

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

$2630 \text{ kJ} < 3310 \text{ kJ} \Rightarrow$ <u><u>Sufficient heat for vaporization</u></u>

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

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

<u>Water balance:</u> $7.0 = m_l + m_v$ **(1)**

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

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

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

<u>Energy balance:</u> $\Delta U = Q - W$

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

$\Rightarrow 2679 m_v + 426.7 m_L - 3667 = 0$ **(2)**

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

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

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

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

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

7.50

1.00 L $H_2O(v)$, $25^\circ C$
$m_{v1}(kg)$

$m_{v2}[kg\ H_2O(v)]$
$= m_{v1} + m_e$

4.00 L $H_2O(l)$, $25^\circ C$
$m_{L1}(kg)$

$m_{L2}[kg\ H_2O(l)]$
$= m_{L1} + m_e$

Assume not all the liquid
is vaporized. Eq. at
T_f, P_f. $m_e = kg\ H_2O$ vaporized.
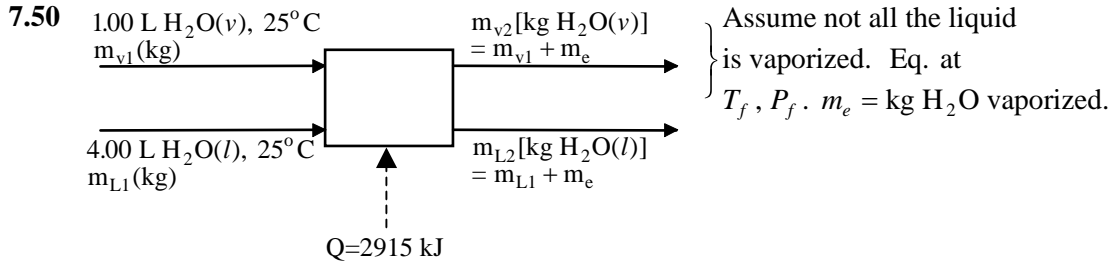
Q=2915 kJ

Initial conditions: Table B.5 $\Rightarrow \hat{U}_{L1} = 104.8$ kJ/kg, $\hat{V}_{L1} = 1.003$ L/kg $P = 0.0317$ bar

$\qquad T = 25^\circ C$, sat'd $\Rightarrow \hat{U}_{v1} = 2409.9$ kJ/kg, $\hat{V}_{L1} = 43,400$ L/kg

$m_{v1} = (1.00\ l)/(43400\ l/kg) = 2.304 \times 10^{-5}$ kg, $m_{LI} = (4.00\ l)/(1.003\ l/kg) = 3.988$ kg

Energy balance:

$$\Delta U = Q \Rightarrow (2.304 \times 10^{-5} + m_e)\hat{U}_v(T_f) + (3.988 - m_e)\hat{U}_L(T_f) - (2.304 \times 10^{-5})(2409.9)$$

$$-(3.988)(104.8) = 2915\ kJ$$

$$\Rightarrow (2.304 \times 10^{-5} + m_e)\hat{U}_v(T_f) + (3.988 - m_e)\hat{U}_v(T_f) = 3333$$

$$\Downarrow$$

$$\Rightarrow m_e = \frac{3333 - (2.304 \times 10^{-5})\hat{U}_v - 3.988\hat{U}_L}{\hat{U}_v - \hat{U}_L} \qquad (1)$$

$$V_L + V_v = V_{tank} \Rightarrow \left(2.304 \times 10^{-5} + \underset{\underset{kg}{\uparrow}}{m_e}\right)\underset{\underset{liters/kg}{\uparrow}}{\hat{V}_L}(T_f) + (3.988 - m_e)\hat{V}_L(T_f) = 5.00\ L$$

$$\Rightarrow m_e = \frac{5.00 - (2.304 \times 10^{-5})\hat{V}_v - 3.988\hat{V}_L}{\hat{V}_v - \hat{V}_L} \qquad (2)$$

$$(1) - (2) \Rightarrow f(T_f) = \frac{3333 - (2.304 \times 10^{-5})\hat{U}_v(T_f) - 3.988\hat{U}_L(T_f)}{\hat{U}_v - \hat{U}_L}$$

$$-\frac{5.00 - (2.304 \times 10^{-5})\hat{V}_v - 3.988\hat{V}_L}{\hat{V}_v - \hat{V}_L} = 0$$

Procedure: Assume $T_f \overset{Table\ 8.5}{\Rightarrow} \hat{U}_v$, $\hat{U}_L$, $\hat{V}_v$, $\hat{V}_L \Rightarrow f(T_f)$ Find T_f such that $f(T_f) = 0$

T_f	$\hat{U}_v$	$\hat{U}_L$	$\hat{V}_v$	$\hat{V}_L$	f
201.4	2593.8	856.7	123.7	1.159	-5.12×10^{-2}
198.3	2592.4	842.9	131.7	1.154	-1.93×10^{-2}
195.0	2590.8	828.5	140.7	1.149	1.34×10^{-2}
196.4	2591.5	834.6	136.9	1.151	-4.03×10^{-4} $\Rightarrow T_f \cong 196.4^\circ C$, $P_f = 14.4$ bars

$\overset{Eq(1)}{\underset{or\ Eq(2)}{\Longrightarrow}}$ $m_e = 2.6 \times 10^{-3}$ kg $\Rightarrow$ 2.6 g evaporated

7.51. Basis: 1 mol feed
B = benzene
T = toluene
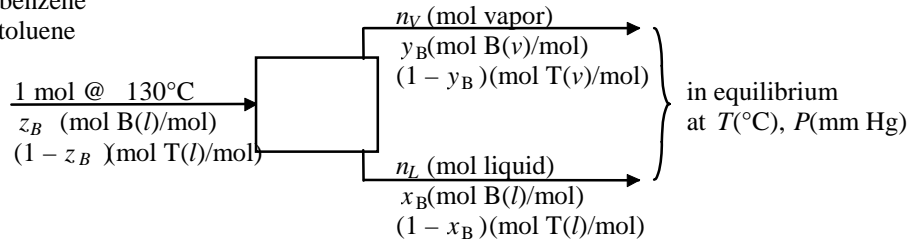
(a) 7 variables: $(n_V,\ y_B,\ n_L,\ x_B,\ Q,\ T,\ P)$
–2 equilibrium equations
–2 material balances
–1 energy balance
2 degrees of freedom. If T and P are fixed, we can calculate n_V, y_B, n_L, x_B, and Q.

(b) Mass balance: $n_V + n_L = 1 \Rightarrow n_V = 1 - n_2$ $\qquad$ **(1)**

Benzene balance: $z_B = n_V y_B + n_L x_B$ $\qquad$ **(2)**

$\underline{C_6H_6(l)}$: $\left(T=0,\ \hat{H}=0\right),\ \left(T=80,\ \hat{H}=10.85\right) \Rightarrow \hat{H}_{BL} = 0.1356T$ $\qquad$ **(3)**

$\underline{C_6H_6(v)}$: $\left(T=80,\ \hat{H}=41.61\right),\left(T=120,\ \hat{H}=45.79\right) \Rightarrow \hat{H}_{BV} = 0.1045T + 33.25$ $\qquad$ **(4)**

$\underline{C_7H_8(l)}$: $\left(T=0,\ \hat{H}=0\right),\ \left(T=111,\ \hat{H}=18.58\right) \Rightarrow \hat{H}_{TL} = 0.1674T$ $\qquad$ **(5)**

$\underline{C_7H_8(v)}$: $\left(T=89,\ \hat{H}=49.18\right),\ \left(T=111,\ \hat{H}=52.05\right) \Rightarrow \hat{H}_{TV} = 0.1304T + 37.57$ $\qquad$ **(6)**

Energy balance: ΔE_p, $W_s = 0$, neglect ΔE_k

$$Q = \Delta H = n_V y_B \hat{H}_{BV} + n_V(1-y_B)\hat{H}_{TV} + n_L x_B \hat{H}_{BL} + n_L(1-x_B)\hat{H}_{TL} - (1)z_B \hat{H}_{BL}(T_F)$$
$$- (1)(1-z_B)\hat{H}_{TL}(T_F) \qquad \textbf{(7)}$$

Raoult's Law: $\qquad y_B P = x_B p_B^*$ $\qquad$ **(8)**

$\qquad\qquad\qquad (1 - y_B)P = (1 - x_B)p_T^*$ $\qquad$ **(9)**

Antoine Equation. For T= 90°C and P=652 mmHg:

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

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

Adding equations (8) and (9) $\Rightarrow$

$$P = x_B p_B^* + (1-x_B)p_T^* \Rightarrow x_B = \frac{P - p_T^*}{p_B^* - p_T^*} = \frac{P - p_T^*}{p_B^* - p_T^*} = \frac{652 - 406.7}{1021 - 406.7} = \underline{\underline{0.399 \text{ mol B}(l)\ /\ \text{mol}}}$$

$$y_B = \frac{x_B p_B^*}{P} = \frac{0.399(1021 \text{ mmHg})}{652 \text{ mmHg}} = \underline{\underline{0.625 \text{ mol B}(v)\ /\ \text{mol}}}$$

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

$$n_L = 1 - n_V = 1 - 0.446 = \underline{\underline{0.554 \text{ mol liquid}}}$$

7.51 (cont'd)

Substituting (3), (4), (5), and (6) in (7) $\Rightarrow$

$$Q = 0.446(0.625)[0.1045(90) + 33.25] + 0.446(1 - 0.625)[0.1304(90) + 37.57]$$
$$+ 0.554(0.399)[0.1356(90)] + 0.554(1 - 0.399)[0.1674(90)] - 0.5[0.1356(130)]$$
$$- 0.5[0.1674(130)] \Rightarrow Q = \underline{8.14 \text{ kJ / mol}}$$

(c). If $P < P_{min}$, all the output is vapor. If $P > P_{max}$, all the output is liquid.

(d) At P=652 mmHg it is necessary to add heat to achieve the equilibrium and at P=714 mmHg, it is necessary to release heat to achieve the equilibrium. The higher the pressure, there is more liquid than vapor, and the liquid has a lower enthalpy than the equilibrium vapor: enthalpy out < enthalpy in.

z_B	T	P	p_B	p_T	x_B	y_B	n_V	n_L	Q
0.5	90	652	1021	406.7	0.399	0.625	0.446	0.554	8.14
0.5	90	714	1021	406.7	0.500	0.715	-0.001	1.001	-6.09
0.5	90	582	1021	406.7	0.285	0.500	0.998	0.002	26.20
0.5	90	590	1021	406.7	0.298	0.516	0.925	0.075	23.8
0.5	90	600	1021	406.7	0.315	0.535	0.840	0.160	21.0
0.5	90	610	1021	406.7	0.331	0.554	0.758	0.242	18.3
0.5	90	620	1021	406.7	0.347	0.572	0.680	0.320	15.8
0.5	90	630	1021	406.7	0.364	0.589	0.605	0.395	13.3
0.5	90	640	1021	406.7	0.380	0.606	0.532	0.468	10.9
0.5	90	650	1021	406.7	0.396	0.622	0.460	0.540	8.60
0.5	90	660	1021	406.7	0.412	0.638	0.389	0.611	6.31
0.5	90	670	1021	406.7	0.429	0.653	0.318	0.682	4.04
0.5	90	680	1021	406.7	0.445	0.668	0.247	0.753	1.78
0.5	90	690	1021	406.7	0.461	0.682	0.176	0.824	-0.50
0.5	90	700	1021	406.7	0.477	0.696	0.103	0.897	-2.80
0.5	90	710	1021	406.7	0.494	0.710	0.029	0.971	-5.14

(e). $P_{max} = 714$ mmHg, $P_{min} = 582$ mmHg

n_V vs. P
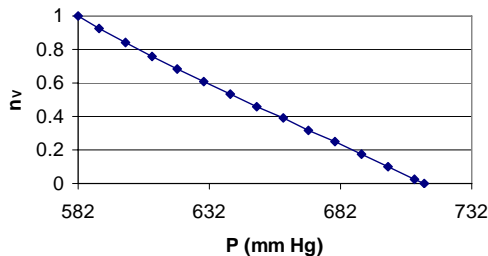
$\underline{\underline{n_V = 0.5 \ @ \ P \cong 640 \text{ mmHg}}}$

7.52 **(a).** Bernoulli equation: $\dfrac{\Delta P}{\rho} + \dfrac{\Delta u^2}{2} + g\Delta z = 0$

$$\dfrac{\Delta P}{\rho} = \dfrac{(0.977 \times 10^{-5} - 1.5 \times 10^5)\text{Pa}}{} \left| \dfrac{1\,\text{N}/\text{m}^2}{\text{Pa}} \right| \dfrac{\text{m}^3}{1.12 \times 10^3\ \text{kg}} = -46.7 \dfrac{\text{m}^2}{\text{s}^2}$$

$$g\Delta z = (9.8066\ \text{m}/\text{s}^2)(6)\text{m} = 58.8\ \text{m}^2/\text{s}^2$$

$$\underline{\text{Bernoulli}} \Rightarrow \dfrac{\Delta u^2}{2} = (46.7 - 58.8)\ \text{m}^2/\text{s}^2 \Rightarrow u_2^2 = u_1^2 + 2(-12.1\ \text{m}^2/\text{s}^2)$$

$$= (5.00)^2\ \text{m}^2/\text{s}^2 - (2)(12.1)\ \text{m}^2/\text{s}^2 = 0.800\ \text{m}^2/\text{s}^2 \Rightarrow u_2 = \underline{\underline{0.894\ \text{m}/\text{s}}}$$

(b). Since the fluid is incompressible, $\dot{V}(\text{m}^3/s) = \pi d_1^2\, u_1/4 = \pi d_2^2\, u_2/4$

$$\Rightarrow d_1 = d_2 \sqrt{\dfrac{u_2}{u_1}} = (6\ \text{cm}) \sqrt{\dfrac{0.894\ \text{m}/\text{s}}{5.00\ \text{m}/\text{s}}} = \underline{\underline{2.54\ \text{cm}}}$$

7.53 **(a).** $\dot{V}(\text{m}^3/s) = A_1(\text{m}^2)u_1(\text{m}/s) = A_2(\text{m}^2)u_2(\text{m}/s) \Rightarrow u_2 = u_1 \dfrac{A_1}{A_2} \overset{A_1 = 4A_2}{\Longrightarrow} \underline{\underline{u_2 = 4u_1}}$

(b). Bernoulli equation ($\Delta z = 0$)

$$\dfrac{\Delta P}{\rho} + \dfrac{\Delta u^2}{2} = 0 \Rightarrow \Delta P = P_2 - P_1 = -\dfrac{\rho(u_2^2 - u_1^2)}{2}$$

Multiply both sides by -1

Substitute $u_2^2 = 16u_1^2$

Multiply top and bottom of right-hand side by A_1^2

note $\dot{V}^2 = A_1^2 u_1^2$

$$P_1 - P_2 = \dfrac{15\rho \dot{V}^2}{2A_1^2}$$

(c) $P_1 - P_2 = (\rho_{\text{Hg}} - \rho_{\text{H}_2\text{O}})gh = \dfrac{15\rho_{\text{H}_2\text{O}}\dot{V}^2}{2A_1^2} \Rightarrow \dot{V}^2 = \dfrac{2A_1^2 gh}{15}\left(\dfrac{\rho_{\text{Hg}}}{\rho_{\text{H}_2\text{O}}} - 1\right)$

$$\dot{V}^2 = \dfrac{2\left[\pi(7.5)^2\right]^2 \text{cm}^4}{15} \left| \dfrac{1}{10^8\ \text{cm}^4} \dfrac{\text{m}^4}{} \right| \dfrac{9.8066\ \text{m}}{\text{s}^2} \left| 38\ \text{cm} \right| \dfrac{1\ \text{m}}{10^2\ \text{cm}} \left| (13.6 - 1) \right. = 1.955 \times 10^{-3}\ \dfrac{\text{m}^6}{\text{s}^2}$$

$$\Rightarrow \dot{V} = 0.044\ \text{m}^3/s = \underline{\underline{44\ \text{L}/s}}$$

7.54 (a). <u>Point 1 - surface of fluid</u> . $P_1 = 3.1$ bar , $z_1 = +7$m , $u_1 = 0(\text{m/s})$

<u>Point 2 - discharge pipe outlet</u> . $P_2 = 1$ atm , $z_2 = 0(\text{m})$, $u_2 = ?$
$$\underset{(=1.013\,\text{bar})}{}$$

$$\frac{\Delta \rho}{\rho} = \frac{(1.013 - 3.1)\text{bar}}{} \left| \frac{10^5\,\text{N}}{\text{m}^2 \cdot \text{bar}} \right| \frac{1}{0.792 \times 10^3} \left| \frac{\text{m}^3}{\text{kg}} \right| = -263.5 \text{ m}^2/\text{s}^2$$

$$g\Delta z = \frac{9.8066\text{ m}}{\text{s}^2} \left| \frac{-7\text{m}}{} \right| = -68.6 \text{ m}^2/\text{s}^2$$

<u>Bernoulli equation</u> $\Rightarrow \dfrac{\Delta u^2}{2} = -\dfrac{\Delta P}{\rho} - g\Delta z = (263.5 + 68.6) \text{ m}^2/\text{s}^2 = 332.1 \text{ m}^2/\text{s}^2$

$$\Delta u^2 = u_2^2 - 0^2$$

$$u_2^2 = 2(332.1 \text{ m}^2/\text{s}^2) = 664.2 \text{ m}^2/\text{s}^2 \Rightarrow u_2 = \underline{25.8 \text{ m} / \text{s}}$$

$$\dot{V} = \frac{\pi(1.00^2) \text{ cm}^2}{4} \left| \frac{2580 \text{ cm}}{1 \quad \text{s}} \right| \frac{1}{10^3} \left| \frac{\text{L}}{\text{cm}^3} \right| \frac{60 \text{ s}}{1 \text{ min}} = \underline{\underline{122 \text{ L} / \text{min}}}$$

(b) The friction loss term of Eq. (7.7-2), which was dropped to derive the Bernoulli equation, becomes increasingly significant as the valve is closed.

7.55 <u>Point 1 - surface of lake</u> . $P_1 = 1$ atm , $z_1 = 0$, $u_1 = 0$

<u>Point 2 - pipe outlet</u> . $P_2 = 1$ atm , $z_2 = z(\text{ft})$

$$u_2 = \frac{\dot{V}}{A} = \frac{95 \text{ gal}}{\text{min}} \left| \frac{1}{7.4805} \frac{\text{ft}^3}{\text{gal}} \right| \frac{1}{\pi(0.5 \times 1.049)^2 \text{ in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \frac{1 \text{ min}}{60 \text{ s}} = 35.3 \text{ ft/s}$$

<u>Pressure drop</u>: $\Delta P/\rho = 0 \quad (P_1 = P_2)$

<u>Friction loss</u>: $F = 0.041(2z) \text{ ft} \cdot \text{lb}_f /\text{lb}_m = 0.0822 \, z \, (\text{ft} \cdot \text{lb}_f /\text{lb}_m)$

$$\left(L = \frac{z}{\sin 30°} = 2z \right)$$

<u>Shaft work:</u> $\dfrac{\dot{W}_s}{\dot{m}} = \dfrac{-8 \text{ hp}}{} \left| \dfrac{0.7376 \text{ ft} \cdot \text{lb}_f / \text{s}}{1.341 \times 10^{-3} \text{ hp}} \right| \dfrac{1 \text{ min}}{95 \text{ gal}} \left| \dfrac{7.4805 \text{ gal}}{1 \text{ ft}^3} \right| \dfrac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \left| \dfrac{60 \text{ s}}{1 \text{ min}} \right.$

$$= -333 \text{ ft} \cdot \text{lb}_f /\text{lb}_m$$

<u>Kinetic energy</u>: $\Delta u^2/2 = \dfrac{\left[(35.3)^2 - 0^2 \right] \text{ft}^2}{2} \left| \dfrac{1}{\text{s}^2} \right| \dfrac{\text{lb}_f}{32.174 \text{ lb}_m \cdot \text{ft} / \text{s}^2} = 19.4 \text{ ft} \cdot \text{lb}_f /\text{lb}_m$

<u>Potential energy</u>: $g\Delta z = \dfrac{32.174 \text{ ft}}{\text{s}^2} \left| \dfrac{z(\text{ft})}{} \right| \dfrac{1 \text{ lb}_f}{32.174 \text{ lb}_m \cdot \text{ft} / \text{s}^2} = z(\text{ft} \cdot \text{lb}_f /\text{lb}_m)$

<u>Eq. (7.7 - 2)</u> $\Rightarrow \dfrac{\Delta P}{\rho} + \dfrac{\Delta u^2}{2} + g\Delta z + F = \dfrac{-\dot{W}_s}{\dot{m}} \Rightarrow 19.4 + z + 0.082z = 333 \Rightarrow z = \underline{\underline{290 \text{ ft}}}$

7.56 <u>Point 1 - surface of reservoir</u> . $P_1 = 1$ atm (assume), $u_1 = 0$, $z_1 = 60$ m

<u>Point 2 - discharge pipe outlet</u> . $P_2 = 1$ atm (assume), $u_2 = ?$, $z_2 = 0$

$\Delta P / \rho = 0$

$$\frac{\Delta u^2}{2} = \frac{u_2^2}{2} = \frac{\left(\dot{V}/A\right)^2}{2} = \frac{\dot{V}^2\,(\text{m}^6 / \text{s}^2)}{(2)} \left| \frac{1}{\left[\pi(35)^2\right]^2 \text{cm}^4} \right| \frac{10^8\ \text{cm}^4}{1\ \text{m}^4} \left| \frac{1\ \text{N}}{1\ \text{kg} \cdot \text{m} / \text{s}^2} \right.$$

$$= 3.376 \dot{V}^2 \left(\text{N} \cdot \text{m/kg}\right)$$

$$g\Delta z = \frac{9.8066\ \text{m}}{\text{s}^2} \left| \frac{-65\ \text{m}}{} \right| \frac{1\ \text{N}}{1\ \text{kg} \cdot \text{m} / \text{s}^2} = -637\ \text{N} \cdot \text{m/kg}$$

$$\frac{\dot{W}_s}{\dot{m}} = \frac{0.80 \times 10^6\ \text{W}}{} \left| \frac{1\ \text{N} \cdot \text{m} / \text{s}}{\text{W}} \right| \frac{\text{s}}{\dot{V}\left(\text{m}^3\right)} \left| \frac{1\ \text{m}^3}{1000\ \text{kg}} \right. = 800/\dot{V} \left(\text{N} \cdot \text{m/kg}\right)$$

<u>Mechanical energy balance</u>: neglect F $\left(\text{Eq. 7.7 - 2}\right)$

$$\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z = \frac{-\dot{W}_s}{\dot{m}} \Rightarrow 3.376\dot{V}^2 - 637 = -\frac{800}{\dot{V}} \overset{T+E}{\Rightarrow} \dot{V} = \frac{1.27\ \text{m}^3}{\text{s}} \left| \frac{60\ \text{s}}{1\ \text{min}} \right. = \underline{\underline{76.2\ \ \text{m}^3/\text{min}}}$$

Include friction (add $F > 0$ to left side of equation) $\Rightarrow \dot{V}$ increases.

7.57 **(a)**. Point 1: Surface at fluid in storage tank, $P_1 = 1$ atm , $u_1 = 0$, $z_1 = H(\text{m})$

Point 2 (just within pipe): Entrance to washing machine. $P_2 = 1$ atm , $z_2 = 0$

$$u_2 = \frac{600\ \text{L}}{\text{min}} \left| \frac{1}{\pi(4.0\ \text{cm})^2 / 4} \right| \frac{10^3\ \text{cm}^3}{1\ \ \text{L}} \left| \frac{1\ \text{min}}{60\ \text{s}} \right| \frac{1\ \text{m}}{100\ \text{cm}} = 7.96\ \text{m/s}$$

$$\frac{\Delta P}{\rho} = 0 ; \quad \frac{\Delta u^2}{2} = \frac{u_2^2}{2} = \frac{(7.96\ \text{m/s})^2}{2} \left| \frac{1\ \text{J}}{1\ \text{kg} \cdot \text{m}^2 / \text{s}^2} \right. = 31.7\ \text{J} / \text{kg}$$

$$g\Delta z = \frac{9.807\ \text{m}}{\text{s}^2} \left| \frac{(0 - H(\text{m}))}{} \right| \frac{1\ \ \text{J}}{1\ \text{kg} \cdot \text{m}^2 / \text{s}^2} = -9.807H\ \ (\text{J} / \text{kg})$$

<u>Bernoulli Equation</u>: $\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z = 0 \Rightarrow \underline{\underline{H = 3.23\ \text{m}}}$

(b). Point 1: Fluid in washing machine. $P_1 = 1$ atm , $u_1 \approx 0$, $z_1 = 0$

Point 2: Entrance to storage tank (within pipe). $P_2 = 1$ atm , $u_2 = 7.96\ \text{m/s}$, $z_2 = 3.23$ m

$$\frac{\Delta P}{\rho} = 0 ; \quad \frac{\Delta u^2}{2} = 31.7\ \frac{\text{J}}{\text{kg}} ; \quad g\Delta z = 9.807(3.23 - 0) = 31.7\ \frac{\text{J}}{\text{kg}} ; \quad F = 72\ \frac{\text{J}}{\text{kg}}$$

<u>Mechanical energy balance</u>: $\dot{W}_s = -\dot{m}\left[\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z + F\right]$

$$\Rightarrow \dot{W}_s = -\frac{600\ \text{L}}{\text{min}} \left| \frac{0.96\ \text{kg}}{\text{L}} \right| \frac{1\ \text{min}}{60\ \text{s}} \left| \frac{(31.7 + 31.7 + 72)\ \text{J}}{\text{kg}} \right| \frac{1\ \ \text{kW}}{10^3\ \ \text{J/s}} = -1.30\ \text{kW}$$

(work applied to the system)

<u>Rated Power</u> $= 1.30\ \text{kW}/0.75 = \underline{1.7\ \text{kW}}$

7.58 <u>Basis</u>: 1000 liters of 95% solution. Assume volume additivity.

<u>Density of 95% solution:</u> $\dfrac{1}{\rho}=\sum\dfrac{x_i}{\rho_i}=\dfrac{0.95}{1.26}+\dfrac{0.05}{1.00}=0.804\dfrac{1}{kg}\Rightarrow\rho=1.24$ kg/liter
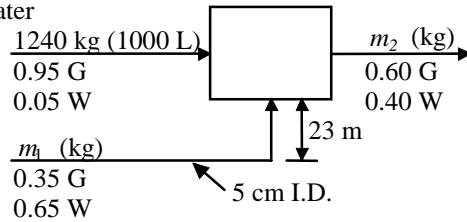(Eq. 6.1-1)

<u>Density of 35% solution:</u> $\dfrac{1}{\rho}=\dfrac{0.35}{1.26}+\dfrac{0.65}{1.00}=0.9278\dfrac{1}{kg}\Rightarrow\rho=1.08$ kg/liter

<u>Mass of 95% solution:</u> $\dfrac{1000\text{ liters}}{}\left|\dfrac{1.24\text{ kg}}{\text{liter}}\right.=1240$ kg

G = glycerol
W = water

```
        1240 kg (1000 L)   ┌──────┐    m₂  (kg)
        0.95 G           ──│      │──   0.60 G
        0.05 W             │      │     0.40 W
                           └──┬───┘
                              │ 23 m
         m₁  (kg)       ┌─────┘
         0.35 G      ───┘↘
         0.65 W            5 cm I.D.
```

<u>Mass balance:</u> $1240+m_1=m_2$
<u>Glycerol balance:</u> $(0.95)(1240)+(0.35)(m_1)=(0.60)(m_2)$ $\Big\}\Rightarrow$ $m_1=1740$ kg 35% solution
$m_2=2980$ kg 60% solution

<u>Volume of 35% solution added</u> $=\dfrac{1740\text{ kg}}{}\left|\dfrac{1\text{ L}}{1.08\text{ kg}}\right.=1610$ L

$\Rightarrow$ <u>Final solution volume</u> $=(1000+1610)\text{ L}=\underline{\underline{2610\text{ L}}}$

Point 1. Surface of fluid in 35% solution storage tank. $P_1=1$ atm , $u_1=0$, $z_1=0$
Point 2. Exit from discharge pipe. $P_2=1$ atm , $z_2=23$ m

$$u_2=\dfrac{1610\text{ L}}{13\text{ min}}\left|\dfrac{1\ \text{m}^3}{10^3\text{ L}}\right|\dfrac{1\text{ min}}{60\text{ s}}\left|\dfrac{1}{\pi(2.5)^2\text{ cm}^2}\right|\dfrac{10^4\text{ cm}^2}{1\ \ \text{m}^2}=1.051\text{ m/s}$$

$$\Delta P/\rho=0,\ \dfrac{\Delta u^2}{2}=\dfrac{\Delta u_2^2}{2}=\dfrac{(1.051)^2\ \text{m}^2/\text{s}^2}{(2)}\left|\dfrac{1\ \text{N}}{1\text{ kg}\cdot\text{m}/\text{s}^2}\right.=0.552\ \text{N}\cdot\text{m/kg}$$

$$g\Delta z=\dfrac{9.8066\text{ m}}{\text{s}^2}\left|\dfrac{23\text{ m}}{}\right|\dfrac{1\text{ N}}{1\text{ kg}\cdot\text{m}/\text{s}^2}=225.6\ \text{N}\cdot\text{m/kg},\ F=50\ \text{J/kg}=50\ \text{N}\cdot\text{m/kg}$$

<u>Mass flow rate:</u> $\dot{m}=\dfrac{1740\text{ kg}}{13\text{ min}}\left|\dfrac{1\text{ min}}{60\text{ s}}\right.=2.23$ kg/s

<u>Mechanical energy balance (Eq. 7.7 - 2)</u>

$$\dot{W}_s=-\dot{m}\left[\dfrac{\Delta P}{\rho}+\dfrac{\Delta u^2}{2}+g\Delta z+F\right]=-\dfrac{2.23\text{ kg}}{\text{s}}\left|\dfrac{(0.552+225.6+50)\text{N}\cdot\text{m}}{\text{kg}}\right|\dfrac{1\text{ J}}{1\text{ N}\cdot\text{m}}\left|\dfrac{1\text{ kW}}{10^3\text{ J/s}}\right.$$

$=-0.62$ kW $\Rightarrow\underline{\underline{0.62\text{ kW}}}$ delivered to fluid by pump.

CHAPTER EIGHT

8.1 **a.** $\hat{U}(T) = 25.96T + 0.02134T^2$ J / mol

$\underline{\underline{\hat{U}(0^\circ\text{C}) = 0 \text{ J / mol}}}$ $\underline{\underline{\hat{U}(100^\circ\text{C}) = 2809 \text{ J / mol}}}$ $\underline{\underline{T_{ref} = 0^\circ\text{C (since } \hat{U}(0^\circ\text{C}) = 0)}}$

b. We can never know the true internal energy. $\hat{U}(100^\circ\text{C})$ is just the change from $\hat{U}(0^\circ\text{C})$ to $\hat{U}(100^\circ\text{C})$.

c. $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$\Downarrow \quad \Delta E_k = 0,\ \Delta E_p = 0,\ W = 0$

$Q = \Delta U = (3.0 \text{ mol})[(2809 - 0) \text{ J / mol}] = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$

d. $C_v = \left(\dfrac{\partial \hat{U}}{\partial T}\right)_{\hat{V}} = \dfrac{d\hat{U}}{dT} = \underline{\underline{[25.96 + 0.04268T] \text{ J / (mol·}^\circ\text{C)}}}$

$\Delta \hat{U} = \int_{T_1}^{T_2} C_v(T)dT = \int_0^{100}(25.96 + 0.04268T)dT = \left(25.96T + 0.04268\dfrac{T^2}{2}\right]_0^{100}\right) \text{ J / mol}$

$\Delta U = (3.0 \text{ mol}) \cdot \Delta \hat{U} \text{ (J / mol)}$

$= (3.0 \text{ mol}) \cdot [25.96(100 - 0) + 0.02134(100^2 - 0)] \text{ (J / mol)} = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$

8.2 **a.** $C_v = C_p - R \Rightarrow C_v = (35.3 + 0.0291T)[\text{J / (mol·}^\circ\text{C)}] - (8.314 \text{ [J / (mol·K)]})(1 \text{ K/1}^\circ\text{C})$

$\Rightarrow \underline{\underline{C_v = 27.0 + 0.0291T \text{ [J / (mol·}^\circ\text{C)]}}}$

b. $\Delta \hat{H} = \int_{25}^{100} C_p dT = 35.3T\big]_{25}^{100} + 0.0291\dfrac{T^2}{2}\bigg]_{25}^{100} = \underline{\underline{2784 \text{ J/mol}}}$

c. $\Delta \hat{U} = \int_{25}^{100} C_v dT = \int_{25}^{100} C_p dT - \int_{25}^{100} R dT = \Delta \hat{H} - R\Delta T = 2784 - (8.314)(100 - 25) = \underline{\underline{2160 \text{ J/mol}}}$

d. $\underline{\underline{\hat{H} \text{ is a state property}}}$

8.3 **a.** $C_v [\text{kJ / (mol·}^\circ\text{C)}] = 0.0252 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2$

$n = \dfrac{PV}{RT} = \dfrac{(2.00 \text{ atm})(3.00 \text{ L})}{(0.08206[\text{atm·L / (mol·K)}])(298 \text{ K})} = 0.245 \text{ mol}$

$Q_1 = n\Delta\hat{U}_1 = (0.245 \text{ mol}) \cdot \int_{25}^{1000} 0.0252 \ dT \text{ (kJ / mol)} = \underline{\underline{6.02 \text{ kJ}}}$

$Q_2 = n\Delta\hat{U}_2 = (0.245) \cdot \int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5}T] \ dT = \underline{\underline{7.91 \text{ kJ}}}$

$Q_3 = n\Delta\hat{U}_3 = (0.245) \cdot \int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2] \ dT = \underline{\underline{7.67 \text{ kJ}}}$

% error in $Q_1 = \dfrac{6.02 - 7.67}{7.67} \times 100\% = \underline{\underline{-21.5\%}}$

% error in $Q_2 = \dfrac{7.91 - 7.67}{7.67} \times 100\% = \underline{\underline{3.13\%}}$

8.3 (cont'd)

    b. $C_p = C_v + R$

$$C_p[\text{kJ}/(\text{mol·}^\circ\text{C})] = (0.0252 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2) + 0.008314$$

$$= \underline{0.0335 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2}$$

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

$$= (0.245 \text{ mol}) \cdot \int_{25}^{1000}[0.0335 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2]\,dT\,[\text{kJ}/(\text{mol·}^\circ\text{C})] = \underline{9.65 \times 10^3 \text{ J}}$$

    Piston moves upward (gas expands).

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

8.4   **a.** $\left(C_p\right)_{C_6H_6(l)}(40^\circ\text{C}) = 0.1265 + 23.4 \times 10^{-5}(40) = \underline{0.1360\;[\text{kJ}/(\text{mol}\cdot\text{K})]}$

    b. $\left(C_p\right)_{C_6H_6(v)}(40^\circ\text{C}) = 0.07406 + 32.95 \times 10^{-5}(40) - 25.20 \times 10^{-8}(40)^2 + 77.57 \times 10^{-12}(40)^3$

$$= \underline{0.08684\;[\text{kJ}/(\text{mol·}^\circ\text{C})]}$$

    c. $\left(C_p\right)_{C(s)}(313\text{ K}) = 0.01118 + 1.095 \times 10^{-5}(313) - 4.891 \times 10^2(313)^{-2} = \underline{0.009615\;[\text{kJ}/(\text{mol}\cdot\text{K})]}$

    d. $\Delta\hat{H}_{C_6H_6(v)} = 0.07406T + \dfrac{32.95 \times 10^{-5}}{2}T^2 - \dfrac{25.20 \times 10^{-8}}{3}T^3 + \dfrac{77.57 \times 10^{-12}}{4}T^4\Big|_{40}^{300} = \underline{31.71\;\text{kJ/mol}}$

    e. $\Delta\hat{H}_{C(s)} = 0.01118T + \dfrac{1.095 \times 10^{-5}}{2}T^2 + 4.891 \times 10^2 T^{-1}\Big|_{313}^{573} = \underline{3.459\;\text{kJ}/\text{mol}}$

8.5 H_2O (v, 100°C, 1 atm) $\rightarrow$ H_2O (v, 350°C, 100 bar)

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

    b. $\hat{H} = \displaystyle\int_{100}^{350}[0.03346 + 0.6886 \times 10^{-5}T + 0.7604 \times 10^{-8}T^2 - 3.593 \times 10^{-12}T^3]\,dT$

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

    Difference results from assumption in (b) that $\hat{H}$ is independent of P. The numerical difference is $\Delta\hat{H}$ for $H_2O(\text{v}, 350^\circ\text{C}, 1\text{ atm}) \rightarrow H_2O(\text{v}, 350^\circ\text{C}, 100\text{ bar})$

8.6 **b.** $\left(C_p\right)_{n-C_6H_{14}(l)} = 0.2163\;\text{kJ}/(\text{mol·}^\circ\text{C}) \Rightarrow \Delta\hat{H} = \displaystyle\int_{25}^{80}[0.2163]\,dT = \underline{11.90\;\text{kJ}/\text{mol}}$

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

    c. $\left(C_p\right)_{n-C_6H_{14}(v)}[\text{kJ}/(\text{mol·}^\circ\text{C})] = 0.13744 + 40.85 \times 10^{-5}T - 23.92 \times 10^{-8}T^2 + 57.66 \times 10^{-12}T^3$

$$\Delta\hat{H} = \int_{500}^{0}[0.13744 + 40.85 \times 10^{-5}T - 23.92 \times 10^{-8}T^2 + 57.66 \times 10^{-12}T^3]\,dT = \underline{-110.7\;\text{kJ}/\text{mol}}$$

    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.

8.7 $T(^\circ C) = \dfrac{1}{1.8}\left[T'(^\circ F) - 32\right] = 0.5556T'(^\circ F) - 17.78$

$C_p(\text{cal/mol} \cdot ^\circ C) = 6.890 + 0.001436\left[0.5556T'(^\circ F) - 17.78\right] = 6.864 + 0.0007978T'(^\circ F)$

$C_p'(\text{Btu/lb-mole} \cdot ^\circ F) \underset{\underset{\text{drop primes}}{\Downarrow}}{=} C_p \dfrac{\text{cal}}{\text{mol} \cdot ^\circ C} \left|\dfrac{453.6\ \text{mol}}{1\ \text{lb-mole}}\right| \dfrac{1\ \text{Btu}}{252\ \text{cal}} \left|\dfrac{1^\circ C}{1.8^\circ F}\right| = (1.00)C_p$

$\underline{\underline{C_p(\text{Btu/lb-mole} \cdot ^\circ F) = 6.864 + 0.0007978T(^\circ F)}}$

8.8 $\left(C_p\right)_{CH_3CH_2OH(l)}(T) = 0.1031 + \dfrac{(0.1588 - 0.1031)}{100}T = \underline{\underline{0.1031 + 0.000557T}} \ [\text{kJ}/(\text{mol} \cdot ^\circ C)]$

$Q = \Delta H = \dfrac{55.0\ \text{L}}{\text{s}} \left|\dfrac{789\ \text{g}}{1\ \text{L}}\right| \dfrac{1\ \text{mol}}{46.07\ \text{g}} \underbrace{\left(0.1031T + \dfrac{0.000557}{2}T^2\right)\Big|_{20}^{78.5}}_{\text{kJ/mol}}$

$= 941.9 \times 7.636\ \text{kJ/s} = \underline{\underline{7193\ \text{kW}}}$

8.9 **a.**

$\dot{Q} = \Delta\dot{H} = (5{,}000\ \text{mol/s}) \cdot \overbrace{\int_{100}^{200}\left[0.03360 + 1.367 \times 10^{-5}T - 1.607 \times 10^{-8}T^2 + 6.473 \times 10^{-12}T^3\right]dT}^{\text{kJ/mol}}$

$= \underline{\underline{17{,}650\ \text{kW}}}$

b. $Q = \Delta U = \Delta H - \Delta PV = \Delta H - nR\Delta T = 17{,}650\ \text{kJ} - (5.0\ \text{kmol}) \cdot (8.314\ [\text{kJ}/(\text{kmol} \cdot \text{K})]) \cdot (100\ \text{K})$

$= \underline{\underline{13{,}490\ \text{kJ}}}$

The difference is the flow work done on the gas in the continuous system.

c. $Q_{\text{additional}}$ = heat needed to raise temperature of vessel wall + heat that escapes from wall to surroundings.

8.10 **a.** $\underline{C_p$ is a constant, i.e. C_p is independent of T.}

b. $Q = mC_p\Delta T \Rightarrow C_p = \dfrac{Q}{m\Delta T}$

$C_p = \dfrac{Q}{m\Delta T} = \dfrac{(16.73 - 6.14)\ \text{kJ}}{(2.00\ \text{L})(3.10\ \text{K})} \left|\dfrac{1\ \text{L}}{659\ \text{g}}\right| \dfrac{86.17\ \text{g}}{1\ \text{mol}} \left|\dfrac{10^3\ \text{J}}{1\ \text{kJ}}\right| = \underline{\underline{0.223\ \text{kJ}/(\text{mol} \cdot \text{K})}}$

Table B.2 $\Rightarrow C_p = 0.216\ \text{kJ}/(\text{mol} \cdot ^\circ C) = 0.216\ \text{kJ}/(\text{mol} \cdot \text{K})$

8.11 $\hat{H} = \hat{U} + P\hat{V} \overset{P\hat{V}=RT}{=\!=\!=\!=\!=\!\Rightarrow} \hat{H} = \hat{U} + RT \overset{(\partial/\partial T)_P}{=\!=\!=\!=\!=\!\Rightarrow} \left(\dfrac{\partial\hat{H}}{\partial T}\right)_p = \left(\dfrac{\partial\hat{U}}{\partial T}\right)_p + R \Rightarrow C_p = \left(\dfrac{\partial\hat{U}}{\partial T}\right)_p + R$

But since $\hat{U}$ depends only on T, $\left(\dfrac{\partial\hat{U}}{\partial T}\right)_p = \dfrac{d\hat{U}}{dT} = \left(\dfrac{\partial\hat{U}}{\partial T}\right)_{\hat{V}} \equiv C_v \Rightarrow \underline{\underline{C_p = C_v + R}}$

8.12 **a.** $\left(C_p\right)_{H_2O(l)} = 75.4 \text{ kJ}/(\text{kmol}\cdot{}^{\circ}\text{C}) = 75.4 \text{ kJ}/(\text{kmol}\cdot{}^{\circ}\text{C})$ V = 1230 L ,

$$n = \frac{V\rho}{M} = \frac{1230 \text{ L}}{} \left| \frac{1 \text{ kg}}{1 \text{ L}} \right| \frac{1 \text{ kmol}}{18 \text{ kg}} = 68.3 \text{ kmol}$$

$$\dot{Q} = \frac{Q}{t} = \frac{n \cdot \int_{T}^{T_2} \left(C_p\right)_{H_2O(l)} dT}{t} = \frac{68.3 \text{ kmol}}{} \left| \frac{75.4 \text{ kJ}}{\text{kmol}\cdot{}^{\circ}\text{C}} \right| \frac{(40-29) \ {}^{\circ}\text{C}}{8 \text{ h}} \left| \frac{1 \text{ h}}{3600 \text{ s}} = \underline{\underline{1.967 \text{ kW}}}$$

b. $\dot{Q}_{\text{total}} = \dot{Q}_{\text{to the surroundings}} + \dot{Q}_{\text{to water}}$, $\dot{Q}_{\text{to the surroundings}} = 1.967 \text{ kW}$

$$\dot{Q}_{\text{to water}} = \frac{Q_{\text{to water}}}{t} = \frac{n \cdot \int_{29}^{40} C_{P(H_2O)} dT}{t} = \frac{68.3 \text{ kmol}}{3 \text{ h}} \left| \frac{75.4 \text{ kJ}/(\text{kmol}\cdot{}^{\circ}\text{C})}{3600 \text{ s}/\text{h}} \right| \frac{11 \ {}^{\circ}\text{C}}{} = 5.245 \text{ kW}$$

$\dot{Q}_{\text{total}} = \underline{\underline{7.212 \text{ kW}}}$ $\Rightarrow E_{\text{total}} = 7.212 \text{ kW} \times 3 \text{ h} = \underline{\underline{21.64 \text{ kW}\cdot\text{h}}}$

c. $Cost_{\text{heating up from 29 }{}^{\circ}\text{C to 40 }{}^{\circ}\text{C}} = 21.64 \text{ kW}\cdot\text{h} \times \$0.10/(\text{kW}\cdot\text{h}) = \underline{\underline{\$2.16}}$

$Cost_{\text{keeping temperature constant for 13 h}} = 1.967 \text{ kW} \times 13 \text{ h} \times \$0.10/(\text{kW}\cdot\text{h}) = \underline{\underline{\$2.56}}$

$Cost_{\text{total}} = \$2.16 + \$2.56 = \underline{\underline{\$4.72}}$

d. If the lid is removed, more heat will be transferred into the surroundings and lost, resulting in higher cost.

8.13 **a.** $\Delta\hat{H}_{N_2(25^{\circ}\text{C})\rightarrow N_2(700^{\circ}\text{C})} = \hat{H}_{N_2(700^{\circ}\text{C})} - \hat{H}_{N_2(25^{\circ}\text{C})} = (20.59 - 0) = \underline{\underline{20.59 \ \text{kJ/mol}}}$

b. $\Delta\hat{H}_{H_2(800^{\circ}\text{F})\rightarrow H_2(77^{\circ}\text{F})} = \hat{H}_{H_2(77^{\circ}\text{F})} - \hat{H}_{H_2(800^{\circ}\text{F})} = (0 - 5021) = \underline{\underline{-5021 \text{ Btu}/\text{lb-mol}}}$

c. $\Delta\hat{H}_{CO_2(300^{\circ}\text{C})\rightarrow CO_2(1250^{\circ}\text{C})} = \hat{H}_{CO_2(1250^{\circ}\text{C})} - \hat{H}_{CO_2(300^{\circ}\text{C})} = (63.06 - 11.58) = \underline{\underline{51.48 \ \text{kJ/mol}}}$

d. $\Delta\hat{H}_{O_2(970^{\circ}\text{F})\rightarrow O_2(0^{\circ}\text{F})} = \hat{H}_{O_2(0^{\circ}\text{F})} - \hat{H}_{O_2(970^{\circ}\text{F})} = (-539 - 6774) = \underline{\underline{-7313 \text{ Btu}/\text{lb-mol}}}$

8.14 **a.** $\dot{m} = 300 \text{ kg}/\text{min}$ $\dot{n} = \frac{300 \text{ kg}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{1000 \text{ g}}{1 \text{ kg}} \left| \frac{1 \text{ mol}}{28.01 \text{ g}} = 178.5 \text{ mol}/\text{s}$

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

$$= (178.5 \text{ mol}/\text{s}) \cdot \int_{450}^{50} [0.02895 + 0.411\times10^{-5}T + 0.3548\times10^{-8}T^2 - 2.22\times10^{-12}T^3] \ dT \text{ [kJ}/\text{mol]}$$

$$= (178.5 \text{ mol}/\text{s})(-12.076 \text{ [kJ}/\text{mol]}) = \underline{\underline{-2,156 \text{ kW}}}$$

b. $\dot{Q} = \dot{n} \cdot \Delta\hat{H} = \dot{n} \cdot \left[\hat{H}_{(50^{\circ}\text{C})} - \hat{H}_{(450^{\circ}\text{C})} \right]$ $= (178.5 \text{ mol}/\text{s})(0.73 - 12.815 \text{[kJ}/\text{mol]}) = \underline{\underline{-2,157 \text{ kW}}}$

8.15 **a.** $\dot{n} = 250 \text{ mol}/\text{h}$

i) $\dot{Q} = \dot{n}\Delta\hat{H} = \frac{250 \text{ mol}}{\text{h}} \left| \frac{(2676-3697) \text{ kJ}}{1 \text{ kg}} \right| \frac{1 \text{ kg}}{1000 \text{ g}} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \frac{18.02 \text{ g}}{1 \text{ mol}} = \underline{\underline{-1.278 \text{ kW}}}$

ii) $\dot{Q} = \dot{n}\Delta\hat{H} = \dot{n} \cdot \int_{T_1}^{T_2} C_p dT \ \Big|$

$$= \frac{250 \text{ mol}}{\text{h}} \left| \frac{1 \text{ h}}{3600 \text{ s}} \int_{600}^{100} [0.03346 + 0.6880\times10^{-5}T + 0.7604\times10^{-8}T^2 - 3.593\times10^{-12}T^3] = \underline{\underline{-1.274 \text{ kW}}} \right.$$

8.15 (cont'd)

     iii) $\dot{Q} = \dfrac{250 \text{ mol}}{3600 \text{ s}} \cdot (2.54 - 20.91) \text{ [kJ / mol]} = \underline{\underline{-1.276 \text{ kW}}}$

  b. Method (i) is most accurate since it takes into account the dependence of enthalpy on pressure and (ii) and (iii) do not.

  c. The enthalpy change for steam going from 10 bar to 1 atm at 600°C.

8.16 Assume ideal gas behavior, so that pressure changes do not affect $\Delta\hat{H}$.

$$\dot{n} = \dfrac{200 \text{ ft}^3}{\text{h}} \left| \dfrac{492^{\circ}R}{537^{\circ}R} \right| \dfrac{1.2 \text{ atm}}{1 \text{ atm}} \left| \dfrac{1 \text{ lb - mol}}{359 \text{ ft}^3 (\text{STP})} \right. = 0.6125 \text{ lb - mole / h}$$

$$\dot{Q} = \dot{n}\Delta\hat{H} = (0.6125 \, \dfrac{\text{lb - mole}}{\text{h}}) \cdot \left((2993 - 0) \text{ [Btu / lb - mole]} \right) = \underline{\underline{1833 \text{ Btu / h}}}$$

8.17   **a.** $\dfrac{50 \text{ kg}}{} \left| \dfrac{1.14 \text{ kJ}}{\text{kg·}^{\circ}\text{C}} \right| \dfrac{(50-10)^{\circ}\text{C}}{} = \underline{\underline{2280 \text{ kJ}}}$

    b.

$$\left(C_p\right)_{\text{Na}_2\text{CO}_3} \approx 2\left(C_p\right)_{\text{Na}} + \left(C_p\right)_{\text{C}} + 3\left(C_p\right)_{\text{O}} = 2(0.026) + 0.0075 + 3(0.017) = 0.1105 \text{ kJ/mol·}^{\circ}\text{C}$$

$$\dfrac{50{,}000 \text{ g}}{} \left| \dfrac{0.1105 \text{ kJ}}{\text{mol·}^{\circ}\text{C}} \right| \dfrac{1 \text{ mol}}{105.99 \text{ g}} \left| \dfrac{(50-10)^{\circ}\text{C}}{} \right. = \underline{\underline{2085 \text{ kJ}}}$$

$$\underline{\% \text{ error}} = \dfrac{2085 - 2280}{2280} \times 100\% = \underline{\underline{-8.6\% \text{ error}}}$$

8.18 $\left(C_p\right)_{\text{C}_6\text{H}_{14}\text{O(l)}} = 6(0.012) + 14(0.018) + 1(0.025) = 0.349 \text{ kJ / (mol·}^{\circ}\text{C)}$ (Kopp's Rule)

$\left(C_p\right)_{\text{CH}_3\text{COCH}_3\,(l)} = 0.1230 + 18.6 \times 10^{-5}\text{T} \text{ kJ/(mol·}^{\circ}\text{C)}$

Assume $\Delta H_{\text{mix}} \cong 0$

$$\qquad\qquad\qquad\quad \downarrow \text{CH}_3\text{COCH}_3 \qquad\qquad\qquad\qquad \downarrow \text{C}_6\text{H}_{14}\text{O}$$

$$C_{pm} = \dfrac{0.30\left(0.1230 + 18.6\times10^{-5}T\right) \text{ kJ}}{\text{mol}\cdot^{\circ}\text{C}} \left| \dfrac{1 \text{ mol}}{58.08 \text{ g}} \right. + \dfrac{0.70(0.349) \text{ kJ}}{\text{mol}\cdot^{\circ}\text{C}} \left| \dfrac{1 \text{ mol}}{102.17 \text{ g}} \right.$$

$$= [0.003026 + 9.607\times10^{-7}\text{T}] \text{ kJ/(g}\cdot^{\circ}\text{C)}$$

$$\Delta\hat{H} = \int_{45}^{20} [0.003026 + 9.607\times10^{-7}\text{T}] \, dT = \underline{\underline{-0.07643 \text{ kJ/g}}}$$

8.19 Assume ideal gas behavior, $\Delta H_{\text{mix}} \cong 0$

$$\overline{M}_w = \dfrac{1}{3}(16.04) + \dfrac{2}{3}(32.00) = 26.68 \, \dfrac{\text{g}}{\text{mol}}$$

$$\Delta\hat{H}_{\text{O}_2} = \int_{25}^{350} \left(C_p\right)_{\text{O}_2} dT = 10.08 \text{ kJ / mol}, \quad \Delta\hat{H}_{\text{CH}_4} = \int_{25}^{350} \left(C_p\right)_{\text{CH}_4} dT = 14.49 \text{ kJ / mol}$$

$$\hat{H} = \left[\dfrac{1}{3}(14.49 \text{ kJ / mol}) + \dfrac{2}{3}(10.08 \text{ kJ / mol})\right]\left(\dfrac{1000 \text{ g}}{1 \text{ kg}}\right)\left(\dfrac{1 \text{ mol}}{26.68 \text{ g}}\right) = \underline{\underline{433 \text{ kJ/kg}}}$$
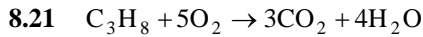
8.20 $n = \dfrac{1000 \text{ m}^3}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} \right| \dfrac{273 \text{ K}}{303 \text{ K}} \left| \dfrac{1 \text{ kmol}}{22.4 \text{ m}^3 (\text{STP})} \right. = 0.6704 \text{ kmol/s} = 670.4 \text{ mol/s}$

Energy balance on air:

$$Q = \Delta H = n\Delta H \xrightarrow{\text{Table B.8 for } \Delta\hat{H}} Q = \dfrac{670.4 \text{ mol}}{\text{s}} \left| \dfrac{0.73 \text{ kJ}}{\text{mol}} \right| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} = 489.4 \text{ kW}$$

$\underline{\text{Solar energy required}} = \dfrac{489.4 \text{ kW heating}}{} \left| \dfrac{1 \text{ kW solar energy}}{0.3 \text{ kW heating}} \right. = 1631 \text{ kW}$

$\underline{\text{Area required}} = \dfrac{1631 \text{ kW}}{} \left| \dfrac{1000 \text{ W}}{1 \text{ kW}} \right| \dfrac{1 \text{ m}^2}{900 \text{ W}} = \underline{\underline{1813 \text{ m}^2}}$

8.21 $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

$\dot{n}_{\text{fuel}} = \dfrac{1.35 \times 10^5 \text{ SCFH}}{\text{h}} \left| \dfrac{1 \text{ lb-mol}}{359 \text{ ft}^3} \right. = 376 \dfrac{\text{lb-mol}}{\text{h}}$
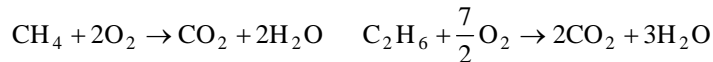
$\dot{n}_{\text{air}} = \dfrac{376 \text{ lb}-\text{mol}}{\text{h}} \left| \dfrac{5 \text{ lb-mol O}_2}{1\text{b-mol C}_3\text{H}_8} \right| \dfrac{1 \text{ lb-mol air}}{0.211\text{b-mol O}_2} \left| \dfrac{1.15}{} \right. = 1.03 \times 10^4 \dfrac{\text{lb}-\text{mol}}{\text{h}}$

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

$= \left(1.03 \times 10^4 \dfrac{\text{lb}-\text{mol}}{\text{h}} \right) \cdot \displaystyle\int_{0}^{302} [0.02894 + 0.4147 \times 10^{-5} T + 0.3191 \times 10^{-8} T^2 - 1.965 \times 10^{-12} T^3]\, dT$

$= \dfrac{1.03 \times 10^4 \text{ lb-mol}}{\text{h}} \left| \dfrac{8.954 \text{ kJ}}{\text{mol}} \right| \dfrac{453.593 \text{ mol}}{\text{lb-mol}} \left| \dfrac{9.486 \times 10^{-1} \text{ Btu}}{\text{kJ}} \right. = \underline{\underline{3.97 \times 10^7 \text{ Btu/h}}}$

8.22 **a.** Basis: 100 mol feed (95 mol CH_4 and 5 mol C_2H_6)

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

$n_{O_2} = 1.25 \cdot \left[\dfrac{95 \text{ mol CH}_4}{} \left| \dfrac{2 \text{ mol O}_2}{1 \text{ mol CH}_4} \right. + \dfrac{5 \text{ mol C}_2\text{H}_6}{} \left| \dfrac{3.5 \text{ mol O}_2}{1 \text{ mol C}_2\text{H}_6} \right. \right] = 259.4 \text{ mol O}_2$

Product Gas:

CO_2: 95(1)+5(2)=105 mol CO_2 $\qquad$ H_2O: 95(2)+5(3)=205 mol H_2O

O_2: 259.4-95(2)-5(3.5)=51.9 mol O_2 $\quad$ N_2: 3.76(259.4)=975 mol N_2

Energy balance (enthalpies from Table B.8)

$\Delta\hat{H}_{CO_2} = \hat{H}_{(CO_2,\ 450^o C)} - \hat{H}_{(CO_2,\ 900^o C)} = 18.845 - 42.94 = -24.09 \text{ kJ/mol}$

$\Delta\hat{H}_{H_2O} = \hat{H}_{(H_2O,\ 450^o C)} - \hat{H}_{(H_2O,\ 900^o C)} = 15.12 - 33.32 = -18.20 \text{ kJ/mol}$

$\Delta\hat{H}_{O_2} = \hat{H}_{(O_2,\ 450^o C)} - \hat{H}_{(O_2,\ 900^o C)} = 13.375 - 28.89 = -15.51 \text{ kJ/mol}$

$\Delta\hat{H}_{N_2} = \hat{H}_{(N_2,\ 450^o C)} - \hat{H}_{(N_2,\ 900^o C)} = 12.695 - 27.19 = -14.49 \text{ kJ/mol}$

$Q = \Delta H = \left[105(-24.09) + 205(-18.20) + 51.9(-15.51) + 975(-14.49) \right]$

$Q = \underline{\underline{21,200 \text{ kJ/100 mol feed}}}$

b. From Table B.5: $\hat{H}_{\text{liq}}(40^o C) = 167.5 \text{ kJ/kg}$; $\hat{H}_{\text{vap}}(50 \text{ bars}) = 2794.2 \text{ kJ/kg}$;

$Q = n \cdot \Delta\hat{H} = n(2794.2 - 167.5) = 21200 \implies n = \underline{\underline{8.07 \text{ kg/100 mol feed}}}$

8.22 (cont'd)

    c. From part (b), 8.07 kg steam is produced per 100 mol feed

$$\dot{n}_{feed} = \frac{1250 \text{ kg steam}}{h}\left|\frac{0.1 \text{ kmol feed}}{8.07 \text{ kg steam}}\right|\frac{1 \text{ h}}{3600 \text{ s}} = \underline{\underline{4.30\times10^{-3} \text{ kmol / s}}}$$

$$\dot{V}_{product\ gas} = \frac{4.30 \text{ mol feed}}{s}\left|\frac{1336.9 \text{ mol product gas}}{100 \text{ mol feed}}\right|\frac{8.314 \text{ Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\left|\frac{723 \text{ K}}{1.01325\times10^5 \text{ Pa}}\right. = \underline{\underline{3.41 \text{ m}^3 / \text{s}}}$$

    d. Steam produced from the waste heat boiler is used for heating, power generation, or process application. Without the waste heat boiler, the steam required will have to be produced with additional cost to the plant.

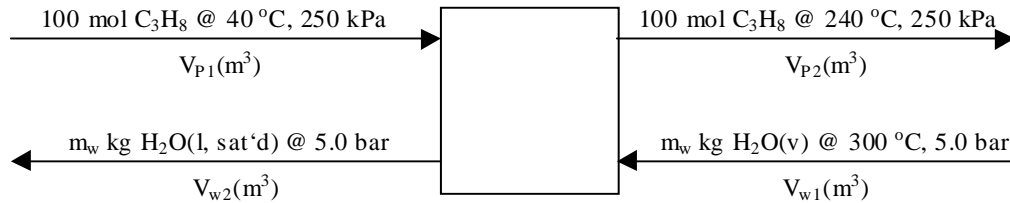**8.23**   Assume $\Delta H_{mix} \cong 0 \Rightarrow \Delta H = \Delta H_{C_{10}H_{12}O_2} + \Delta H_{C_6H_6}$

    <u>Kopp's rule</u>: $\left(C_p\right)_{C_{10}H_{12}O_2} = 10(12)+12(18)+2(25) = 386 \text{ J}\big/\left(\text{mol}\cdot^\text{o}\text{C}\right) = 2.35 \text{ J}\big/\left(\text{g}\cdot^\text{o}\text{C}\right)$

$$\Delta H_{C_{10}H_{12}O_2} = \frac{20.0 \text{ L}}{}\left|\frac{1021 \text{ g}}{L}\right|\frac{1 \text{ kJ}}{10^3 \text{ J}}\left|\frac{2.35 \text{ J}}{\text{g}\cdot^\text{o}\text{C}}\right|\frac{(71-25)\ ^\text{o}\text{C}}{} = 2207 \text{ kJ}$$

$$\Delta H_{C_6H_6} = \frac{15.0 \text{ L}}{}\left|\frac{879 \text{ g}}{L}\right|\frac{1 \text{ mol}}{78.11 \text{ g}}\cdot\left[\int_{298}^{348}[0.06255+23.4\times10^{-5}\text{T}] \text{ dT}\right] = 1166 \text{ kJ}$$

$$\Delta H = 2207+1166 = \underline{\underline{3373 \text{ kJ}}}$$

8.24   **a.**

    b. <u>References</u>: H_2O (l, 0.01 $^\text{o}$C), C_3H_8 (gas, 40 $^\text{o}$C)

$$\underline{C_3H_8}: \ \hat{H}_{in} = \underline{\underline{0 \text{ kJ / mol}}}; \ \hat{H}_{out} = \int_{40}^{240} C_{pC_3H_8} dT = \underline{\underline{19.36 \text{ kJ/mol}}} \ (C_p \text{ from Table B.2})$$

$$\underline{H_2O}: \ \hat{H}_{in} = \underline{\underline{3065 \text{ kJ/kg}}} \text{ (Table B.7)}; \ \hat{H}_{out} = \underline{\underline{640.1 \text{ kJ/kg}}} \text{ (Table B.6)}$$

    c. $\Delta\hat{H}_{C_3H_8} = 19.36 \text{ kJ/mol}, \Delta\hat{H}_w = (640.1-3065) \text{ kJ/kg} = -2425 \text{ kJ/kg}$

$$Q = \Delta H = 100\Delta\hat{H}_{C_3H_8} + m_w\Delta\hat{H}_w = 0 \Rightarrow m_w = \underline{\underline{0.798 \text{ kg}}}$$

    From Table B.7: $\hat{V}_{steam}(5.0 \text{ bar}, 300^\circ\text{C}) = 0.522 \text{ m}^3\big/\text{kg}$

$$\hat{V}_{C_3H_8}(40^\circ\text{C}, 250 \text{ kPa}) = \frac{0.008314 \text{ m}^3\cdot\text{kPa}\big/(\text{mol}\cdot\text{K})}{250 \text{ kPa}}\left|\frac{313 \text{ K}}{}\right. = 0.0104 \text{ m}^3\big/\text{mol } C_3H_8$$

$$\frac{0.798 \text{ kg steam}}{100 \text{ mol } C_3H_8}\left|\frac{0.522 \text{ m}^3 \text{ steam}}{1 \text{ kg steam}}\right|\frac{1 \text{ mol } C_3H_8}{0.0104 \text{ m}^3 C_3H_8} = \underline{\underline{0.400 \text{ m}^3 \text{ steam}\big/\text{m}^3 C_3H_8}}$$

    d.
$$Q = m_w\Delta\hat{H}_w = \frac{0.798 \text{ kg steam}}{100 \text{ mol } C_3H_8}\left|\frac{2425 \text{ kJ}}{\text{kg steam}}\right|\frac{1 \text{ mol } C_3H_8}{0.0104 \text{ m}^3 C_3H_8} = \underline{\underline{1860 \ \frac{\text{kJ}}{\text{m}^3 C_3H_8 \text{ fed}}}}$$

    e. A lower outlet temperature for propane and a higher outlet temperature for steam.

8.25 a.

5500 L(STP)/min CH$_3$OH (v) 65°C $\quad\longrightarrow\quad$ n_2 mol/min CH$_3$OH (v) 260°C

n_2 (mol/min)

$\longleftarrow$ m_w kg/min H$_2$O(l, sat'd) @ 90°C $\qquad\qquad$ m_w kg/min H$_2$O(v, sat'd) @ 300°C $\longleftarrow$

V_{w2}(m^3/min) $\qquad\qquad\qquad\qquad\qquad\qquad$ V_{w1}(m^3/min)
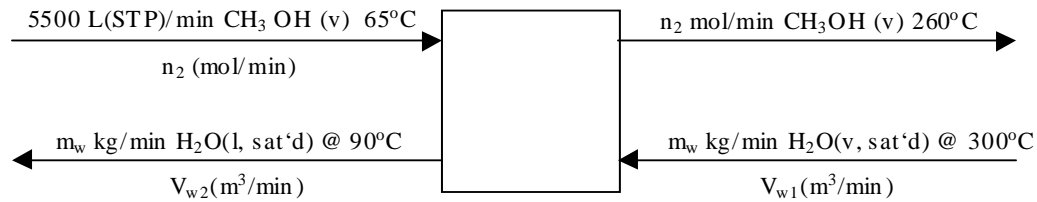
$$n_2 = \frac{5500 \text{ L(STP)}}{\text{min}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right. = 245.5 \text{ mol CH}_3\text{OH(v)/min}$$

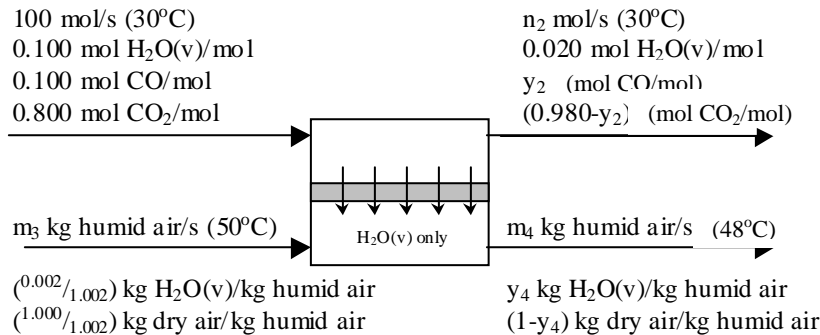An energy balance on the unit is then written, using Tables B.5 and B.6 for the specific enthalpies of the outlet and inlet water, respectively, and Table B.2 for the heat capacity of methanol vapor. The only unknown is the flow rate of water, which is calculated to be 1.13 kg H$_2$O/min.

b.

$$\dot{Q} = \left(1.13\frac{\text{kg}}{\text{min}}\right)\left(2373.9\frac{\text{kJ}}{\text{kg}}\right)\left(\frac{1 \text{ min}}{60 \text{ sec}}\right)\left(\frac{1 \text{ kW}}{1 \text{ kJ/s}}\right) = \underline{\underline{44.7 \text{ kW}}}$$

8.26 a.

100 mol/s (30°C) $\qquad\qquad\qquad\qquad$ n_2 mol/s (30°C)
0.100 mol H$_2$O(v)/mol $\qquad\qquad\qquad$ 0.020 mol H$_2$O(v)/mol
0.100 mol CO/mol $\qquad\qquad\qquad\qquad$ y_2 (mol CO/mol)
0.800 mol CO$_2$/mol $\qquad\qquad\qquad$ (0.980-y_2) (mol CO$_2$/mol)

m_3 kg humid air/s (50°C) $\qquad$ H$_2$O(v) only $\qquad$ m_4 kg humid air/s (48°C)

$(^{0.002}/_{1.002})$ kg H$_2$O(v)/kg humid air $\qquad$ y_4 kg H$_2$O(v)/kg humid air
$(^{1.000}/_{1.002})$ kg dry air/kg humid air $\qquad$ (1-y_4) kg dry air/kg humid air

Basis: 100 mol gas mixture/s
 5 unknowns: n_2, m_3, m_4, y_2, y_4
 – 4 independent material balances, H$_2$O(v), CO, CO$_2$, dry air
 – 1 energy balance equation
  0 degrees of freedom (all unknowns may be determined)

b. (1) CO balance: $(100)(0.100) = \dot{n}_2 y_2$
    (2) CO$_2$ balance: $(100)(0.800) = n_2(1-y_2)$ $\Big\} \Rightarrow \dot{n}_2 = 91.84 \text{ mol/s}, \; x_2 = 0.1089 \text{ mol CO/mol}$

    (3) Dry air balance: $m_3 \dfrac{1.000}{1.002} = m_4(1-y_4)$

    (4) H$_2$O balance: $\dfrac{(100)(0.100)(18)}{1000} + \dot{m}_3 \dfrac{0.002}{1.002} = 91.84\dfrac{(0.020)(18)}{1000} + \dot{m}_4 y_4$

References: CO, CO$_2$, H$_2$O(v), air at 25°C ($\hat{H}$ values from Table B.8)

substance	$\dot{n}_{in}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
H$_2$O(v)	10	0.169	91.84(0.020)	0.169
CO	10	0.146	10	0.146
CO$_2$	80	0.193	80	0.193
H$_2$O(v)	$m_3(^{0.002}/_{1.002})(^{1000}/_{18})$	0.847	$m_4 y_4(^{1000}/_{18})$	0.779
dry air	$m_3(^{1.000}/_{1.002})(^{1000}/_{29})$	0.727	$m_4(1-y_4)(^{1000}/_{29})$	0.672

8.26 (cont'd)

(5) Energy balance:

$$10(0.169) + m_3\left(\frac{0.002}{1.002}\right)\left(\frac{1000}{18}\right)(0.847) + m_3\left(\frac{1.000}{1.002}\right)\left(\frac{1000}{29}\right)(0.727)$$

$$= 91.84(0.020)(0.169) + m_4\,y_4\,(0.779)\left(\frac{1000}{18}\right) + m_4\,(1-y_4)(0.672)\left(\frac{1000}{29}\right)$$

Solve Eqs. (3)–(5) simultaneously $\Rightarrow m_3 = 2.55$ kg/s, $m_4 = 2.70$ kg/s, $y_4 = 0.0564$ kg H$_2$O/kg

$$\frac{2.55 \text{ kg humid air / s}}{100 \text{ mol gas / s}} = 0.0255\,\frac{\text{kg humid air}}{\text{mol gas}}$$

Mole fraction of water : $\dfrac{0.0564 \text{ kg H}_2\text{O}}{(1-.0564)\text{ kg dry air}}\left|\dfrac{29 \text{ kg DA}}{\text{kmol DA}}\right|\dfrac{1 \text{ kmol H}_2\text{O}}{18 \text{ kg H}_2\text{O}} = .0963\,\dfrac{\text{kmol H}_2\text{O}}{\text{kmol DA}}$

$$\Rightarrow \frac{0.0963 \text{ kmol H}_2\text{O}}{(1+0.0963) \text{ kmol humid air}} = 0.0878\,\frac{\text{kmol H}_2\text{O}}{\text{kmol humid air}}$$

Relative humidity: $\dfrac{p_{\text{H}_2\text{O}}}{p^*_{\text{H}_2\text{O}}\left(48^\circ\text{C}\right)} = \dfrac{(0.0878)(760 \text{ mm Hg})}{83.71 \text{ mm Hg}} \times 100\% = \underline{\underline{79.7\%}}$

c. The membrane must be permeable to water, impermeable to CO, CO$_2$, O$_2$, and N$_2$, and both durable and leakproof at temperatures up to 50°C.

8.27 a. $y_{\text{H}_2\text{O}} = \dfrac{p^*(57^\circ\text{C})}{P} = \dfrac{129.82 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.171$ mol H$_2$O/mol

$$\downarrow$$

$$\frac{28.5 \text{ m}^3(\text{STP})}{\text{h}}\left|\frac{1 \text{ mol}}{0.0224 \text{ m}^3(\text{STP})}\right. = 1270 \text{ mol/h} \Rightarrow 217.2 \text{ mol H}_2\text{O/h} \quad (3.91 \text{ kg H}_2\text{O/h})$$

$$1270 - 217.2 = 1053\,\frac{\text{mol dry gas}}{\text{h}} \xRightarrow[\text{percentages}]{\text{given}} \begin{cases} 89.5 \text{ mol CO/h} \\ 110.5 \text{ mol CO}_2/\text{h} \\ 5.3 \text{ mol O}_2/\text{h} \\ 847.6 \text{ mol N}_2/\text{h} \end{cases}$$

1270 mol/h, 620°C →

425°C →

m (kg H$_2$O(l)/h), 20°C →
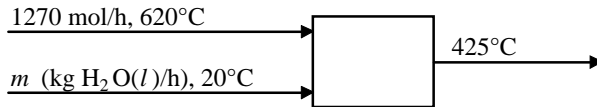
References for enthalpy calculations:

CO, CO$_2$, O$_2$, N$_2$ at 25°C (Table B.8); H$_2$O$\left(l,\ 0.01^\circ\text{ C}\right)$ (steam tables)

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
CO	89.5	18.22	89.5	12.03	
CO$_2$	110.6	27.60	110.6	17.60	n in mol/h
O$_2$	5.3	19.10	5.3	12.54	$\hat{H}$ in kJ/mol
N$_2$	847.6	18.03	847.6	11.92	
H$_2$O(v)	3.91	3749	3.91$+m$	3330	n in kg/h
H$_2$O(l)	m	83.9	--	--	$\hat{H}$ in kJ/kg

8.27 (cont'd)

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -8504 + 3246m = 0 \Rightarrow \underline{\underline{m = 2.62 \ \text{kg/h}}}$$
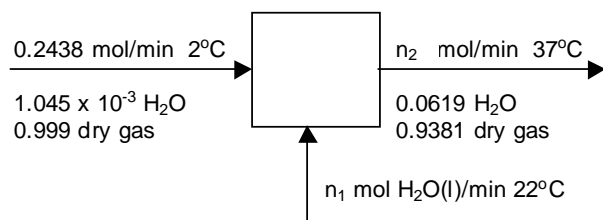
b. When cold water contacts hot gas, heat is transferred from the hot gas to the cold water lowering the temperature of the gas (the object of the process) and raising the temperature of the water.

8.28 2°C, 15% rel. humidity $\Rightarrow p_{H_2O} = (0.15)(5.294 \ \text{mm Hg}) = 0.7941 \ \text{mm Hg}$

$$\left(y_{H_2O}\right)_{\text{inhaled}} (0.7941)/(760) = 1.045 \times 10^{-3} \ \text{mol } H_2O/\text{mol inhaled air}$$

$$\dot{n}_{\text{inhaled}} = \frac{5500 \ \text{ml}}{\text{min}} \left| \frac{273 \ \text{K}}{275 \ \text{K}} \right| \frac{1 \ \text{liter}}{10^3 \ \text{ml}} \left| \frac{1 \ \text{mol}}{22.4 \ \text{liters(STP)}} \right. = 0.2438 \ \text{mol air inhaled/min}$$

$$\underline{\text{Saturation at 37 °C}} \Rightarrow y_{H_2O} = \frac{p^*(37°\text{C})}{760 \ \text{mm Hg}} = \frac{47.067}{760} = 0.0619 \ \text{mol } H_2O/\text{mol exhaled dry gas}$$

```
0.2438 mol/min  2°C   ┌──────────┐   n₂  mol/min  37°C
───────────────────→  │          │   ──────────────────→
1.045 x 10⁻³ H₂O      │          │   0.0619 H₂O
0.999 dry gas         │          │   0.9381 dry gas
                      └────▲─────┘
                           │
                n₁ mol H₂O(l)/min 22°C
```

$$\underline{\text{Mass of dry gas inhaled (and exhaled)}} = \frac{(0.2438)(0.999)\text{mol dry gas}}{\text{min}} \left| \frac{29.0 \ \text{g}}{\text{mol}} \right. = 7.063 \ \text{g/min}$$

$$\underline{\text{Dry gas balance:}} \ (0.999)(0.2438) = 0.9381 \dot{n}_2 \Rightarrow \dot{n}_2 = 0.2596 \ \text{mols exhaled/min}$$

$$\underline{H_2O \ \text{balance:}} \ (0.2438)(1.045 \times 10^{-3}) + \dot{n}_1 = (0.2596)(0.0619) \Rightarrow \dot{n}_1 = 0.0158 \ \text{mol } H_2O/\text{min}$$

$\underline{\text{References for enthalpy calculations:}}$ $H_2O(l)$ at triple point, dry gas at 2 °C

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$
Dry gas	7.063	0	7.063	36.75
$H_2O(v)$	0.00459	2505	0.290	2569
$H_2O(l)$	0.285	92.2	—	—

$\dot{m}$ in g/min $\quad \dot{m}_{H_2O} = 18.02 \dot{n}_{H_2O}$

$\hat{H}$ in J/g $\quad \hat{H}_{H_2O}$ from Table 8.4

$\quad\quad\quad\quad \hat{H}_{\text{dry gas}} = 1.05(T-2)$

$$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \frac{966.8 \ \text{J}}{\text{min}} \left| \frac{60 \ \text{min}}{1 \ \text{hr}} \right| \frac{24 \ \text{hr}}{1 \ \text{day}} = \underline{\underline{1.39 \times 10^6 \ \text{J/day}}}$$

8.29 **a.**

$$\frac{75 \text{ liters } C_2H_5OH(l)}{} \left| \frac{789 \text{ g}}{\text{liter}} \right| \frac{1 \text{ mol}}{46.07 \text{ g}} = 1284 \text{ mol } C_2H_3OH(l)$$

$(C_p)_{CH_3OH} = 0.1031 + 0.557 \times 10^{-3} T \left(kJ / (mol \cdot {}^\circ C) \right)$ (fitting the two values in Table B.2)

$$\frac{55 \text{ L } H_2O(l)}{} \left| \frac{1000 \text{ g}}{\text{liter}} \right| \frac{1 \text{ mol}}{18.01 \text{ g}} = 3054 \text{ mol } H_2O(l) \quad (C_p)_{H_2O} = 0.0754 \left(kJ/mol \cdot {}^\circ C \right)$$

1284 mol C₂H₅OH(l) (70.0°C)

3054 mol H₂O(l) (20.0°C)

1284 mol C₂H₅OH (l) (T°C)

3054 mol H₂O(l) (T°C)
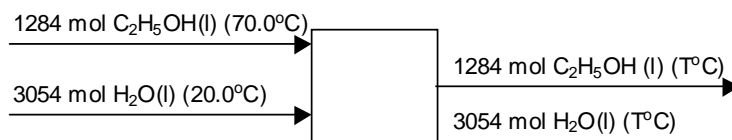
$$0 = 1284 \int_{70}^{T} \left(0.1031 + 0.557 \times 10^{-3} T \right) dT + 3054 \int_{25}^{T} \left(0.0754 \right) dT$$

$\left. \begin{array}{l} Q = \Delta U \cong \Delta H \left(\text{liquids} \right) \\ Q = 0 \left(\text{adiabatic} \right) \end{array} \right\} \Rightarrow \Downarrow$ Integrate, solve quadratic equation

$\underline{T=44.3 \ {}^\circ C}$

b. 1. Heat of mixing could affect the final temperature.
2. Heat loss to the outside (not adiabatic)
3. Heat absorbed by the flask wall & thermometer
4. Evaporation of the liquids will affect the final temperature.
5. Heat capacity of ethanol may not be linear; heat capacity of water may not be constant
6. Mistakes in measured volumes & initial temperatures of feed liquids
7. Thermometer is wrong

8.30 **a.**

1515 L/s air

500°C, 835 tor,
$T_{dp}=30^\circ C$

110 g/s H₂O, T=25°C

1515 L/s air , 1 atm

110 g/s H₂O(v)
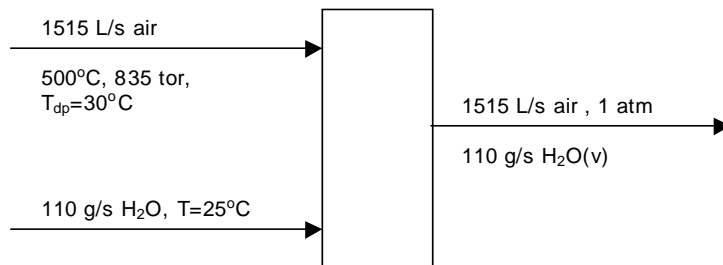
Let $\dot{n}_1$ (mol / s) be the molar flow rate of dry air in the air stream, and $\dot{n}_2$ (mol / s) be the molar flow rate of H₂O in the air stream.

$$\dot{n}_1 + \dot{n}_2 = \frac{1515 \text{ L}}{s} \left| \frac{835 \text{ mm Hg}}{773 \text{ K}} \right| \frac{mol \cdot K}{62.36 \text{ L} \cdot mm \text{ Hg}} = 26.2 \text{ mol / s}$$

$$\frac{\dot{n}_2}{\dot{n}_1 + \dot{n}_2} = y = \frac{p * (30^\circ C)}{P_{total}} = \frac{31.824 \text{ mmHg}}{835 \text{ mmHg}} = 0.0381 \text{ mol } H_2O / \text{ mol air}$$

$$\Rightarrow \dot{n}_1 = 25.2 \text{ mol dry air / s}; \ \dot{n}_2 = 1.0 \text{ mol } H_2O / s$$

8.30 (cont'd)

References: H_2O (l, 25°C), Air (v, 25°C)

substances	$\dot{n}_{in}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
dry air	25.2	14.37	25.2	$\int_{25}^{T}\left(C_p\right)_{air}dT$
H_2O(v)	1.0	$\int_{25}^{100}\left(C_p\right)_{H_2O(l)}dT+\hat{H}_{vap}$ $\int_{100}^{500}\left(C_p\right)_{H_2O(v)}dT$	7.1	$\int_{25}^{100}\left(C_p\right)_{H_2O(l)}dT+\hat{H}_{vap}$ $\int_{100}^{T}\left(C_p\right)_{H_2O(v)}dT$
H_2O(l)	6.1	0	--	--

$$\Delta H = 0 = \dot{n}_{out}\cdot\hat{H}_{out} - \dot{n}_{in}\cdot\hat{H}_{in}$$

$$(25.2)\left(\int_{25}^{T}\left(C_p\right)_{air}dT\right)+(7.1)\left(\int_{25}^{100}\left(C_p\right)_{H_2O(l)}dT+\hat{H}_{vap}+\int_{100}^{T}\left(C_p\right)_{H_2O(v)}dT\right)$$

$$-(25.2)(14.37)-(1.00)\left(\int_{25}^{100}\left(C_p\right)_{H_2O(l)}dT+\hat{H}_{vap}+\int_{100}^{500}\left(C_p\right)_{H_2O(v)}dT\right)=0$$

Integrate, solve : $\underline{T = 139°\,C}$

b. $\dot{Q}=-(25.2)\int_{500}^{139}\left(C_p\right)_{air}dT-(1.00)\int_{500}^{139}\left(C_p\right)_{H_2O(v)}dT=\underline{\underline{-290\text{ kW}}}$

This heat goes to vaporize the entering liquid water and bring it to the final temperature of 139°C.

c. When cold water contacts hot air, heat is transferred from the air to the cold water mist, lowering the temperature of the gas and raising the temperature of the cooling water.

8.31 Basis: $\dfrac{520 \text{ kg NH}_3}{\text{h}}\left|\dfrac{10^3 \text{ g}}{1 \text{ kg}}\right|\dfrac{1 \text{ mol}}{17.03 \text{ g}}\left|\dfrac{1 \text{ h}}{3600 \text{ s}}\right. = 8.48 \text{ mol NH}_3/\text{s}$
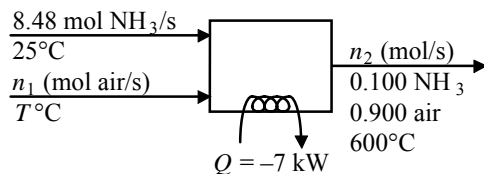
NH$_3$ balance: $8.48 = 0.100 n_2 \Rightarrow n_2 = 84.8 \text{ mol/s}$

Air balance: $n_1 = (0.900)(84.8) = 76.3 \text{ mol air/s}$

References for enthalphy calculations: NH$_3$(g), air at 25°C

NH$_3$ $\quad \hat{H}_{in} = 0.0$

$$\hat{H}_{out} = \int_{25}^{600}(C_p)_{NH_3} dT \underset{\text{Table B.2}}{\overset{C_p \text{ from}}{\Rightarrow}} \hat{H}_{out} = 25.62 \text{ kJ/mol}$$

Air: $C_p (\text{J/mol}\cdot°\text{C}) = 0.02894 + 0.4147\times10^{-5}T + 0.3191\times10^{-8}T^2 - 1.965\times10^{-12}T^3$

$$\hat{H}_{in} = \int_{25}^{T} C_p dT$$
$$= \left(-0.4913\times10^{-12}T^4 + 0.1064\times10^{-8}T^3 + 0.20735\times10^{-5}T^2 + 0.02894T - 0.7248\right)(\text{kJ/mol})$$

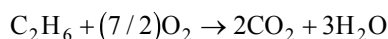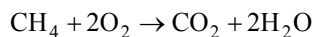$$\hat{H}_{out} = \int_{25}^{600} C_p dT = 17.55 \text{ kJ/mol}$$

Energy balance: $\quad Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i$

$$\Downarrow$$

$-7 \text{ kJ/s} = (8.48 \text{ mols NH}_3/\text{s})(25.62 \text{ kJ/mol}) + (76.3 \text{ mols air/s})(17.55 \text{ kJ/mol}) - (8.48)(0.0)$

$\quad -(76.3)\left(-0.4913\times10^{-12}T^4 + 0.1064\times10^{-8}T^3 + 0.20735\times10^{-5}T^2 + 0.02894T - 0.7248\right)$

Solve for T by trial-and-error, E-Z Solve, or Excel/Goal Seek $\Rightarrow T = \underline{\underline{691°\text{C}}}$

8.32 a. Basis: 100 mol/s of natural gas. Let M represent methane, and E for ethane

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

$C_2H_6 + (7/2)O_2 \rightarrow 2CO_2 + 3H_2O$
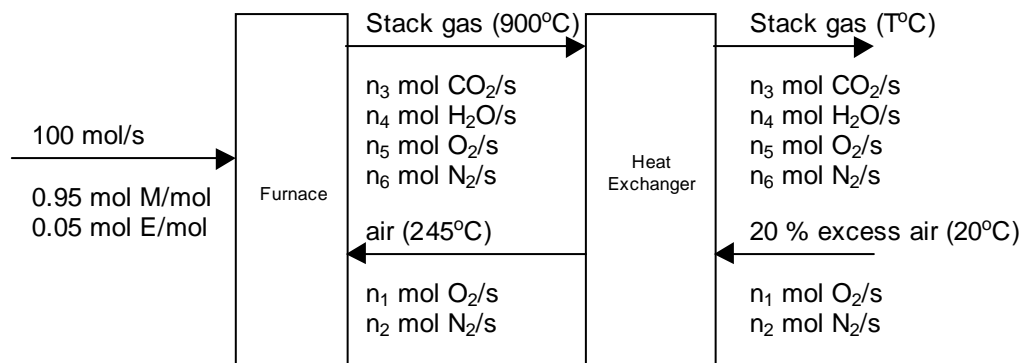
8.32 (cont'd)

$$\dot{n}_{air} = 1.2\left[\frac{95 \text{ mol M}}{s}\left|\frac{2 \text{ mol O}_2}{1 \text{ mol M}}\right|\frac{4.76 \text{ mol air}}{\text{mol O}_2} + \frac{5 \text{ mol E}}{s}\left|\frac{3.5 \text{ mol O}_2}{1 \text{ mol E}}\right|\frac{4.76 \text{ mol air}}{\text{mol O}_2}\right]$$

$$\dot{n}_{air} = \underline{1185 \text{ mol air/s}}$$

$$\dot{n}_1 = 0.21 \times 1185 = 249 \text{ mol O}_2/s, \ \dot{n}_2 = 0.79 \times 1185 = 936 \text{ mol N}_2/s$$

$$\dot{n}_3 = \frac{95 \text{ mol M}}{s}\left|\frac{1 \text{ mol CO}_2}{1 \text{ mol M}} + \frac{5 \text{ mol E}}{s}\right|\frac{2 \text{ mol CO}_2}{1 \text{ mol E}} = \underline{\underline{105 \text{ mol CO}_2/s}}$$

$$\dot{n}_4 = \frac{95 \text{ mol M}}{s}\left|\frac{2 \text{ mol H}_2O}{1 \text{ mol M}} + \frac{5 \text{ mol E}}{s}\right|\frac{3 \text{ mol H}_2O}{1 \text{ mol E}} = \underline{\underline{205 \text{ mol H}_2O/s}}$$

$$\dot{n}_5 = 249 - \frac{95 \text{ mol M}}{s}\left|\frac{2 \text{ mol O}_2}{1 \text{ mol M}} + \frac{5 \text{ mol E}}{s}\right|\frac{3.5 \text{ mol O}_2}{1 \text{ mol E}} = \underline{\underline{41.5 \text{ mol O}_2/s}}$$

$$\dot{n}_6 = \dot{n}_2 = \underline{\underline{936 \text{ mol N}_2/s}}$$

Energy balance on air:

$$\dot{Q} = \dot{n}_{air}\int_{20}^{245}(C_p)_{air}\,dT = \left(1185\,\frac{\text{mol air}}{s}\right)\left(6.649\,\frac{\text{kJ}}{\text{mol air}}\right) = 7879\,\frac{\text{kJ}}{s}(= 7879 \text{ kW})$$

Energy balance on stack gas:

$$\dot{Q} = -\Delta H = -\sum_{i=3}^{6}\left(\dot{n}_i\int_{900}^{T}(C_p)_i\,dT\right)$$

$$-7879 = \dot{n}_3\int_{900}^{T}(C_p)_{CO_2}\,dT + \dot{n}_4\int_{900}^{T}(C_p)_{H_2O(v)}\,dT + \dot{n}_5\int_{900}^{T}(C_p)_{O_2}\,dT + \dot{n}_6\int_{900}^{T}(C_p)_{N_2}\,dT$$

Substitute for the heat capacities (Table B.2), integrate, solve for T using E-Z Solve $\Rightarrow$ $\underline{\underline{T = 732\,°C}}$

b.

$$\frac{350 \text{ m}^3(\text{STP})}{h}\left|\frac{\text{mol}}{22.4 \text{ L(STP)}}\right|\frac{1000 \text{ L}}{\text{m}^3}\left|\frac{1 \text{ h}}{3600 \text{ s}}\right. = 4.34 \text{ mol/s}$$

$$\underline{\text{Scale factor}} = \frac{4.34 \text{ mol/s}}{100 \text{ mol/s}} = 0.0434$$

$$\dot{Q}' = 0.0434(7851) = \underline{\underline{341 \text{ kW}}}$$

8.33 a. $\Delta\hat{H} = \int_0^{600}C_p\,dT = \frac{100}{3}[33.5 + 4(35.1 + 38.4 + 42.0) + 2(36.7 + 40.2)43.9] = 23100 \text{ J/mol}$

$$Q = \Delta H = n\Delta\hat{H} = \frac{150 \text{ mol}}{s}\left|\frac{23100 \text{ J}}{\text{mol}}\right|\frac{1 \text{ kW}}{1000 \text{ J/s}} = \underline{\underline{3465 \text{ kW}}}$$

b. The method of least squares (Equations A1-4 and A1-5) yields (for $X = T$, $y = C_p$)

$$\underline{\underline{C_p = 0.0334 + 1.732 \times 10^{-5}T(°C)[\text{kJ/(mol·°C)}]}} \Rightarrow Q = 150\int_0^{600}\left[0.0334 + 1.732 \times 10^{-5}T\right]dT = \underline{\underline{3474 \text{ kW}}}$$

The estimates are exactly identical; in general, (a) would be more reliable, since a linear fit is forced in (b).

8.34 a. $\ln C_p = bT^{1/2} + \ln a \Rightarrow C_p = a\exp(bT^{1/2})$, $\sqrt{T_1} = 7.1$, $C_{p1} = 0.329$, $\sqrt{T_2} = 17.3$, $C_{p2} = 0.533$

$$\left.\begin{array}{l} b = \dfrac{\ln C_{p2}/C_{p1}}{\sqrt{T_2} - \sqrt{T_1}} = 0.0473 \\[2mm] \ln a = \ln C_{p1} - b\sqrt{T_1} = -1.4475 \Rightarrow a = e^{-1.4475} = 0.235 \end{array}\right\} \Rightarrow \underline{\underline{C_p = 0.235\exp(0.0473T^{1/2})}}$$

8.34 (cont'd)

b. $\int_{1800}^{150} 0.235 \exp\left(0.0473 T^{1/2}\right) dT = \dfrac{(0.235)(2)}{0.0473} \left\{ \exp\left(0.473 T^{1/2}\right)\left[T^{1/2} - \dfrac{1}{.0473} \right] \right\}_{1800}^{150} = -1730 \ \text{cal/g}$

```
      DIMENSIONS CP(101), NPTS(2)
      WRITE (6, 1)
  1   FORMAT (1H1, 20X'SOLUTION TO PROBLEM 8.37'/)
      NPTS(1) = 51
      NPTS(2) = 101
      DO 200K = 1, 2
      N = NPTS (K)
      NM1 = N – 1
      NM2 = N – 2
      DT = (150.0 – 1800.0)/FLOAT (NM1)
      T = 1800.0
      DO 20 J = 1, N
      CP (J) = 0.235*EXP(0.0473*SQRT(T))
  20  T = T + DT
      SUMI = 0.0
      DO 30 J = 2, NM1, 2
  30  SUMI = SUMI + CP(J)
      SUM2 = 0.0
      DO 40 J = 3, NM2, 2
  40  SUM2 = SUM2 + CP (J)
      DH = DT*(CP(1) + 4.0 = SUM1 + 2.0 =  SUM2 + CP(N))/3.0
      WRITE (6, 2) N, DH
  2   FORMAT (1H0, 5XI3, 'bPOINT INTEGRATIONbbbDELTA(H)b= ', E11.4,'bCAL/G')
 200  CONTINUE
      STOP
      END
```

Solution: $N = 11 \Rightarrow \Delta\hat{H} = -1731 \ \text{cal/g}$

$N = 101 \Rightarrow \Delta\hat{H} = -1731 \ \text{cal/g}$

Simpson's rule with $N = 11$ thus provides an excellent approximation

8.35 a. $\left.\begin{array}{l} \dot{m} = 175 \ \text{kg / min} \\ M.W.= 62.07 \ \text{g / mol} \\ \Delta\hat{H}_v = 56.9 \ \text{kJ / mol} \end{array}\right\} \Rightarrow \dot{Q} = \Delta H = \dfrac{175 \ \text{kg}}{\text{min}} \left|\dfrac{1000 \ \text{g}}{\text{kg}}\right| \dfrac{1 \ \text{mol}}{62.07 \ \text{g}} \left|\dfrac{56.9 \ \text{kJ}}{\text{mol}}\right| \dfrac{1 \ \text{min}}{60 \ \text{s}} = \underline{\underline{2670 \ \text{kW}}}$

b. The product stream will be a mixture of vapor and liquid.

c. The product stream will be a supercooled liquid. The stream goes from state A to state B as shown in the following phase diagram.
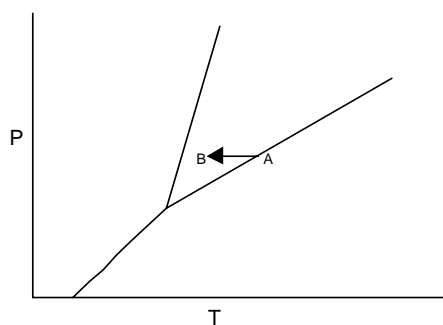
8.36 **a.** Table B.1 $\Rightarrow T_b = 68.74^\circ C$, $\Delta \hat{H}_v(T_b) = 28.85$ kJ / mol

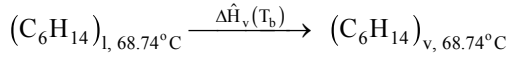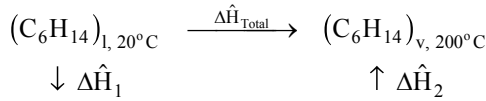Assume: n-hexane vapor is an ideal gas, i.e. $\Delta \hat{H}$ is not a function of pressure

$$\left(C_6H_{14}\right)_{l,\ 20^\circ C} \xrightarrow{\quad \Delta \hat{H}_{Total} \quad} \left(C_6H_{14}\right)_{v,\ 200^\circ C}$$
$$\downarrow \Delta \hat{H}_1 \qquad\qquad\qquad \uparrow \Delta \hat{H}_2$$
$$\left(C_6H_{14}\right)_{l,\ 68.74^\circ C} \xrightarrow{\quad \Delta \hat{H}_v(T_b) \quad} \left(C_6H_{14}\right)_{v,\ 68.74^\circ C}$$

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

$$\Delta \hat{H}_2 = \int_{68.74}^{200} \left[0.13744 + 40.85 \times 10^{-5}\,T - 23.92 \times 10^{-8}\,T^2 + 57.66 \times 10^{-9}\,T^3 \right] dT$$

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

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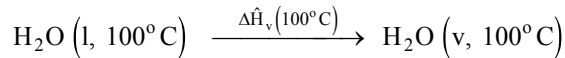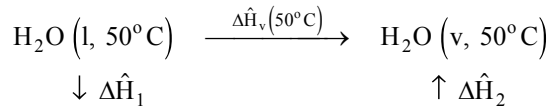
b. $\Delta \hat{H} = \underline{\underline{-64.05 \text{ kJ / mol}}}$

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

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

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

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

$$H_2O\left(l,\ 50^\circ C\right) \xrightarrow{\quad \Delta \hat{H}_v(50^\circ C) \quad} H_2O\left(v,\ 50^\circ C\right)$$
$$\downarrow \Delta \hat{H}_1 \qquad\qquad\qquad \uparrow \Delta \hat{H}_2$$
$$H_2O\left(l,\ 100^\circ C\right) \xrightarrow{\quad \Delta \hat{H}_v(100^\circ C) \quad} H_2O\left(v,\ 100^\circ C\right)$$

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

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

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

Steam table: $\dfrac{(2547.3 - 104.8)\text{kJ}}{\text{kg}} \left| \dfrac{18.01 \text{ g}}{1 \text{ mol}} \right| \dfrac{1 \text{ kg}}{1000 \text{ g}} = 44.0 \text{ kJ/mol}$

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

$\dfrac{1.75 \text{ m}^3}{2.0 \text{ min}} \left| \dfrac{879 \text{ kg}}{\text{m}^3} \right| \dfrac{1 \text{ kmol}}{78.11 \text{ kg}} \left| \dfrac{1000 \text{ mol}}{1 \text{ kmol}} \right| \dfrac{1 \text{ min}}{60 \text{ s}} = 164.1 \text{ mol/s}$

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

8.38 (cont'd)

$$C_6H_6 \left(v,\ 580^\circ C \right) \quad \longrightarrow \quad C_6H_6 \left(l,\ 25^\circ C \right)$$

$$\downarrow \Delta \hat{H}_1 \qquad\qquad\qquad \uparrow \Delta \hat{H}_2$$

$$C_6H_6 \left(v,\ 80.1^\circ C \right) \xrightarrow{\ -\Delta \hat{H}_v\ } C_6H_6 \left(l,\ 80.1^\circ C \right)$$

$$\Delta \hat{H}_1 = \int_{580}^{80.1} C_{pC_6H_6(v)} dT = -77.23\ \text{kJ/mol}$$

$$\Delta \hat{H}_2 = \int_{353.1}^{298} C_{pC_6H_6(l)} dT = -7.699\ \text{kJ/mol}$$

$$\Delta \hat{H} = \Delta \hat{H}_1 - \Delta \hat{H}_v \left(80.1^\circ C \right) + \Delta \hat{H}_2 = -115.7\ \text{kJ / mol}$$

$$Q = \Delta H = n\Delta \hat{H} = \left(164.1\ \text{mol / s} \right)\left(-115.7\ \text{kJ / mol} \right) = \underline{\underline{-1.90 x 10^{-4}\ \text{kW}}}$$

8.39

$$\left. \begin{array}{l} 35^\circ C \\ 15\%\ \text{relative saturation} \end{array} \right\} \Rightarrow y_{CCl_4} = 0.15 \frac{\overset{\text{Antoine}}{\downarrow} P_V^*(25^\circ C)}{1\ \text{atm}} = 0.15 \frac{176.0\ \text{mm Hg}}{760\ \text{mm Hg}} = 0.0347\ \text{mol}\ CCl_4/\text{mol}$$

$$\left(\Delta \hat{H}_v \right)_{CCl_4} \overset{\text{Table B.1}}{=} 30.0\ \frac{\text{kJ}}{\text{mol}} \Rightarrow Q = \Delta H = \frac{10\ \text{mol}}{\text{min}} \left| \frac{0.0347\ \text{mol}\ CCl_4}{\text{mol}} \right| \frac{30.0\ \text{kJ}}{\text{mol}\ CCl_4} = \underline{\underline{10.4\ \text{kJ/min}}}$$

Time to Saturation

$$\frac{6\ \text{kg carbon}}{} \left| \frac{0.40\ \text{g}\ CCl_4}{\text{g carbon}} \right| \frac{1\ \text{mol}\ CCl_4}{153.84\ \text{g}\ CCl_4} \left| \frac{1\ \text{mol gas}}{0.0347\ \text{mol}\ CCl_4} \right| \frac{1\ \text{min}}{10\ \text{mol gas}} = \underline{\underline{45.0\ \text{min}}}$$

8.40 a.

$$CO_2(g,\ 20^\circ C) \rightarrow CO_2(s,\ -78.4^\circ C): \quad \Delta \hat{H} = \int_{20}^{-78.4} \left(C_p \right)_{CO_2(g)} dT - \Delta \hat{H}_{sub} \left(-78.4^\circ C \right)$$

In the absence of better heat capacity data; we use the formula given in Table B.2 (which is strictly applicable only above $0^\circ C$).

$$\Delta \hat{H} \approx \int_{20}^{-78.4} \left[.03611 + 4.233 \times 10^{-5}T - 2.887 \times 10^{-8}T^2 + 7.464 \times 10^{-12}T^3 \right] dT \left(\frac{\text{kJ}}{\text{mol}} \right)$$

$$- 6030 \frac{\text{cal}}{\text{mol}} \left| \frac{4.184 \times 10^{-3}\ \text{kJ}}{1\ \text{cal}} \right. = -28.66\ \text{kJ/mol}$$

$$Q = \Delta H = n\Delta \hat{H} = \frac{300\ \text{kg}\ CO_2}{h} \left| \frac{10^3\ \text{g}}{1\ \text{kg}} \right| \frac{1\ \text{mol}}{44.01\ \text{g}} \left| \frac{28.66\ \text{kJ removed}}{\text{mol}\ CO_2} \right. = \underline{\underline{1.95 \times 10^5\ \text{k J/h}}}$$

(or 6.23×10^7 cal/hr or 72.4 kW)

b. According to Figure 6.1-1b, T_{fusion}=-56ºC

$$\dot{Q} = \Delta H = \dot{n}\Delta \hat{H}$$

where, $\Delta \hat{H} = \int_{20}^{-56} \left(C_p \right)_{CO_2(v)} dT + \Delta \hat{H}_v \left(-56^\circ C \right) + \int_{-56}^{-78.4} \left(C_p \right)_{CO_2(l)} dT$

$$\underline{\underline{\dot{Q} = \dot{n} \left[\int_{20}^{-56} \left(C_p \right)_{CO_2(v)} dT + \Delta \hat{H}_v \left(-56^\circ C \right) + \int_{-56}^{-78.4} \left(C_p \right)_{CO_2(l)} dT \right]}}$$

8.41 a. $C_p = a + bT$

$$b = \frac{53.94 - 50.41}{500 - 300} = 0.01765$$

$$a = 53.94 - (0.01765)(500) = 45.12$$

$$\Rightarrow C_p(\text{J/mol}\cdot\text{K}) = \underline{\underline{45.12 + 0.01765T(\text{K})}}$$

$$\text{NaCl}\ (s, 300\ \text{K}) \rightarrow \text{NaCl}(s, 1073\ \text{K}) \rightarrow \text{NaCl}(l, 1073\ \text{K})$$
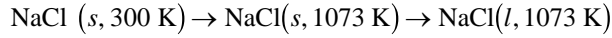
$$\Delta\hat{H} = \int_{300}^{1073} C_{ps}\,dT + \Delta\hat{H}_m(1073\ \text{K}) = \left[\int_{300}^{1073}(45.12 + 0.01765T)dT\right]\frac{\text{J}}{\text{mol}} + \frac{30.21\ \text{kJ}}{\text{mol}}\left|\frac{10^3\ \text{J}}{1\ \text{kJ}}\right.$$

$$= \underline{\underline{7.44\times 10^4\ \text{J/mol}}}$$

b. $Q = \Delta U = n\int_{300}^{1073} C_v\,dT + \Delta\hat{U}_m(1073\ \text{K})$

$$\Big\Downarrow \begin{array}{l} C_v \approx C_p \\ \Delta U_m \cong \Delta H_m \end{array}$$

$$Q \approx \Delta H = n\Delta\hat{H} = \frac{200\ \text{kg}}{}\left|\frac{10^3\ \text{g}}{1\ \text{kg}}\right|\frac{1\ \text{mol}}{58.44\ \text{g}}\left|\frac{74450\ \text{J}}{\text{mol}}\right. = \underline{\underline{2.55\times 10^8\ \text{J}}}$$

c. $t = \dfrac{2.55\times 10^8\ \text{J}}{}\left|\dfrac{\text{s}}{0.85\times 3000\ \text{kJ}}\right|\dfrac{1\ \text{kJ}}{10^3\ \text{J}} = \underline{\underline{100\ \text{s}}}$

8.42 $\Delta\hat{H}_v = 35.98\ \text{kJ/mol}$, $T_b = 136.2°\text{C} = 409.4\ \text{K}$, $P_c = 37.0\ \text{atm}$, $T_c = 619.7\ \text{K}$ (from Table B.1)

<u>Trouton's rule:</u> $\Delta\hat{H}_v \approx 0.088T_b = (0.088)(409.4\ \text{K}) = \underline{\underline{36.0\ \text{kJ/mol}}}(0.1\%\ \text{error})$

<u>Chen's rule:</u>

$$\Delta\hat{H}_v \approx \frac{T_b\left[0.0331\left(\dfrac{T_b}{T_c}\right) - 0.0327 + 0.0297\log_{10} P_c\right]}{1.07 - \left(\dfrac{T_b}{T_c}\right)} = \underline{\underline{35.7\ \text{kJ/mol}}}\ (-0.7\%\ \text{error})$$

<u>Watson's correlation</u>: $\Delta\hat{H}_v(100°\text{C}) \approx 35.98\left(\dfrac{619.7 - 373.2}{619.7 - 409.4}\right)^{0.38} = \underline{\underline{38.2\ \text{kJ/mol}}}$

8.43 $\underline{C_7H_2N}$: <u>Kopp's Rule</u> $\Rightarrow C_p \approx 7(0.012) + 12(0.018) + 0.033 = 0.333\ \text{kJ/(mol}\cdot°\text{C)}$

<u>Trouton's Rule</u> $\Rightarrow \Delta\hat{H}_v(200°\text{C}) = 0.088(200 + 273.2) = 41.6\ \text{kJ/mol}$

$$C_7H_{12}N(l,\ 25°\text{C}) \rightarrow C_7H_{12}N(l,\ 200°\text{C}) \rightarrow C_7H_{12}N(v,\ 200°\text{C})$$
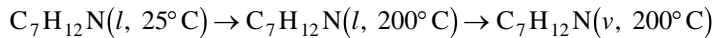
$$\boxed{\Delta\hat{H} = \int_{25}^{200} C_p\,dT + \Delta\hat{H}_v(200°\text{C}) \approx 0.333(200 - 25)\frac{\text{kJ}}{\text{mol}} + 41.6\ \frac{\text{kJ}}{\text{mol}} = \underline{\underline{100\ \text{kJ/mol}}}}$$

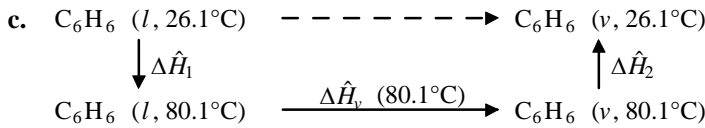**8.44** **a.** Antoine equation: $T_b(°C) = \dfrac{1211.033}{6.90565 - \log(100)} - 220.790 = 26.1°\,C$

Watson Correction: $\Delta\hat{H}_v(26.1°\,C) = 30.765\left(\dfrac{562.6 - 299.3}{562.6 - 353.1}\right)^{0.38} = \underline{\underline{33.6\ \text{kJ/mol}}}$

b. Antoine equation: $T_b(50\ \text{mm Hg}) = 11.8°C$; $T_b(150\ \text{mm Hg}) = 35.2°C$

Clausius-Clapeyron: $\ln p = -\dfrac{\Delta\hat{H}_v}{RT} + C \Rightarrow \Delta\hat{H}_v = -R\,\dfrac{\ln(p_2/p_1)}{1/T_2 - 1/T_1}$

$\Delta\hat{H}_v = -0.008314\,\dfrac{\text{kJ}}{\text{mol}\cdot\text{K}}\left\{\dfrac{\ln(150/50)}{1/308.4\ \text{K} - 1/285.0\ \text{K}}\right\} = \underline{\underline{34.3\ \text{kJ/mol}}}$

c. $C_6H_6\ (l, 26.1°C) \quad - - - - - - \rightarrow \quad C_6H_6\ (v, 26.1°C)$

$\Big\downarrow \Delta\hat{H}_1 \qquad\qquad\qquad\qquad\qquad\qquad \Big\uparrow \Delta\hat{H}_2$

$\qquad\qquad\qquad\qquad\quad \Delta\hat{H}_v\ (80.1°C)$

$C_6H_6\ (l, 80.1°C) \quad \xrightarrow{\hspace{3cm}} \quad C_6H_6\ (v, 80.1°C)$

$\Delta\hat{H}_1 = \displaystyle\int_{26.1}^{80.1}(C_p)_l\,dT = 7.50\ \text{kJ/mol}$

$\Delta\hat{H}_2 = \displaystyle\int_{80.1}^{26.1}(C_p)_v\,dT = -4.90\ \text{kJ/mol}$

$\Delta\hat{H}_v(26.1°\,C) = 7.50 + 30.765 - 4.90 = \underline{\underline{33.4\ \text{kJ/mol}}}$

8.45 **a.** $\underline{T_{\text{out}} = 49.3°C}$. The only temperature at which a pure species can exist as both vapor and liquid at 1 atm is the normal boiling point, which from Table B.1 is 49.3°C for cyclopentane.

b. Let $\dot{n}_f, \dot{n}_v$, and $\dot{n}_l$ denote the molar flow rates of the feed, vapor product, and liquid product streams, respectively.

Ideal gas equation of state

$$\dot{n}_f = \dfrac{1550\ \text{L}}{\text{s}}\left|\dfrac{273\ \text{K}}{423\ \text{K}}\right|\dfrac{1\ \text{mol}}{22.4\ \text{L(STP)}} = 44.66\ \text{mol }C_5H_{10}(v)\,/\,s$$

55% condensation: $\dot{n}_l = 0.550(44.66\ \text{mol/s}) = 24.56\ \text{mol }C_5H_{10}(l)\,/\,s$

Cyclopentane balance $\Rightarrow \dot{n}_v = (44.66 - 24.56)\ \text{mol }C_5H_{10}\,/\,s = 20.10\ \text{mol }C_5H_{10}(v)\,/\,s$

Reference: $C_5H_{10}(l)$ at 49.3°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)
C_5H_{10} (l)	—	—	24.56	0
C_5H_{10} (v)	44.66	$\hat{H}_f$	20.10	$\hat{H}_v$

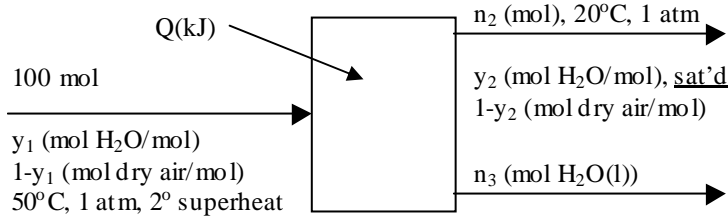$$H_i = \Delta\hat{H}_v + \int_{49.3°C}^{T_i} C_p\,dT$$

8.45 (cont'd)

Substituting for $\Delta \hat{H}_v$ from Table B.1 and for C_p from Table B.2

$$\Rightarrow \hat{H}_f = 38.36 \text{ kJ / mol}, \ \hat{H}_v = 27.30 \text{ kJ / mol}$$

Energy balance: $\dot{Q} = \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in} = -1.16 \times 10^3 \text{ kJ / s} = \underline{\underline{-1.16 \times 10^3 \text{ kW}}}$

8.46 a. Basis: 100 mol humid air fed

There are five unknowns (n_2, n_3, y_1, y_2, Q) and five equations (two independent material balances, 2°C superheat, saturation at outlet, energy balance). The problem can be solved.

b.

$\underline{\underline{2°\text{C superheat}}} \Rightarrow \underline{\underline{y_1}} = \dfrac{p*(48°\text{C})}{p}$

$\underline{\text{saturation at outlet}} \Rightarrow \underline{\underline{y_2}} = \dfrac{p*(20°\text{C})}{p}$

$\underline{\text{dry air balance:}} \ (100)(1 - y_1) = \underline{\underline{n_2}}(1 - y_2)$

$\underline{\text{H}_2\text{O balance:}} \ (100)(y_1) = (n_2)(y_2) + \underline{\underline{n_3}}$

c. $\underline{\text{References:}}$ Air $(25°\text{C})$, $\text{H}_2\text{O}(l, \ 20°\text{C})$

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
Air	$100 \cdot (1 - y_1)$	$\hat{H}_1$	$n_2 \cdot (1 - y_2)$	$\hat{H}_3$	n in mol
$\text{H}_2\text{O}(v)$	$100 \cdot y_1$	$\hat{H}_2$	$n_2 \cdot y_2$	$\hat{H}_4$	$\hat{H}$ in kJ/mol
$\text{H}_2\text{O}(l)$	–	–	n_3	0	

$\hat{H}_1 = \int_{25}^{50} (C_p)_{air} dT = \int_{25}^{50} \left[0.02894 + 0.4147 \times 10^{-5} T + 0.3191 \times 10^{-8} T^2 - 1.965 \times 10^{-12} T^3 \right] dT$

$\hat{H}_2 = \int_{20}^{100} (C_p)_{\text{H}_2\text{O}(l)} dT + \Delta \hat{H}_v (100°\text{C}) + \int_{100}^{50} (C_p)_{\text{H}_2\text{O}(v)} dT$

$\quad = \int_{20}^{100} [0.0754] dT + 40.656 + $

$\quad \int_{100}^{50} \left[0.03346 + 0.688 \times 10^{-5} T + 0.7604 \times 10^{-8} T^2 - 3.593 \times 10^{-12} T^3 \right] dT$

$\hat{H}_3 = \int_{25}^{20} (C_p)_{air} dT$

$\hat{H}_2 = \int_{20}^{100} (C_p)_{\text{H}_2\text{O}(l)} dT + \Delta \hat{H}_v (100°\text{C}) + \int_{100}^{20} (C_p)_{\text{H}_2\text{O}(v)} dT$

8.46 (cont'd)

c.

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i \qquad V_{air} = \frac{100 \text{ mol}}{} \left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \frac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}}$$

$$\Rightarrow \frac{Q}{V_{air}} = \frac{\displaystyle\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i}{\dfrac{100 \text{ mol}}{} \left| \dfrac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \dfrac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}}}$$

d.

$$\underline{2°C \text{ superheat}} \Rightarrow y_1 = \frac{p*(48°C)}{p} = \frac{83.71 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.110 \text{ mol } H_2O/\text{mol}$$

$$\underline{\text{saturation at outlet}} \Rightarrow y_2 = \frac{p*(20°C)}{p} = \frac{17.535 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.023 \text{ mol } H_2O/\text{mol}$$

$$\underline{\text{dry air balance:}} \quad (100)(1 - 0.110) = n_2(1 - 0.023) \Rightarrow n_2 = 91.10 \text{ mol}$$

$$\underline{H_2O \text{ balance:}} \quad (100)(0.110) = (91.10)(0.023) + n_3 \Rightarrow n_3 = \frac{8.90 \text{ mol } H_2O}{} \left| \frac{0.018 \text{ kg}}{1 \text{ mol}} \right.$$

$$= 0.160 \text{ kg } H_2O \text{ condensed}$$

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = -480.5 \text{ kJ}$$

$$V_{air} = \frac{100 \text{ mol}}{} \left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \frac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}} = 2.65 \text{ m}^3$$
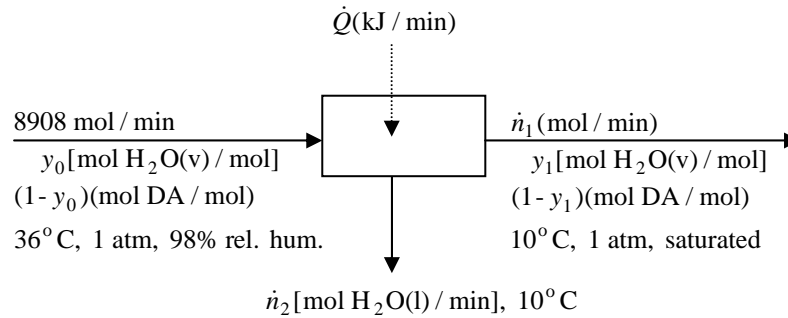
$$\Rightarrow \frac{0.160 \text{ kg } H_2O \text{ condensed}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{0.0604 \text{ kg } H_2O \text{ condensed} / \text{m}^3 \text{ air fed}}}$$

$$\Rightarrow \frac{-480.5 \text{ kJ}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{-181 \text{ kJ} / \text{m}^3 \text{ air fed}}}$$

e. Solve equations with E-Z Solve.

f.

$$Q = \frac{-181 \text{ kJ}}{\text{m}^3 \text{ air fed}} \left| \frac{250 \text{ m}^3 \text{ air fed}}{\text{h}} \right| \frac{1 \text{ h}}{3600 \text{ s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ} / \text{s}} \right. = \underline{\underline{-12.6 \text{ kW}}}$$

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

$$\dot{Q}(\text{kJ} / \text{min})$$

8908 mol / min
$y_0 [\text{mol H}_2\text{O(v)} / \text{mol}]$
$(1 - y_0)(\text{mol DA} / \text{mol})$
36° C, 1 atm, 98% rel. hum.

$\dot{n}_1 (\text{mol} / \text{min})$
$y_1 [\text{mol H}_2\text{O(v)} / \text{mol}]$
$(1 - y_1)(\text{mol DA} / \text{mol})$
10° C, 1 atm, saturated

$\dot{n}_2 [\text{mol H}_2\text{O(l)} / \text{min}],\ 10^\circ$ C

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: $y_0 P = 0.98 \overset{\underset{\text{Table B.3}}{\downarrow}}{p_w^*} (36^\circ\text{C}) \Rightarrow y_0 = \dfrac{0.98(44.563 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.0575$ mol $\text{H}_2\text{O(v)}/\text{mol}$

Outlet air: $y_1 = p^*(10^\circ\text{C}) / P = (9.209 \text{ mm Hg})/(760 \text{ mm Hg}) = 0.0121$ mol $\text{H}_2\text{O(v)}/\text{mol}$

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

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

References: $\text{H}_2\text{O}(l, \text{ triple point}),\ \text{air} (77^\circ \text{F})$

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	8396	0.3198	8396	−0.4352	$\dot{n}$ in mol/min
$\text{H}_2\text{O}(v)$	512	46.2	103	45.3	$\hat{H}$ in kJ/mol
$\text{H}_2\text{O}(l)$	–	–	409	0.741	

Air: $\hat{H}$ from Table B.8
H_2O: $\hat{H}(\text{kJ} / \text{kg})$ from Table B.5 $\times$ (0.018 kg / mol)
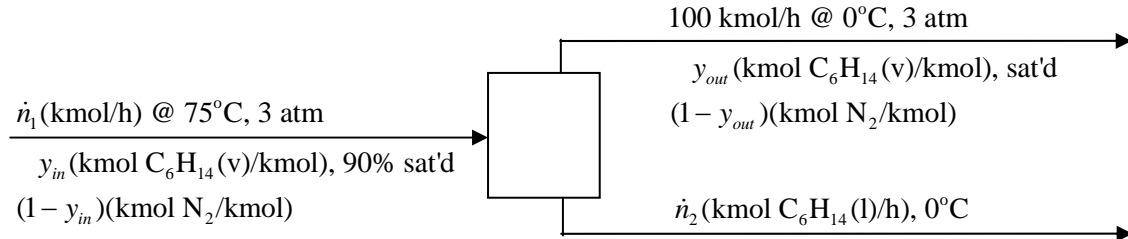
Energy balance:

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

8.48

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

100 kmol/h @ 0°C, 3 atm

y_{out} (kmol C_6H_{14} (v)/kmol), sat'd

$(1 - y_{out})$(kmol N_2/kmol)

$\dot{n}_1$(kmol/h) @ 75°C, 3 atm

y_{in}(kmol C_6H_{14} (v)/kmol), 90% sat'd

$(1 - y_{in})$(kmol N_2/kmol)

$\dot{n}_2$ (kmol C_6H_{14} (l)/h), 0°C

Antoine:

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

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

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

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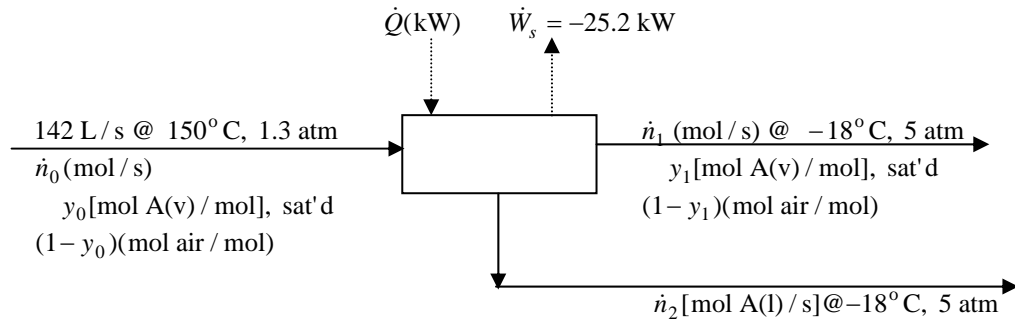
Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
N_2	98000	1.46	98000	−0.726	$\dot{n}$ in mol/h
n-$C_6H_{14}(r)$	55800	44.75	2000	33.33	$\hat{H}$ in kJ/mol
n-$C_6H_{14}(l)$	–	–	53800	0.0	

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

Energy balance: $Q = \Delta H = (-2.64 \times 10^6 \text{ kJ/h})(1 \text{ h}/3600 \text{ s}) \Rightarrow \underline{\underline{-733 \text{ kW}}}$

$$\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i$$

8.49 Let A denote acetone.

$$\dot{Q}(\text{kW}) \qquad \dot{W}_s = -25.2 \text{ kW}$$

142 L/s @ 150°C, 1.3 atm
$\dot{n}_0$ (mol/s)
y_0[mol A(v)/mol], sat'd
$(1-y_0)$(mol air/mol)

$\dot{n}_1$ (mol/s) @ $-18°$C, 5 atm
y_1[mol A(v)/mol], sat'd
$(1-y_1)$(mol air/mol)

$\dot{n}_2$[mol A(l)/s]@$-18°$C, 5 atm

a. <u>Degree of freedom analysis:</u>   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. <u>Ideal gas equation of state</u>   <u>Raoult's law</u>

(1) $\dot{n}_0 = \dfrac{P_0 \dot{V}_0}{R T_0}$

(2) $y_1 = \dfrac{p_A^*(-18°\text{C})}{5 \text{ atm}}$ (Antoine equation for p_A^*)

<u>Feed stream analysis</u>

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

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

<u>Reference states:</u> A(l, –18°C), air(25°C)

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (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) $\hat{H}_{A(v)}(T) = \displaystyle\int_{-18°\text{C}}^{56°\text{C}} (C_p)_{A(l)} \, dT + (\Delta \hat{H}_v)_A + \int_{56°\text{C}}^{T} (C_p)_{A(v)} \, dT$

Table B.2   Tab le B.1   Ta ble B.2

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

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

8.49 (cont'd)

c.

$(1) \Rightarrow \dot{n}_0 = \underline{\underline{5.32 \text{ mol feed gas/s}}}$ $\qquad$ $(2) \Rightarrow y_1 = \underline{\underline{6.58 \times 10^{-3} \text{ mol A(v)/mol outlet gas}}}$

$(3) \Rightarrow y_0 = \underline{\underline{0.147 \text{ mol A(v)/mol feed gas}}}$

$(4) \Rightarrow \dot{n}_1 = 4.57 \text{ mol outlet gas/s}$ $\qquad$ $(5) \Rightarrow \dot{n}_2 = 0.75 \text{ mol A(l)/s}$
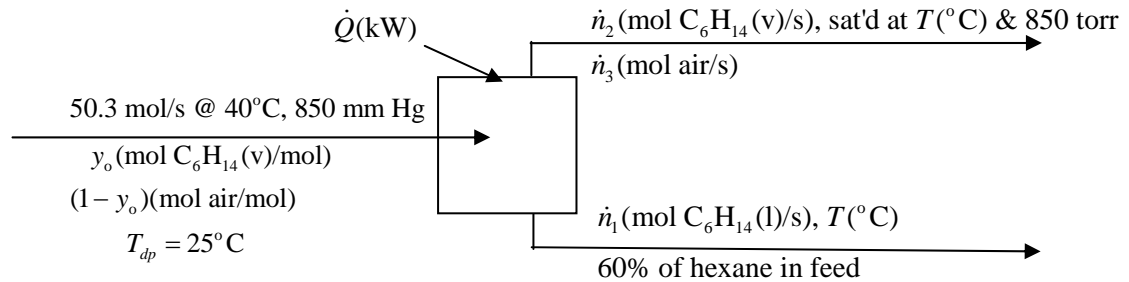
$(6) \Rightarrow \hat{H}_{A0} = 48.1 \text{ kJ/mol}, \ \hat{H}_{A1} = 34.0 \text{ kJ/mol}$

$(7) \Rightarrow \hat{H}_{a0} = 3.666 \text{ kJ/mol}, \ \hat{H}_{a1} = -1.245 \text{ kJ/mol}$

$(8) \Rightarrow \underline{\underline{\dot{Q} = -84.1 \text{ kW}}}$

8.50 **a.** $\underline{\text{Feed}}$:

$$\frac{3 \text{ m}}{\text{s}} \left| \frac{\pi(35)^2 \text{ cm}^2}{} \right| \frac{1 \text{ m}^2}{10^4 \text{ cm}^2} \left| \frac{273 \text{ K}}{(273+40)\text{K}} \right| \frac{850 \text{ torr}}{760 \text{ torr}} \left| \frac{1 \text{ kmol}}{22.4 \text{ m}^3(\text{STP})} \right| \frac{10^3 \text{ mol}}{1 \text{ kmol}} = 50.3 \frac{\text{mol}}{\text{s}}$$

Assume outlet gas is at 850 mm Hg.

$\dot{Q}(\text{kW})$

$\dot{n}_2 (\text{mol } C_6H_{14}(v)/s)$, sat'd at $T(°C)$ & 850 torr
$\dot{n}_3 (\text{mol air/s})$

50.3 mol/s @ 40°C, 850 mm Hg
$y_0 (\text{mol } C_6H_{14}(v)/\text{mol})$
$(1 - y_0)(\text{mol air/mol})$
$T_{dp} = 25°C$

$\dot{n}_1 (\text{mol } C_6H_{14}(l)/s), \ T(°C)$
60% of hexane in feed

<u>Degree-of-freedom analysis</u>

6 unknowns $\ (y_0, \dot{n}_1, \dot{n}_2, \dot{n}_3, T, \dot{Q})$
– 2 independent material balances
– 2 Raoult's law (for feed and outlet gases)
– 1 60% recovery equation
– 1 energy balance
0 degrees of freedom $\Rightarrow$ All unknowns can be calculated.

b. Let $H = C_6H_{14}$ $\qquad\qquad\qquad\qquad$ Antoine equation, Table B.4

$$\underline{\left(T_{dp}\right)_{\text{feed}} = 25 \text{ °C}} \Rightarrow y_0 = \frac{p_H^*(25°C)}{P} = \frac{151 \text{ mm Hg}}{850 \text{ mm Hg}} = 0.178 \text{ mol H/mol}$$

$$\underline{60\% \text{ recovery}} \Rightarrow \dot{n}_1 = \frac{0.600 \left| (50.3)(0.178) \text{ mols H feed} \right.}{\text{s}} = 5.37 \text{ mol } H(l)/s$$

<u>Hexane balance</u>: $(0.178)(50.3) = 5.37 + \dot{n}_2 \Rightarrow \dot{n}_2 = 3.58 \text{ mol } H(v)/s$

8.50 (cont'd)

Air balance: $\dot{n}_3 = (50.3)(1 - 0.178) = 41.3$ mol air/s

Mole fraction of hexane in outlet gas:

$$\frac{\dot{n}_2}{\dot{n}_2 + \dot{n}_3} = \frac{3.58}{(3.58 + 41.3)} = \frac{p_H(T)}{850 \text{ mm Hg}} \Rightarrow p_H(T) = 67.8 \text{ mm Hg}$$

Saturation at outlet: $p_H^*(T) = p_H(T) = 67.8$ mm Hg $\xrightarrow{\text{Table B.4}} \underline{\underline{T = 7.8°C}}$

Reference states: $C_6H_{14}(l, 7.8°C)$, air (25°C)

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
$C_6H_{14}(v)$	8.95	37.5	3.58	32.7	$\dot{n}$ in mol/s
$C_6H_{14}(l)$	—	—	5.37	0	$\hat{H}$ in kJ/mol
Air	41.3	0.435	41.3	–0.499	

$$C_6H_{14}(v): \quad \hat{H} = \int_{7.8}^{68.74} C_{pl}\, dT + \Delta\hat{H}_v(68.74 \text{ °C}) + \int_{68.74}^{T} C_{pv}\, dT, \quad \begin{array}{l} C_p \text{ from Table B.2} \\ \Delta\hat{H}_v \text{ from Table B.1} \end{array}$$

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

Energy balance: $Q = \Delta H = \sum\limits_{out} \dot{n}_i \hat{H}_i - \sum\limits_{in} \dot{n}_i \hat{H}_i = \dfrac{-257 \text{ kJ/s}}{} \left| \dfrac{1 \text{ kW cooling}}{-1 \text{ kJ/s}} \right| = \underline{\underline{257 \text{ kW}}}$

c.

$$u \cdot A = u' \cdot A'; \quad A = \frac{\pi \cdot D^2}{4}; \quad D' = \frac{1}{2} D \Bigg\} \Rightarrow u' = 4 \cdot u = \underline{\underline{12.0 \text{ m/s}}}$$

8.51

$\dot{n}_v\,(\text{mol}/\text{min})\ @\ 65^\circ\text{C},\ P_0\,(\text{atm})$
$y[\text{mol P(v)}/\text{mol}],\ \text{sat'd}$
$(1-y)(\text{mol H(v)}/\text{mol})$

100 mol / s @80°C, 5.0 atm
0.500 mol P(l) / mol
0.500 mol H(l) / mol

$\dot{Q}\,(\text{kJ}/\text{s})$

$\dot{n}_l\,(\text{mol}/\text{min})\ @\ 65^\circ\text{C},\ P_0\,(\text{atm})$
0.41 mol P(l) / mol
0.59 mol H(l) / mol
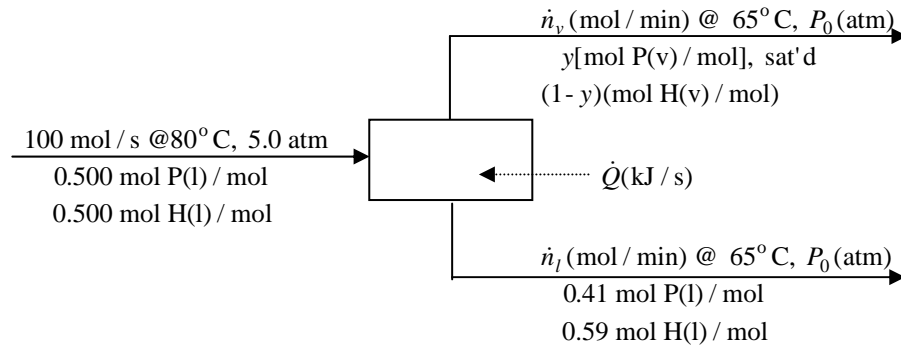
a. Degree of freedom analysis

5 unknowns – 2 material balances – 2 equilibrium relations (Raoult's law) at outlet – 1 energy balance

= 0 degrees of freedom

Antoine equation (Table B.4) $\Rightarrow p_P^*(65^\circ\text{C}) = 1851$ mm Hg, $p_H^*(65^\circ\text{C}) = 675$ mm Hg

Raoult's law for pentane and hexane

$0.410 p_P^*(65^\circ\text{C}) = yP_0$

$0.590 p_H^*(65^\circ\text{C}) = (1-y)P_0$

$\Rightarrow$

$\underline{y = 0.656 \text{ mol P(v)}/\text{mol}}$

$\underline{\underline{P_0 = 1157 \text{ mm Hg } (1.52 \text{ atm})}}$

Total mole balance: $100 \text{ mol} = \dot{n}_v + \dot{n}_l$

Pentane balance: $50 \text{ mole P} = 0.656\dot{n}_v + 0.410\dot{n}_l$

$\Rightarrow$

$\dot{n}_v = 36.6 \text{ mol vapor / s}$

$\dot{n}_l = 63.4 \text{ mol liquid / s}$

Ideal gas equation of state: $V_v = \dfrac{n_v RT}{P_0} = \dfrac{36.6 \text{ mol}}{\text{s}} \left| \dfrac{0.08206 \text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} \right| \dfrac{(65+273)\text{K}}{1.52 \text{ atm}} = \underline{\underline{667 \text{ L / s}}}$

Fractional vaporization of propane: $f = \dfrac{(0.656\times 36.6) \text{ mol P(v)/s}}{50.0 \text{ mol P(l) fed/s}} = \underline{\underline{0.480 \dfrac{\text{mol P vaporized}}{\text{mol fed}}}}$

References: P(l), H(l) at 65°C

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
P(v)	–	–	24.0	24.33	$\dot{n}$ in mol/s
P(l)	50	2.806	26.0	0	$\hat{H}$ in kJ / mol
H(v)	–	–	12.6	29.05	
H(l)	50	3.245	37.4	0	

Vapor: $\hat{H}(T) = \displaystyle\int_{65^\circ\text{C}}^{T_b} C_{pl}\,dT + \Delta\hat{H}_v(T_b) + \int_{T_b}^{T} C_{pv}\,dT$

Liquid: $\hat{H}(T) = \displaystyle\int_{65^\circ\text{C}}^{T} C_{pl}\,dT$

T_b and $\Delta\hat{H}_v$ from Table B.1, C_p from Table B.2

Energy balance: $\dot{Q} = \sum \dot{n}_{\text{out}}\hat{H}_{\text{out}} - \sum \dot{n}_{\text{in}}\hat{H}_{\text{in}} = \underline{\underline{647 \text{ kW}}}$

8.52 **a.** B=benzene; T=toluene
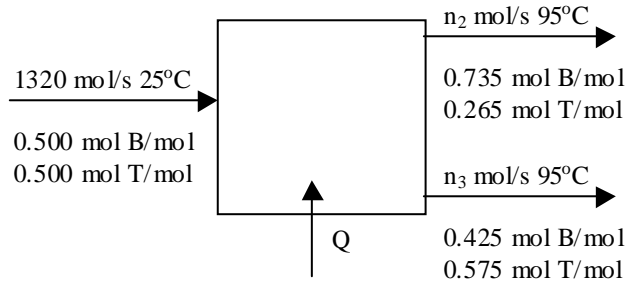
Total mole balance: $1320 = n_2 + n_3$

Benzene balance: $1320(0.500) = n_2(0.735) + n_3(0.425)$

$\Rightarrow \begin{cases} n_2 = 319 \text{ mol/s} \\ n_3 = 1001 \text{ mol/s} \end{cases}$

<u>References</u>: B(l, 25°C), T(l, 25°C)

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
B(l)	660	0	425	9.838
B(v)	--	--	234	39.91
T(l)	660	0	576	11.78
T(v)	--	--	85	46.06

$$Q = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{2.42 \times 10^4 \text{ kW}}}$$

b. Antoine equation (Table B.4) $\Rightarrow p_B^*(95° \text{ C}) = 1176$ torr , $p_T^*(95° \text{ C}) = 476.9$ torr

<u>Raoult's law</u>

Benzene: $(0.425)(1176) = (0.735)P \Rightarrow P = 680$ torr

Toluene: $(0.575)(476.9) = (0.265)P' \Rightarrow P' = 1035$ torr

$\Rightarrow P \neq P'$

$\Rightarrow$ <u><u>Analyses are inconsistent.</u></u>

Possible reasons: The analyses are wrong; the evaporator had not reached steady state when the samples were taken; the vapor and liquid product streams are not in equilibrium; Raoult's law is invalid at the system conditions (not likely).

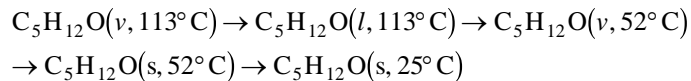**8.53** <u>Kopp's rule (Table B.10):</u> $C_5H_{12}O(s) \text{ --- } C_p = (5)(7.5) + (12)(9.6) + 17 = 170$ J/mol

$$C_5H_{12}O(l) \text{ --- } C_p = (5)(12) + (12)(18) + 25 = 301 \text{ J/mol}$$

<u>Trouton's rule</u> — Eq. (8.4-3): $\Delta H_v = (0.109)(113 + 273) = 42.1$ kJ/mol

<u>Eq. (8.4-5)</u> $\Rightarrow \Delta \hat{H}_m = (0.050)(52 + 273) = 16.25$ k J/mol

Basis: $\dfrac{235 \text{ m}^3}{\text{h}} \left| \dfrac{273 \text{ K}}{389 \text{ K}} \right. \left| \dfrac{1 \text{ kmol}}{22.4 \text{ m}^3(\text{STP})} \right. \left| \dfrac{10^3 \text{ mol}}{1 \text{ kmol}} \right. \left| \dfrac{1 \text{ h}}{3600 \text{ s}} \right. = 2.05$ mol/s

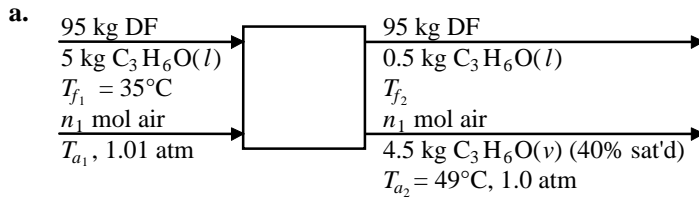<u>Neglect enthalpy change for the vapor transition from 116°C to 113°C.</u>

$C_5H_{12}O(v, 113° \text{ C}) \to C_5H_{12}O(l, 113° \text{ C}) \to C_5H_{12}O(v, 52° \text{ C})$

$\to C_5H_{12}O(s, 52° \text{ C}) \to C_5H_{12}O(s, 25° \text{ C})$

8.53 (cont'd)

$$\Delta\hat{H} = -\Delta\hat{H}_v + C_{pl}(52-113) - \Delta\hat{H}_m + C_{ps}(25-52)$$

$$= -42.1\,\frac{kJ}{mol} - 16.2\,\frac{kJ}{mol} - \left[(301)(61) + (170)(27)\right]\frac{J}{mol} \times \frac{1\,kJ}{10^3\,J} = -81.3\ kJ/mol$$

<u>Required heat transfer:</u> $Q = \Delta H = n\Delta\hat{H} = \dfrac{2.05\ mol}{s} \left| \dfrac{-81.3\ kJ}{mol} \right| \dfrac{1\ kW}{1\ kJ/s} = \underline{\underline{-167\ kW}}$

8.54

<u>Basis: 100 kg wet film</u> $\Rightarrow$ $\left.\begin{array}{l}\text{95 kg dry film}\\[4pt]\text{5 kg acetone}\end{array}\right\}$ $\xRightarrow{\text{90\% A evaporation}}$ $\begin{array}{l}\text{0.5 kg acetone remain in film}\\[4pt]\text{4.5 kg acetone exit in gas phase}\end{array}$

a.

$\begin{array}{l}\text{95 kg DF}\\ \text{5 kg } C_3H_6O(l)\\ T_{f_1} = 35°C\\ n_1 \text{ mol air}\\ T_{a_1},\ 1.01\ atm\end{array}$ $\begin{array}{l}\text{95 kg DF}\\ \text{0.5 kg } C_3H_6O(l)\\ T_{f_2}\\ n_1 \text{ mol air}\\ \text{4.5 kg } C_3H_6O(v)\ (40\%\ \text{sat'd})\\ T_{a_2} = 49°C,\ 1.0\ atm\end{array}$

<u>Antoine equation (Table B.4)</u> $\Rightarrow p^*_{C_3H_6O} = 591.18\ mm\ Hg$

$$\frac{4.5\ kg\ C_3H_6O}{}\left|\frac{1\ kmol}{58.08\ kg}\right|\frac{10^3\ mol}{kmol} = 77.5\ mol\ C_3H_6O(v)\ \text{in exit gas}$$

$$\Rightarrow y = \frac{77.5}{77.5 + n_1} = \frac{0.40(591.18\ mm\ Hg)}{760\ mm\ Hg} \Rightarrow n_1 = \frac{171.6\ mol}{}\left|\frac{22.4\ L(STP)}{mol}\right|\frac{}{95\ kg\ DF} = \underline{\underline{40.5\ \frac{L(STP)}{kg\ DF}}}$$

b.   <u>References:</u> $Air(25°C), C_3H_6O(l, 35°C),\ DF(35°C)$

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
DF	95	0	95	$1.33(T_{f2}-35)$	n in kg $\hat{H}$ in kJ/kg
$C_6H_{14}O(l)$	86.1	0	8.6	$0.129(T_{f2}-35)$	n in mol
$C_6H_{14}O(v)$	—	—	77.5	32.3	$\hat{H}$ in kJ/mol
Air	171.6	$\int_{25}^{T_{a1}}(C_p)_{air}\,dT$	171.6	0.70	

$$\hat{H}_{A(v)} = \int_{35}^{86}(C_p)_l\,dT + \Delta\hat{H}_v + \int_{86}^{49}(C_p)_v\,dT,\quad \hat{H}_{DF} = C_p(T-35)$$

<u>Energy balance</u>

$$\Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 126.4(T_{f2}-35) + 1.11(T_{f2}-35) + 2623.4 - 171.6\int_{25}^{T_{a1}}(C_p)_{air}\,dT = 0$$

$$\Rightarrow \underline{\underline{\int_{25}^{T_{a1}}(C_p)_{air}\,dT = \frac{127.5(T_{f2}-35) + 2623.4}{171.6}}}$$

c. $T_{a_1} = 120°C \Rightarrow \int_{25}^{T_{a1}}(C_p)_{air}\,dT = 2.78\ kJ/mol \Rightarrow (T_{f2}-35)\ °C = \underline{\underline{-16.8°C}}$

8.54 (cont'd)

d. $T_{f2} = 34°C \overset{T\&E}{\Rightarrow} \underline{\underline{T_{a_1} = 506°C}}$, $T_{f2} = 36°C \overset{T\&E}{\Rightarrow} \underline{\underline{T_{a1} = 552°C}}$

e.   In an adiabatic system, when a liquid evaporates, the temperature of the remaining condensed phase drops. In this problem, the heat transferred from the air goes to (1) vaporize 90% of the acetone in the feed; (2) raise the temperature of the remaining wet film above what it would be if the process were adiabatic. If the feed air temperature is above about 530 °C, enough heat is transferred to keep the film above its inlet temperature of 35 °C; otherwise, the film temperature drops.

8.55 $T_{set}(p = 200 \text{ psia}) \approx 100° F$ (Cox chart – Fig. 6.1-4)

a.   <u>Basis:</u> $\dfrac{3.00 \times 10^3 \text{ SCF}}{h} \left| \dfrac{1 \text{ lb - mole}}{359 \text{ SCF}} \right. = 8.357 \text{ lb} \cdot \text{mole/h } C_3H_8$
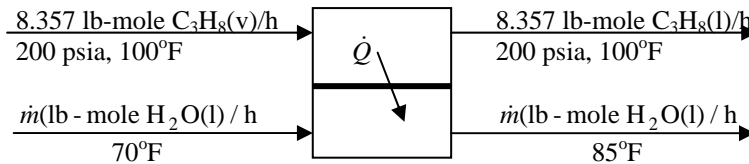
The outlet water temperature is <u>85°F</u>. It must be <u>less</u> than the outlet propane temperature; otherwise, heat would be transferred from the water to the propane near the outlet, causing vaporization rather than condensation of the propane.
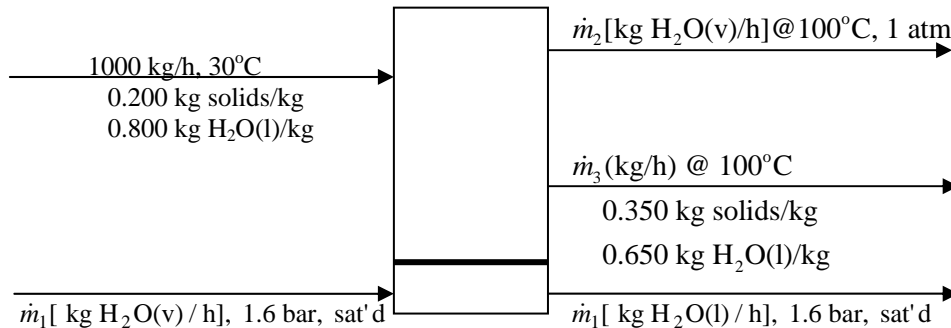
b.   <u>Energy balance on propane:</u>

$$\dot{Q} = \Delta\dot{H} = -\dot{n}\Delta\hat{H}_v = \dfrac{8.357 \text{ lb} - \text{moles}}{h} \left| \dfrac{-18.77 \text{ kJ}}{\text{mol}} \right| \dfrac{0.9486 \text{ Btu}}{\text{kJ}} \left| \dfrac{453.593 \text{ mol}}{1 \text{ lb} \cdot \text{mole}} \right. = -6.75 \times 10^4 \dfrac{\text{Btu}}{h}$$

(Table B.1 ↓)

<u>Energy balance on cooling water:</u> Assume no heat loss to surroundings.

$$\dot{Q} = \Delta\dot{H} = \dot{m}C_p\Delta T \Rightarrow \dot{m} = \dfrac{6.75 \times 10^4 \text{ Btu}}{h} \left| \dfrac{\text{lb}_m \cdot °F}{1.0 \text{ Btu}} \right| \dfrac{1}{15 \text{ °F}} = 4500 \dfrac{\text{lb}_m \text{ cooling water}}{h}$$

8.56

a.   <u>Solids balance:</u> $200 = 0.35m_3$ $\Rightarrow m_3 = 571.4$ kg/h slurry

<u>H_2O balance:</u> $800 = m_2 + 0.65(571.4)$ $\Rightarrow m_2 = 428.6$ kg/h $H_2O(v)$

**8.56 (cont'd)**

References: Solids (0.01°C), $H_2O\,(l, 0.01°C)$

Substance	$\dot{m}_{in}$	$\hat{H}_{in}$	$\dot{m}_{out}$	$\hat{H}_{out}$	
Solids	200	62.85	200	209.6	$\dot{m}(kg/h)$ $\hat{H}_{H_2O}$ from steam tables
$H_2O(l)$	800	125.7	571.4	419.1	$\hat{H}(kJ/kg)$
$H_2O(v)$	—	—	428.6	2676	
H_2O, 1.6 bar	$\dot{m}_1$	2696.2	$\dot{m}_1$	475.4	

E.B. $Q = \Delta H = \sum_{out}\dot{m}_i\hat{H}_i - \sum_{in}\dot{m}_i\hat{H}_i = 0 \Rightarrow 1.315\times10^6 - 2221\dot{m}_1 = 0 \Rightarrow \dot{m}_1 = \underline{\underline{592}}$ kg steam/h

b. $(592.0 - 428.6) = \underline{163}$ kg/h additional steam

c. The cost of compressing and reheating the steam vs. the cost of obtaining it externally.

8.57 Basis: 15,000 kg feed/h.   A = acetone, B = acetic acid, C = acetic anhydride
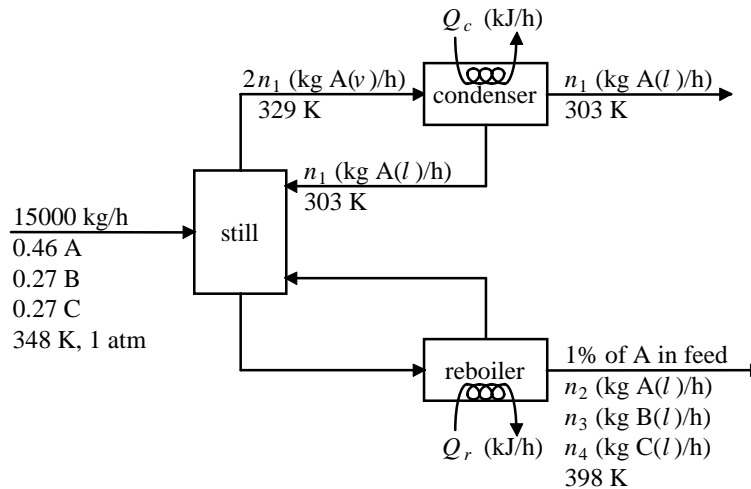
a. $\dot{n}_2 = (0.01)(0.46)(15,000 \text{ kg/h}) = \underline{69}$ kg A/h

Acetic acid balance: $\dot{n}_3 = (0.27)(15,000) = 4050$ kg B/h

Acetic anhydride balance: $\dot{n}_4 = (0.27)(15,000) = 4050$ kg/h

Acetone balance: $(0.46)(15,000) = n_1 + 69 \Rightarrow n_1 = 6831$ kg/h`
⇓
Distillate product: $\underline{6831}$ kg acetone/h

Bottoms product: $(69 + 4050 + 4050)$ kg/h $= \begin{matrix} 8169 \text{ kg/h} \\ 0.8\% \text{ acetone} \\ 49.6\% \text{ acetic acid} \\ 49.6\% \text{ acetic anhydride} \end{matrix}$

b. Energy balance on condenser

$$C_3H_6O(v, 329\ K) \rightarrow C_3H_6O(l, 329\ K) \rightarrow C_3H_6O(l, 303\ K)$$
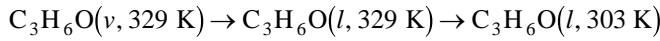
$$\Delta\hat{H} = -\Delta\hat{H}_v(329\ K) + \int_{329}^{303} C_{pl}dT = -520.6 + (2.3)(-26) = -580.4\ \ kJ/kg$$

$$\dot{Q}_c = \Delta\dot{H} = \dot{n}\Delta\hat{H} = \frac{(2\times 6831)kg}{h} \left| \frac{-580.4\ kJ}{kg} \right. = -7.93\times 10^6\ \ kJ/h$$

c. Overall process energy balance

Reference states: A(l), B(l), C(l) at 348 K (All $\hat{H}_m = 0$)

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
A $(l, 303\ K)$	—	0	6831	−103.5	$\dot{n}$ in kg/h
A $(l, 398\ K)$	—	0	69	115.0	$\hat{H}$ in kJ/kg
B $(l, 398\ K)$	—	0	4050	109.0	
C $(l, 398\ K)$	—	0	4050	113	

Acetic anhydride (l): $C_p \approx \left[(4\times 12) + (6\times 18) + (3\times 25)\right]\dfrac{J}{mol\cdot {}^\circ C} \left| \dfrac{1\ mol}{102.1\ g} \right| \dfrac{10^3\ g}{1\ kg} \left| \dfrac{1\ kJ}{10^3\ J} \right.$

$$= 2.3\ \ kJ/kg\cdot {}^\circ C$$

$$\hat{H}(T) = C_p(T - 348)\ \ \text{(all substances)}$$

$$\dot{Q} = \Delta\dot{H} \Rightarrow \dot{Q}_c + \dot{Q}_r = \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i \Rightarrow \dot{Q}_r = -\dot{Q}_c + \sum_{out}\dot{n}_i\hat{H}_i = \left(7.93\times 10^6 + 2.00\times 10^5\right)kJ/h$$

$$\uparrow = 0 \qquad\qquad\qquad = \underline{\underline{8.13\times 10^6\ \ kJ/h}}$$
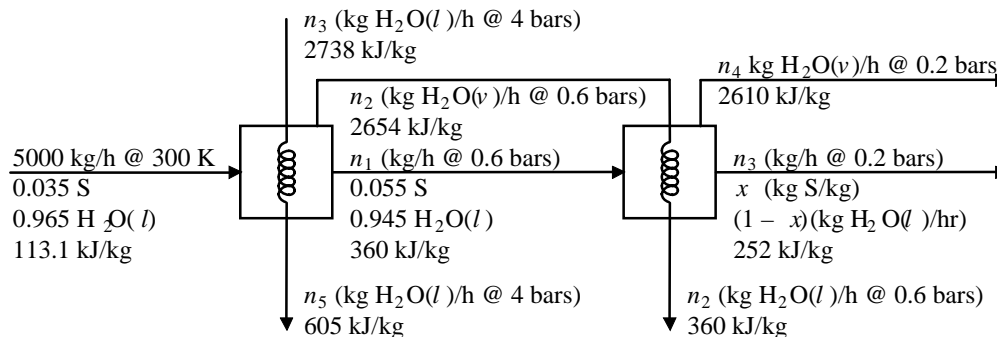
(We have neglected heat losses from the still.)

d. H_2O (saturated at ≈ 11 bars): $\Delta\hat{H}_v = 1999\ \ kJ/kg$ (Table 8.6)

$$\dot{Q}_r = \dot{n}_{H_2O}\Delta\hat{H}_v \Rightarrow \dot{n}_{H_2O} = \frac{8.13\times 10^6\ \ kJ/h}{1999\ \ kJ/kg} = \underline{\underline{4070\ \ kg\ steam/h}}$$

8.58 Basis: 5000 kg seawater/h

a. S = Salt

b. S balance on 1st effect: $(0.035)(5000) = 0.055\dot{n}_1 \Rightarrow \dot{n}_1 = 3182\ \ kg/h$

Mass balance on 1st effect: $5000 = 3182 + \dot{n}_2 \Rightarrow \dot{n}_2 = 1818\ \ kg/h$

8.58 (cont'd)

Energy balance on 1st effect:

$$\Delta \dot{H} = 0 \Rightarrow (\dot{n}_2)(2654) + (\dot{n}_1)(360) + (\dot{n}_5)(605 - 2738) - (5000)(113.1) = 0$$

$$\underset{\substack{\dot{n}_1 = 3182 \\ \dot{n}_2 = 1818}}{\Longrightarrow} \dot{n}_5 = 2534 \text{ kg } H_2O(v)/h$$

c. Mass balance on 2nd effect: $3182 = \dot{n}_3 + \dot{n}_4$ (1)

Energy balance on 2nd effect: $(\Delta H = 0)$

$$(n_4)(2610) + (n_3)(252) + (n_2)(360 - 2654) - (n_1)(360) = 0$$
$$\Downarrow n_1 = 3182, n_2 = 1818$$
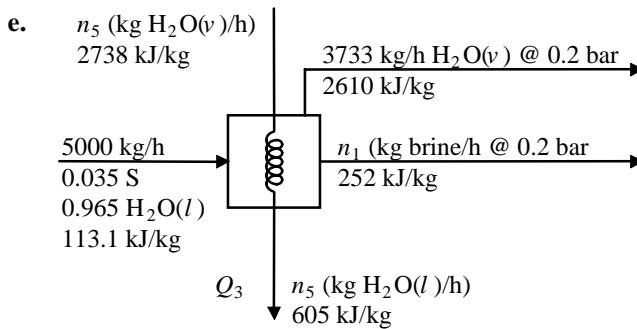$$5.316 \times 10^6 = 252n_3 + 2610n_4 \qquad (2)$$

Solve (1) and (2) simultaneously:

$$\dot{n}_3 = 1267 \text{ kg/h brine solution}$$

$$\dot{n}_4 = 1915 \text{ kg/h } H_2O(v)$$

Production rate of fresh water $= \dot{n}_2 + \dot{n}_4 = (1818 + 1915) = 3733 \text{ kg/h fresh water}$

Overall S balance: $(0.035)(5000) = 1267x \Rightarrow x = 0.138 \text{ kg salt/kg}$

d. The entering steam must be at a higher temperature (and hence a higher saturation pressure) than that of the liquid to be vaporized for the required heat transfer to take place.

e.
n_5 (kg $H_2O(v)$/h)
2738 kJ/kg

3733 kg/h $H_2O(v)$ @ 0.2 bar
2610 kJ/kg

5000 kg/h
0.035 S
0.965 $H_2O(l)$
113.1 kJ/kg

n_1 (kg brine/h @ 0.2 bar
252 kJ/kg

Q_3 | n_5 (kg $H_2O(l)$/h)
605 kJ/kg

Mass balance: $5000 = 3733 + \dot{n}_1 \Rightarrow \dot{n}_1 = 1267 \text{ kg/h}$

Energy balance: $(\Delta \dot{H} = 0)$

$$(3733)(2610) + (1267)(252) + \dot{n}_5(605 - 2738) - (5000)(113.1) = 0$$
$$\Rightarrow \dot{n}_5 = 4452 \text{ kg } H_2O(v)/h$$

Which costs more: the additional 1918 kg/hr fresh steam required for the single-stage process, or the construction and maintenance of the second effect?

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:

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

Energy balance on i^{th} effect:

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

$$\Rightarrow (\dot{n}_v)_{L-1} = \frac{\dot{n}_{vi}\hat{H}_{vi} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{i+1}(\hat{H}_L)_{i+1}}{(\hat{H}_v)_{i-1} - (\hat{H}_L)_{L-1}} \tag{2}$$
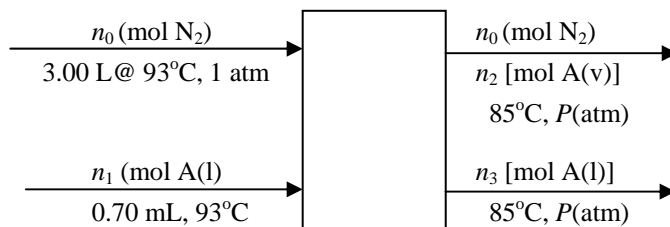
Mass balance on $(i-1)^{\text{th}}$ effect:

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

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	---

8.60 **a.** $\left(C_p\right)_v = \left(C_p\right)_l = \underline{\underline{20\ \text{cal}/(\text{mol}\cdot{}^\circ\text{C})}}$; $\left(C_v\right)_v \approx \left(C_p\right)_v - R \approx (10-2)\dfrac{\text{cal}}{\text{mol}\cdot{}^\circ\text{C}} = \underline{\underline{8\ \text{cal}/(\text{mol}\cdot{}^\circ\text{C})}}$

b.

$$n_0 = \frac{3.00\ \text{L}}{} \left|\frac{273\ \text{K}}{(273+93)\text{K}}\right| \frac{1\ \text{mol}}{22.4\ \text{L(STP)}} = 0.100\ \text{mol N}_2$$

$$n_1 = \frac{70.0\ \text{mL}}{} \left|\frac{0.90\ \text{g}}{\text{mL}}\right| \frac{1\ \text{mol}}{42\ \text{g}} = 1.5\ \text{mol }A(l)$$

Energy balance $\Rightarrow \Delta U = 0 \Rightarrow \underbrace{\sum n_i \hat{U}_i}_{\text{out}} - \underbrace{\sum n_i \hat{U}_i}_{\text{in}} = 0$

c. References: $N_2(g)$, $A(l)(85^\circ\text{C},\ 1\ \text{atm})$

Substance	n_{in}	$\hat{U}_{in}$	n_{out}	$\hat{U}_{out}$	
N_2	0.10	39.8	0.10	0	n in mol
$A(l)$	1.5	160	n_3	0	$\hat{U}$ in cal/mol
$A(v)$	–	–	n_2	20050	

$A(l,\ 93^\circ\text{C})$ and $N_2(g,\ 93^\circ\text{C})$: $\hat{U} = C_v(93-85)$

$A(v,\ 85^\circ\text{C})$: $\hat{U}_{A(v)} = 20(90-85)+20{,}000+10(85-90) = 20050\ \text{cal/mol}$

$\Delta U = 0 \Rightarrow n_{v1}(20050) - (0.10)(39.8) - (1.5)(160) = 0 \Rightarrow n_{v1} = 0.012\ \text{mol }A$ evaporate

$$\Rightarrow \frac{0.012\ \text{mol }A}{} \left|\frac{42\ \text{g }A}{\text{mol }A}\right. = \underline{\underline{0.51\ \text{g evaporate}}}$$

d. Ideal gas equation of state

$$P = \frac{(n_0 + n_2)RT}{V} = \frac{0.112\ \text{mol}}{3.00\ \text{liters}} \left|\frac{(273+85)\text{K}}{}\right| \frac{0.08206\ \text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} = 1.097\ \text{atm}$$

Raoult's law

$$p_A^*(85^\circ\text{C}) = y_A P = \frac{n_2}{n_0 + n_2}P = \frac{0.012\ \text{mol}}{0.112\ \text{mol}}\left|\frac{1.097\ \text{atm}}{}\right. = \underline{\underline{0.117\ \text{atm}}}\quad (=89.3\ \text{mmHg})$$

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

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

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

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

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

$\underline{\text{Energy balance}}$: The data show that C_v is independent of temperature

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

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

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

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

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

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

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

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

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

$\underline{\text{Vapor}}$: 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) $\underline{\text{Expt. 3}} \Rightarrow \quad T = 315K, \; p^* = (763 - 564)\text{mm Hg} = 199 \text{ mm Hg}$

$T = 334K, \; p^* = 401 \text{ mm Hg}$

$T = 354K, \; p^* = 761 \text{ mm Hg}$

$T = 379K, \; p^* = 1521 \text{ mm Hg}$

8.61 (cont'd)

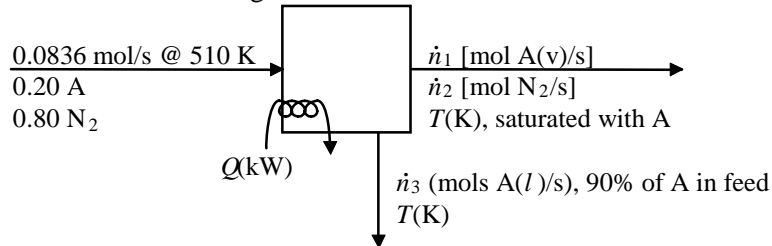Plot p^* (log scale) vs. $1/T$ (linear scale); straight line fit yields

$$\ln p^* = \frac{-3770}{T(\text{K})} + 17.28 \quad \text{or} \quad p^* = 3.196 \times 10^7 \exp(-3770/T)$$

vi) $p^* = 760$ mm Hg $\underset{\underset{\text{Part v}}{\uparrow}}{\Rightarrow} \dfrac{1}{T_b} = \dfrac{17.28 - \ln(760)}{3770} = 2.824 \times 10^{-3}\,\text{K}^{-1} \Rightarrow \underline{\underline{T_b = 354\text{ K}}}$

vii) $\dfrac{\Delta \hat{H}_v}{R} \underset{\underset{\text{Part v}}{\uparrow}}{=} 3770(\text{K}) \Rightarrow \Delta \hat{H}_v = (3770\text{ K})(8.314\text{ J/mol}\cdot\text{K}) \Rightarrow \underline{\underline{\Delta \hat{H}_v = 31{,}300\text{ J/mol}}}$

(b) <u>Basis:</u> $\dfrac{3.5\text{ L feed}}{\text{s}}\left|\dfrac{273\text{ K}}{510\text{ K}}\right|\dfrac{1\text{ mol}}{22.4l(\text{STP})} = 0.0836$ mol/s feed gas

Let A denote the drug

$$\begin{array}{l}
\text{0.0836 mol/s @ 510 K} \\
\text{0.20 A} \\
\text{0.80 N}_2
\end{array}
\longrightarrow
\boxed{}
\longrightarrow
\begin{array}{l}
\dot{n}_1 \text{ [mol A(v)/s]} \\
\dot{n}_2 \text{ [mol N}_2\text{/s]} \\
T(\text{K}), \text{ saturated with A}
\end{array}$$

$$Q(\text{kW}) \downarrow \qquad \begin{array}{l} \dot{n}_3 \text{ (mols A(l)/s), 90\% of A in feed} \\ T(\text{K}) \end{array}$$

<u>N$_2$ balance:</u> $\dot{n}_2 = (0.800)(0.0836\text{ mol/s}) = 0.0669$ mol N$_2$/s

<u>90% condensation:</u> $\dot{n}_3 = (0.900)(0.200 \times 0.0836) = 0.01505$ mol $A(l)$/s

$$\dot{n}_1 = (0.100)(0.200 \times 0.0836) = 1.67 \times 10^{-3}\text{ mol }A(v)/\text{s}$$

<u>Partial pressure of A in outlet gas:</u>

$$p_A = \frac{\dot{n}_1}{(\dot{n}_1 + \dot{n}_2)}P = \frac{1.67 \times 10^{-3}\text{ mol}}{0.0686\text{ mol}}(760\text{ mm Hg}) = 18.5\text{ mm Hg} = p_A^*(T)$$

$$\Downarrow \text{ Part (a) - (v)}$$

$$\frac{1}{T} = \frac{17.28 - \ln(18.5)}{3770} = 3.81 \times 10^{-3}\,\text{K}^{-1}$$

$$\Downarrow$$

$$T = 262\text{ K}$$

(c) <u>Reference states:</u> N$_2$, $A(l)$ at 262 K

substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
N$_2$	0.0669	7286	0.0669	0	$\dot{n}$ in mol/s
$A(v)$	0.0167	37575	1.67×10^{-3}	31686	$\hat{H}$ in J/mol
$A(l)$	–	–	0.01505	0	

8.61 (cont'd)

$\underline{N_2(510\ K)}$: $\hat{H}_{N_2}(510K) - \hat{H}_{N_2}(262K) = \hat{H}_{N_2}(237^{\circ}C) - \hat{H}_{N_2}(-11^{\circ}C)$

$\underset{\downarrow}{\text{Table B.8}}$

$\quad = \quad [6.24 - (-1.05)]\ kJ\,/\,mol = 7.286\ kJ\,/\,mol = 7286\ J\,/\,mol$

$\underline{A(v,\,262K)}:$ $\hat{H} = C_{pl}(T_b - 262) + \Delta\hat{H}_v(359K) + \int_{T_b}^{262} C_{pv}dT$

$\qquad\qquad\Big\|$ Part (a) results for T_b, C_{pl}, C_{pv}, $\Delta\hat{H}_v$

$\qquad\qquad\hat{H} = 24(354 - 262) + 31300 + \left[4.245 + 0.05052\dfrac{T^2}{2}\right]_{354}^{262} = 31686\ J/mol$

$\underline{A(v,\,510K)}:$ $\hat{H} = C_{pl}(T_b - 262) + \Delta\hat{H}_v(354K) + \int_{T_b}^{510} C_{pv}dT = 37575\ J/mol$

$\qquad\underline{\text{Energy balance:}}\ \dot{Q} = \Delta\dot{H} = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = \dfrac{-1060\ J/s}{}\left|\dfrac{1\ kW\ cooling}{-10^3\ kJ/s}\right. = \underline{\underline{1.06\ kW}}$

8.62 a. <u>Basis: 50 kg wet steaks/min</u>
D.M. = dry meat

50 kg/min @ –26°C
0.72 H$_2$O(s)
0.28 D.M.

m_1(kg H$_2$O(v)/min)(96% of H$_2$O in feed)
60°C

m_2(kg D.M./min)
m_3(kg H$_2$O(l)/min)
50°C

Q(kW)
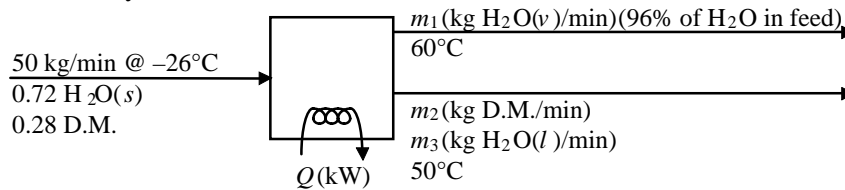
<u>96% vaporization:</u>
$\dot{m}_1 = 0.96(0.72 \times 50\ kg/min) = 34.56\ kg\ H_2O(v)/min$
$\dot{m}_3 = 0.04(0.72 \times 50\ kg/min) = 1.44\ kg\ H_2O(l)/min$
<u>Dry meat balance:</u>
$\dot{m}_2 = (0.28)(50) = 14.0\ kg\ D.M./min$

<u>Reference states:</u> Dry meat at $-26^{\circ}C$, H$_2$O$(l,\ 0^{\circ}C)$

substance	$\dot{m}_{in}$	$\hat{H}_{in}$	$\dot{m}_{out}$	$\hat{H}_{out}$	
dry meat	14.0	0	14.0	105	$\dot{m}$ in kg/min
H$_2$O(s, -26°C)	36.0	–390	–	–	$\hat{H}$ in kJ/kg
H$_2$O(l, 50°C)	–	–	1.44	209	
H$_2$O(v, 60°C)	–	–	34.56	2599	

<u>Dry meat:</u> $\hat{H}(50^{\circ}C) = C_p[50 - (-26)] = \dfrac{1.38\ kJ}{kg\cdot C^{\circ}}\left|\dfrac{76^{\circ}C}{}\right. = 105\ kJ/kg$

$\underline{H_2O(s,\ -26^{\circ}C)}:\ H_2O(l,\ 0^{\circ}C) \rightarrow H_2O(s,\ 0^{\circ}C) \rightarrow H_2O(s,\ -26^{\circ}C)$

8.62 (cont'd)

$$\Delta\hat{H} = -\Delta\hat{H}_m(0°C) + \int_0^{-26} \hat{C}_p dT = \frac{-6.01 \text{ kJ}}{\underset{\underset{\text{Table B.1}}{\uparrow}}{\text{mol}}} \left| \frac{1 \text{ mol}}{18.02 \text{ g}} \right| \frac{10^3 \text{ g}}{1 \text{ kg}} + \frac{2.17 \text{ kJ}}{\text{kg·°C}} \left| \frac{-26°C}{} \right. = -390 \text{ kJ/kg}$$

$\underline{H_2O(l, 50°C)}$: $H_2O(l, 0°C) \rightarrow H_2O(l, 50°C)$

$$\Delta\hat{H} = \int_0^{50} C_p dT = \frac{0.0754 \text{ kJ}}{\underset{\underset{\text{Table B.2}}{\uparrow}}{\text{mol °C}}} \left| \frac{(50-0)°C}{} \right| \frac{1 \text{ mol}}{18.02 \text{ g}} \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right. = 209 \text{ kJ/kg}$$

$\underline{H_2O(v, \ 60°C)}$: $H_2O(l, \ 0°C) \rightarrow H_2O(l, \ 100°C) \rightarrow H_2O(v, \ 100°C) \rightarrow H_2O(v, \ 60°C)$

$$\Delta\hat{H} = \frac{0.0754 \text{ kJ}}{\underset{\underset{\text{Table B.2}}{\uparrow}}{\text{mol·°C}}} \left| \frac{(100-0)°C}{} \right. + 40.656 \underset{\underset{\text{Table B.1} (\Delta\hat{H}_v)}{\uparrow}}{\frac{\text{kJ}}{\text{mol}}} + \int_{100}^{60} (C_p)_{\underset{\underset{\text{Table B.2}}{\uparrow}}{H_2O(v)}} dT$$

$$= \frac{46.830 \text{ kJ}}{\text{mol}} \left| \frac{1 \text{ mol}}{18.02 \text{ g}} \right| \frac{1000 \text{ g}}{1 \text{ kg}} = 2599 \text{ kJ/kg}$$

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} m_i \hat{H}_i - \sum_{\text{in}} m_i \hat{H}_i = \frac{1.06 \times 10^5 \text{ kJ}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{1760 \text{ kW}}}$$

8.63 <u>Basis:</u> 20,000 kg/h ice crystallized. S = solids in juice. W = water
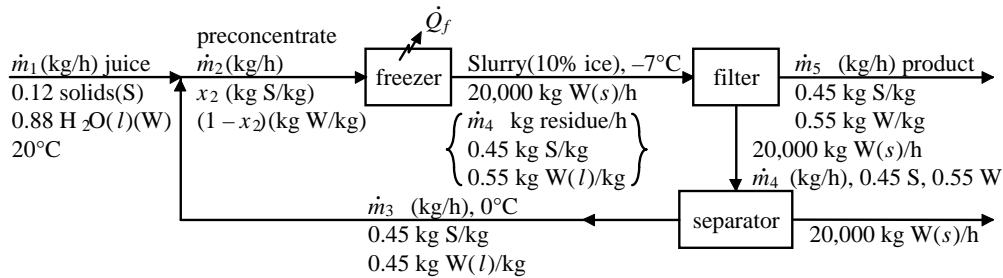
(a) <u>10% ice in slurry</u> $\Rightarrow \dfrac{20000}{\dot{m}_4} = \dfrac{10}{90} \Rightarrow \dot{m}_4 = 180000$ kg/h concentrate leaving freezer

$\left. \begin{array}{l} \underline{\text{Overall S balance:}} \ 0.12\dot{m}_1 = 0.45\dot{m}_5 \\ \underline{\text{Overall mass balance:}} \ \dot{m}_1 = \dot{m}_5 + 20000 \end{array} \right\} \Rightarrow \begin{array}{l} \dot{m}_1 = \underline{27273} \text{ kg/h feed} \\ \dot{m}_5 = \overline{\underline{7273}} \text{ kg/h concentrate product} \end{array}$

<u>Mass balance on filter:</u> $20000 + \dot{m}_4 + \dot{m}_5 + 20000 + \dot{m}_6 \underset{\underset{\dot{m}_5 = 7273}{\dot{m}_4 = 180000}}{\Rightarrow} \dot{m}_6 = 172730$ kg/h recycle

<u>Mass balance on mixing point:</u>

$27273 + 172730 = \dot{m}_2 \Rightarrow \dot{m}_2 = \underline{\underline{2.000 \times 10^5}}$ kg/h preconcentrate

8.63 (Cont'd)

S balance on mixing point:

$$(0.12)(27273) + (0.45)(172730) = 2.000 \times 10^5 \, X_2 \Rightarrow X_2 \cdot 100\% = \underline{40.5\% \text{ S}}$$

(b) Draw system boundary for every balance to enclose freezer and mixing point (Inputs: fresh feed and recycle streams; output; slurry leaving freezer)

Refs: S, $H_2O(l)$ at $-7°C$

substance	$\dot{m}_{in}$	$\hat{H}_{in}$	$\dot{m}_{out}$	$\hat{H}_{out}$	
12% soln	27273	108	–	–	$\dot{m}(kg/h)$
45% soln	172730	28	180000	0	$\hat{H}(kJ/kg)$
$H_2O(s)$	–	–	20000	–337	

Solutions: $\hat{H}(T) = 4.00[T - (-7)]$ kJ/kg

Ice: $\hat{H} = -\Delta\hat{H}_m(-T°C) \approx -\Delta\hat{H}_m(0°C)$

$\quad = -6.0095$ kJ/mol $\Rightarrow -337$ kJ/kg

$\quad \Uparrow$ Table B.1

E.B. $\dot{Q}_c = \Delta\dot{H} = \sum_{out} \dot{m}_i \hat{H}_i - \sum_{in} \dot{m}_i \hat{H}_i = \dfrac{-1.452 \times 10^7 \text{ kJ}}{\text{h}} \left| \dfrac{1 \text{ h}}{3600 \text{ s}} \right| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-4030 \text{ kW}}}$

8.64 a. B=n-butane, I=iso-butane, hf=heating fluid. $(C_p)_{hf} = 2.62$ kJ $/ (kg·°C)$
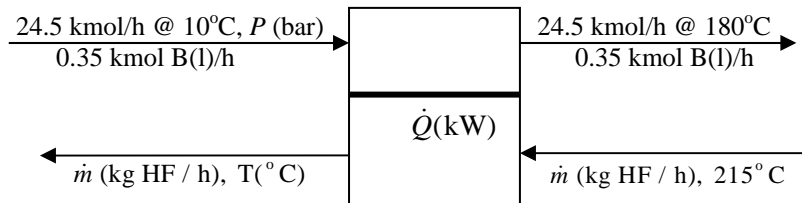
From the Cox chart (Figure 6.1-4)

$p_B^*(10°C) = 22$ psi, $p_I^*(10°C) = 32$ psi

$P_{min} = p_B + p_I = x_B p_B^* + x_I p_I^* = 28.5 \text{ psi}\left(\dfrac{1.01325 \text{ bar}}{14.696 \text{ psi}}\right) = \underline{\underline{1.96 \text{ bar}}}$

b.

$B\left(l, \, 10°C\right) \xrightarrow{\Delta\hat{H}_v} B\left(v, \, 10°C\right) \xrightarrow{\Delta\hat{H}_1} B\left(v, \, 180°C\right)$

$I\left(l, \, 10°C\right) \xrightarrow{\Delta\hat{H}_v} I\left(v, \, 10°C\right) \xrightarrow{\Delta\hat{H}_2} I\left(v, \, 180°C\right)$

Assume temperature remains constant during vaporization.
Assume mixture vaporizes at $10°C$ i.e. won't vaporize at respective boiling points as a pure component.

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

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

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

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

$$\underline{\Delta\dot{H} = 1.015 \times 10^6 \text{ kJ / h}}$$

c. $\quad Q = 1.015 \times 10^6 \text{ kJ / h} = \dot{m}_{hf}\left[2.62 \text{ kJ / }\left(\text{kg·}^\circ\text{C}\right)\right]\left[(215-45)^\circ\text{C}\right]$

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

d. $\quad (2540 \text{ kg / h})\left[2.62 \text{ kJ / }\left(\text{kg·}^\circ\text{C}\right)\right]\left[(215-45)^\circ\text{C}\right] = 1.131 \times 10^6 \text{ kJ / h}$

$\quad$ Heat transfer rate $= 1.131 \times 10^6 - 1.015 \times 10^6 = \underline{\underline{1.16 \times 10^5 \text{ kJ / h}}}$

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, $SG_{Benzene}=0.879$: $SG_{Toluene}=0.866$

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

$$V_{total} = \frac{50 \text{ g}}{0.879 \text{ g / cm}^3} + \frac{50 \text{ g}}{0.866 \text{ g / cm}^3} = 114.6 \text{ cm}^3$$

$$\left(x_f\right)_{C_6H_6} = \frac{0.640 \text{ mol C}_6\text{H}_6}{1.183 \text{ mol}} = \underline{\underline{0.541 \text{ mol C}_6\text{H}_6/\text{mol}}}$$

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

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

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

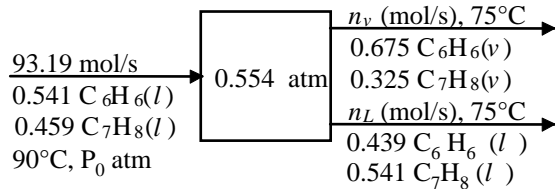$\qquad\qquad = \dfrac{739.2 \text{ mmHg}}{}\left|\dfrac{1 \text{ atm}}{760 \text{ mmHg}}\right. = 0.973 \text{ atm} \Rightarrow \underline{\underline{P_0 > 0.973 \text{ atm}}}$

8.65 (cont'd)

(b) $T = 75°C \Rightarrow p^*_{C_6H_6} = 648$ mm Hg, $p^*_{C_7H_8} = 244$ mm Hg (from Table 6.1-1)

<u>Raoult's law</u> $\Rightarrow p_{tank} = x_{C_6H_6} p^*_{C_6H_6} + x_{C_7H_8} p^*_{C_7H_8} = (0.439)(648) + (0.561)(244)$

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

$$y_{C_6H_6} = \frac{284 \text{ mm Hg}}{421 \text{ mm Hg}} = \underline{\underline{0.675 \text{ mol } C_6H_6(v)/\text{mol}}}$$

$$
\begin{array}{ccc}
 & & n_v \text{ (mol/s), } 75°C \\
 & & 0.675 \text{ } C_6H_6(v) \\
\text{93.19 mol/s} & \boxed{0.554 \text{ atm}} & 0.325 \text{ } C_7H_8(v) \\
0.541 \text{ } C_6H_6(l) & & n_L \text{ (mol/s), } 75°C \\
0.459 \text{ } C_7H_8(l) & & 0.439 \text{ } C_6H_6 \text{ } (l) \\
90°C, P_0 \text{ atm} & & 0.541 \text{ } C_7H_8 \text{ } (l)
\end{array}
$$

<u>Mole balance:</u> $93.19 = n_v + n_L$

C_6H_6 balance: $(0.541)(93.19) = 0.675 n_v + 0.439 n_L$ $\left. \right\} \Rightarrow \begin{array}{l} \underline{\underline{n_v = 40.27 \text{ mol vapor/s}}} \\ \underline{\underline{n_L = 52.92 \text{ mol liquid/s}}} \end{array}$

(c) <u>Reference states:</u> $C_6H_6(l)$, $C_6H_6(l)$ at $75°C$

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
$C_6H_6(v)$	–	–	27.18	31.0	$\dot{n}$ in mol/s
$C_6H_6(l)$	50.41	2.16	23.23	0	$\hat{H}$ in kJ/mol
$C_7H_8(v)$	–	–	13.09	35.3	
$C_7H_8(l)$	42.78	2.64	29.69	0	

$\underline{C_6H_6(l, \, 90°C)}$: $\hat{H} = (0.144)(90 - 75) = 2.16$ kJ/mol

$\underline{C_7H_8(l, \, 90°C)}$: $\hat{H} = (0.176)(90 - 75) = 2.64$ kJ/mol

$\underline{C_6H_6(v, \, 75°C)}$: $\hat{H} = (0.144)(80.1 - 75) + \underset{\underset{\Delta\hat{H}_v(80.1°C)}{\uparrow}}{30.77} + \int_{80.1}^{75} [0.074 + 0.330 \times 10^{-3} T] dT$

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

$\underline{C_7H_8(v, \, 75°C)}$: $\hat{H} = (0.176)(110.6 - 75) + 33.47 + \int_{110.6}^{75} [0.0942 + 0.380 \times 10^{-3} T] dT$

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

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

(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 $T > T_{ambient}$. If insufficient heat is provided to the vessel, the temperature drops. To run the experiment isothermally, a greater heating rate is required.

8.66 a. <u>Basis: 1 mol feed/s</u>
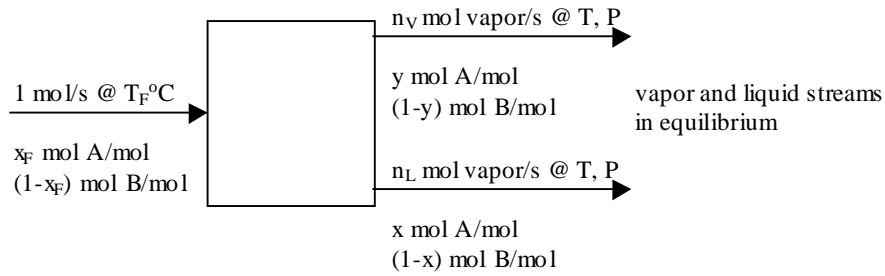
<u>Raoult's law</u> $\Rightarrow x \cdot p_A^*(T) + (1-x) \cdot p_B^*(T) = P \Rightarrow x = \dfrac{P - p_B^*(T)}{p_A^*(T) - p_B^*(T)}$ **(1)**

$p_A = y \cdot P = x \cdot p_A^*(T) \Rightarrow y = \dfrac{x \cdot p_A^*(T)}{P}$ **(2)**

<u>Mole balance:</u> $1 = \dot{n}_L + \dot{n}_V \Rightarrow \dot{n}_V = 1 - \dot{n}_L$ **(4)**

<u>A balance:</u> $(x_F)(1) = y \cdot \dot{n}_V + x \cdot \dot{n}_L \xrightarrow{\text{Substitute for } n_v \text{ from (4)}} \dot{n}_L = \dfrac{y - x_F}{y - x}$ **(3)**

<u>Energy balance:</u> $\Delta \dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 0$ **(5)**

b.

ref(deg.C) = 25								
Compound	A	B	C	al	av	bv	Tbp	DHv
n-pentane	6.84471	1060.793	231.541	0.195	0.115	3.41E-04	36.07	25.77
n-hexane	6.88555	1175.817	224.867	0.216	0.137	4.09E-04	68.74	28.85
xF	0.5	0.5	0.5					
Tf(deg.C)	110	110	150					
P(mm Hg)	760	1000	1000					
HAF(kJ/mol)	16.6	16.6	24.4					
HBF(kJ/mol)	18.4	18.4	27.0					
T(deg.C)	**51.8**	**60.0**	**62.3**					
pA*(mm Hg)	1262	1609	1714					
pB*(mm Hg)	432	573	617					
x	0.395	0.412	0.349					
y	0.656	0.663	0.598					
nL(mol/s)	0.598	0.648	0.394					
nV(mol/s)	0.402	0.352	0.606					
HAL(kJ/mol)	5.2	6.8	7.3					
HBL(kJ/mol)	5.8	7.6	8.0					
HAV(kJ/mol)	31.4	32.5	32.8					
HBV(kJ/mol)	42.4	43.7	44.1					
DH(kJ/s)	0.00	0.00	0.00					

```
C*      PROGRAM FOR PROBLEM 8.66
        IMPLICIT REAL (N)
        READ (5, 1) A1, B1, C1, A2, B2, C2
C*      ANTOINE EQUATION COEFFICIENTS FOR A AND B

  1     FORMAT (8F10.4)
        READ (5, 1) TRA, TRB
C*      ARBITRARY REFERENCE TEMPERATURES (DEG.C.) FOR A AND B
        READ (5, 1) CAL, TBPA, DHVA, CAV1, CAV2
        READ (5, 1) CBL, TBPB, DHVB, CBV1, CBV2
C*      CP(LIQ, KS/MBL-DEG.C.), NORMAL BOILING POINT (DEG.C), HEAT
            OF
        VAPORIZATION
C*      (KJ/MOL), COEFFICIENTS OF CP(VAP., KJ/MOL-DEG.C) = CV1 +
            CV2*T(DEG.C)
        READ (5, 1) XF, TF, P
C*      MOLE FRACTION OF A IN FEED, FEED TEMP.(DEG.C), EVAPORATOR
        PRESSURE (MMHG)
        WRITE (6, 2) TF, XF, P
  2     FORMAT (1H0, 'FEEDbATb', F6.1, 'bDEG.CbCONTAINSb', F6.3,'
        bMOLESbA/MOLEbT
        *OTAL'//1X'EVAPORATORbPRESSUREb=', E11.4, 'bMMbHG'/)

        ITER = 0
        DT = 0.5
        HAF = CAL*(TF – TRA)
        HBF = CBL*(TF – TRB)
        F1 = XF*HAF + (1.0 – XF)*HBF
        F2 = CAL*(TBPA – TRA) + DHVA – CAV1*TBPA – 0.5*CAV2*TBPA**2
        F3 = CBL*(TBPB – TRB) + DHVB – CBV1*TBPB – 0.5*CBV2*TBPB**2
        T = TF
 20     INTER = ITER + 1
        IF(ITER – 200) 30, 30, 25
 25     WRITE (6, 3)
  3     FORMAT (1H0, 'NO CONVERGENCE')
        STOP
 30     PAV = 10.0** (A1 – B1/(T + C1))
        PAV = 10.0** (A2 – B2/(T + C2))
        XL = (P – PBV)/(PAV – PBV)
        XV = XL*PAV/P
        NL = (XV – XF)/(XV – XL)
        NV = 1.0 – NL
        IF (XL.LE.00.OR.XL.GE.1.0.OR.NL.LE.0.0.OR.NL.GE.1.0) GO TO 45
        HAL = CAL*(T – TRA)
        HBL = CBL*(T – TRB)
        HAV = F2 + CAV1*T + 0.5*CAV2*T**2
        HBV = F3 + CBV1*T + 0.5*CBV2*T**2
```

8.66(cont'd)

```
        DELH = NL *(XL*HAL + (1.0 – XL)*HBL) + NV*(XV*HAV + (1.0 –
            XV)*HBV) – F1
        WRITE (6, 4) T, NL, NV, DELH
  4     FORMAT (1Hb, 5X' Tb=', F6.1, 3X' NLb=', F7.4, 3X' NVb=', F7.4, 3X'DELHb
            =',* E11.4)
        WRITE (6, 5) PAV, PBV, XL, HAL, HBL, XV, HAV, HBV
  5     FORMAT (1Hb, 5X' PAV, PBVb=', 2F8.1, 3X' XL, HAL, HBLb=', F7.4,
            2E13.4,3X' XV, HAV, HBVb=', F7.4, 2E13.4/)
        IF (DELH) 50, 50, 40
 40     DHOLD = DELH
        TOLD = T
 45     T = T – DT
        GO TO 20
 50     T = (T*DHOLD – TOLD*DELH)/(DHOLD – DELH)
        PAV = 10.0**(A1 – B1/(T + C1))
        PBV = 10.0**(A2 – B2/(T + C2))
        XL = (P – PBV)/(PAV – PBV)
        XV = XL * PAV/P
        NL = (XV – XF)/(XV – XL)
        NV = 1.0 – NL
        WRITE (6, 6) T, NL, XL, NV, XV
  6     FORMAT (1H0, 'PROCEDUREbCONVERGED'//3X'EVAPORATORb
        TEMPERATUREb=', F6.
        *1//3X' LIQUIDbPRODUCTb--', F6.3, 'bMOLEbCONTAININGb', F6.3,
            'bMOLEbA/
        *MOLEbTOTAL'//3X' VAPORbPRODUCTb--', F6.3,
            MOLEbCONTAININGb,' F6.3,
        *'bMOLEbA/MOLEb TOTAL')
        STOP
        END
```
$DATA (Fields of 10 Columns)

Solution:

$$T_{\text{evaportor}} = 52.2°\text{C}$$

$$n_L = 0.552 \text{ mol}, \left(x_{C_5H_{12}}\right)_{\text{liquid}} = 0.383 \text{ mol } C_5H_{12}/\text{mol liquid}$$

$$n_v = 0.448 \text{ mol}, \left(x_{C_5H_{12}}\right)_{\text{vapor}} = 0.644 \text{ mol } C_5H_{12}/\text{mol liquid}$$

8.67 <u>Basis:</u> $\dfrac{2500 \text{ kmol product}}{\text{h}} \Bigg| \dfrac{1 \text{ kmol condensate}}{.25 \text{ kmol product}} = 10{,}000 \text{ kmol/h fed to condenser}$

$\dot{m}_1 , \text{ (kg/h) at } T_1$

1090 kmol/h $C_3H_8(v)$ P (mm Hg)   1090 kmol/h $C_3H_8(l)$
7520 kmol/h i-$C_4H_{10}(v)$ 7520 kmol/h i-$C_4H_{10}(l)$
1390 kmol/h n-$C_4H_{10}(v)$ 1390 kmol/h n-$C_4H_{10}(l)$
saturated vapor at T_f, P T_{out}

$\dot{m}_1$ (kg/h) at T_2
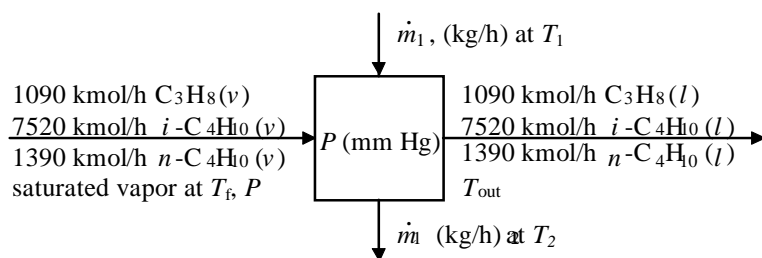
(a) <u>Refrigerant:</u> $T_{out} = 0^o C$, $T_1 = T_2 = -6^o C$.

Antoine constants	A	B	C
C_3H_8	7.58163	1133.65	283.26
$i - C_4H_{10}$	6.78866	899.617	241.942
$n - C_4H_{10}$	6.82485	943.453	239.711

<u>Calculate P for $T_{out} = T_{\text{bubble pt.}}$</u>

$$P = \sum_i x_i p_i^* (0°C) = 0.109(3797 \text{ mm Hg}) + 0.752(1176 \text{ mm Hg}) + 0.139(775 \text{ mm Hg})$$

$$\Rightarrow \underline{\underline{P = 1406 \text{ mm Hg}}}$$

<u>Dew pt.</u> $T_f = T_{dp} \Rightarrow f(T_f) = 1 - P \sum_i \dfrac{y_i}{p_i^*(T_f)} = 0$ trial & error to find $T_f \Rightarrow \underline{\underline{T_f = 5.00^o C}}$

<u>Refs:</u> $C_3H_8(l)$, $C_4H_{10}(l)$ at 0 °C, Refrigerant @ –6°C

Assume: $\Delta \hat{H}_v (T_b)$, Table B.1

substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$		
C_3H_8	1090	19110	1090	0	$\dot{n}$ (kmol/h)	$\hat{H}_2 (\text{vapor}) = \Delta \hat{H}_v (0°C) -$
$i - C_4H_{10}$	7520	21740	7520	0	$\hat{H}$ (kJ/kmol)	$\int_0^{4.95} C_p dT (\text{Table B.2})$
$n - C_4H_{10}$	1390	22760	1390	0		
Refrigerant	$\dot{m}_1$	0	$\dot{m}_1$	151	$\dot{m}$ (kg/h)	$\hat{H} = \Delta \hat{H}_v$
					$\hat{H}$ (kJ/kmol)	

<u>E.B.:</u>

$$\Delta H = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = 0 \Rightarrow 151 \dot{m}_1 - 2.16 \times 10^6 = 0 \Rightarrow \underline{\underline{\dot{m}_1 = 1.43 \times 10^6 \text{ kg/h refrigerant}}}$$

8.67 (cont'd)

(b) Cooling water: $T_{out} = 40°C$, $T_2 = 34°C$, $T_1 = 25°C$

$$P = \sum_i x_i p_i^*(40°C) = 0.109(11{,}877) + 0.752(3961) + 0.139(2831) = \underline{\underline{4667 \text{ mm Hg}}}$$
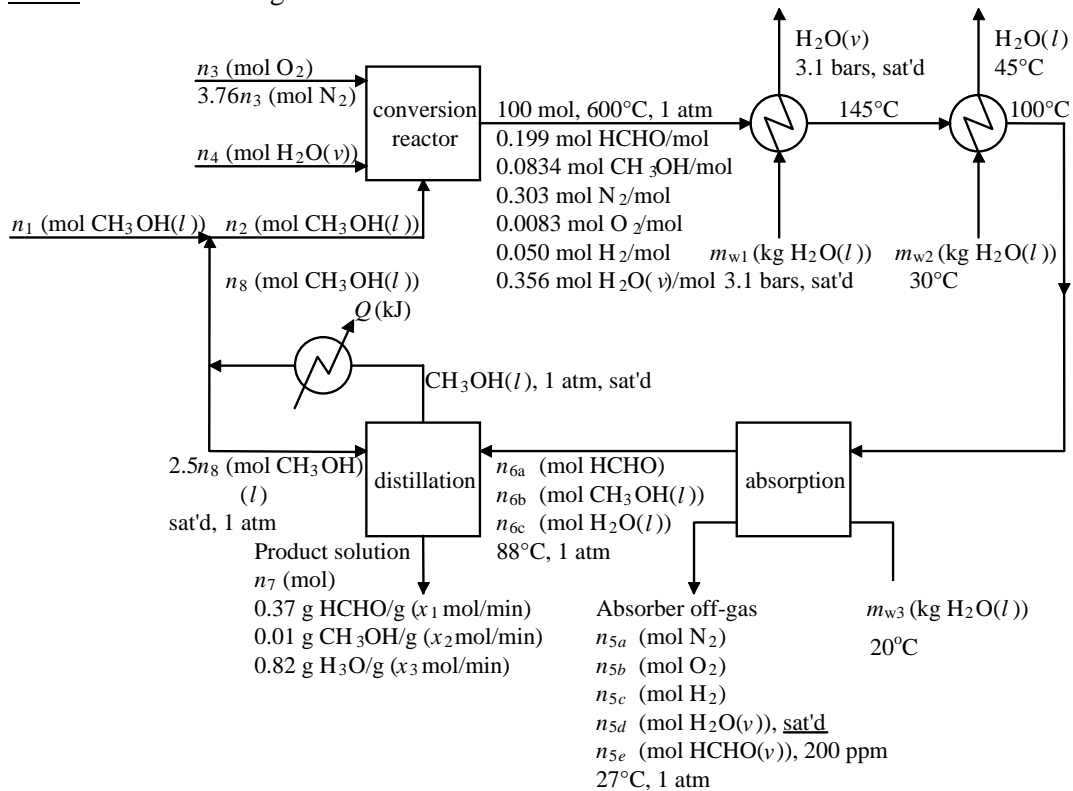
$$f(T_f) = 1 - P\sum_i \frac{y_i}{p_i^*(T_f)} = 0 \overset{T+E}{\Rightarrow} \underline{\underline{T_f = 45.7°C}}$$

Refs: $C_3H_8(l)$, $C_4H_{10}(l)$ @ 40°C, $H_2O(l)$ @ 25°C.

$$\Delta\dot{H} = 0 \Rightarrow 37.7\dot{m}_1 - 2.17 \times 10^8 = 0 \Rightarrow \underline{\underline{\dot{m}_1 = 5.74 \times 10^6 \text{ kg H}_2O / h}}$$

(c) Cost of refrigerant pumping and recompression, cost of cooling water pumping, cost of maintaining system at the higher pressure of part (b).

8.68 Basis: 100 mol leaving conversion reactor

a. Strategy

C balance on conversion reactor $\Rightarrow n_2$, N_2 balance on conversion reactor $\Rightarrow n_3$

H balance on conversion reactor $\Rightarrow n_4$, (O balance on conversion reactor to check consistency)

N_2 balance on absorber $\Rightarrow n_{5a}$, O_2 balance on absorber $\Rightarrow n_{5b}$

H_2 balance on absorber $\Rightarrow n_{5e}$

$\left.\begin{array}{l} H_2O \text{ saturation of absorber off - gas} \\ 200 \text{ ppm HCHO in absorber off - gas} \end{array}\right\} \Rightarrow n_{5d}, n_{5b}$

8.68 (cont'd)

HCHO balance on absorber $\Rightarrow n_{6a}$, CH_3OH balance on absorber $\Rightarrow n_{6b}$

Wt. fractions of product solution $\Rightarrow x_1, x_2, x_3$

HCHO balance on distillation column $\Rightarrow n_7$

CH_3OH balance on distillation column $\Rightarrow n_8$

CH_3OH balance on recycle mixing point $\Rightarrow n_1$

Energy balance on waste heat boiler $\Rightarrow m_{w1}$, E.B. on cooler $\Rightarrow m_{w2}$

Energy balance on reboiler $\Rightarrow Q$

C balance on conversion reactor:
$$n_2 = 19.9 \text{ mol HCHO} + 8.34 \text{ mol CH}_3\text{OH} = 28.24 \text{ mol CH}_3\text{OH}$$

N$_2$ balance on conversion reactor:

$$3.76 n_3 = 30.3 \Rightarrow n_3 = 8.06 \text{ mol O}_2, \ 3.76 \times 8.06 = 30.3 \text{ mol N}_2 \text{ feed}$$

H balance on conversion reactor:

$$n_4(2) + 28.24(4) - 19.9(2) + 8.34(4) + 5(2) + 35.6(2) \Rightarrow n_4 = 20.7 \text{ mol H}_2\text{O fed}$$

O balance: 65.1 mol O in, 65.5 mol O out. Accept (precision error)

N$_2$ balance on absorber: $\ 30.3 = n_{5a} \Rightarrow n_{5a} = 30.3 \text{ mol N}_2$

O$_2$ balance on absorber: $\ 0.83 = n_{5b} \Rightarrow n_{5b} = 0.83 \text{ mol O}_2$

H$_2$ balance on absorber: $\ 5.00 = n_{5c} \Rightarrow n_{5c} = 5.00 \text{ mol H}_2$

H$_2$O saturation of off - gas:

$$y_w = \frac{p_w^*(27°\text{C})}{P} = \left[\frac{26.739 \text{ mm Hg}}{760 \text{ mm Hg}} = \frac{n_{5d}}{30.3 + 0.83 + 5.00 + n_{5d} + n_{5e}} \right]$$

$$\Rightarrow n_{5d} = 0.03518(36.13 + n_{5d} + n_{5e}) \, [1]$$

$$\begin{array}{l} \underline{\text{200 ppm HCHO in off gas:}} \\ \\ \Rightarrow \ \dfrac{n_{5e}}{36.13 + n_{5d} + n_{5e}} = \dfrac{200}{10^6} \, [2] \end{array} \left. \begin{array}{l} \\ \\ \\ \end{array} \right\} \overset{\text{solve}}{\Rightarrow} \begin{array}{l} n_{5d} = 1.318 \text{ mol H}_2\text{O} \\ \\ n_{5e} = 7.49 \times 10^{-3} \text{ mol HCHO} \end{array}$$

Moles of absorber off-gas $= n_{5a} + n_{5b} + n_{5c} + n_{5e} = 37.46 \text{ mol off - gas}$

HCHO balance on absorber: $\ 19.9 = n_{6a} + 7.49 \times 10^{-3} \Rightarrow n_{6a} - 19.89 \text{ mol HCHO}$

CH_3OH balance on absorber: $\ 8.34 = n_{6b} \Rightarrow n_{6b} = 8.34 \text{ mol CH}_3\text{OH}$

Product solution

$$\text{Basis - 100 g} \Rightarrow \left. \begin{array}{l} 37.0 \text{ g HCHO} \overset{\%MW}{\Rightarrow} 1.232 \text{ mol HCHO} \\ 1.0 \text{ g CH}_3\text{OH} \Rightarrow 0.031 \text{ mol CH}_3\text{OH} \\ 62.0 \text{ g H}_2\text{O} \Rightarrow 3.441 \text{ mol H}_2\text{O} \end{array} \right\} \Rightarrow \begin{array}{l} x_1 = 0.262 \text{ mol HCHO/mol} \\ x_2 = 0.006 \text{ mol CH}_3\text{OH/mol} \\ x_3 = 0.732 \text{ mol H}_2\text{O/mol} \end{array}$$

8.68 (cont'd)

HCHO balance on distillation column (include the condenser + reflux stream within the system for this and the next balance):

$$19.89 = 0.262 n_7 \Rightarrow n_7 = 75.9 \text{ mol product}$$

CH$_3$OH balance on distillation column:

$$8.34 = 0.006(75.9) + n_8 \Rightarrow n_8 = 7.88 \text{ mol CH}_3\text{OH}$$

CH$_3$OH balance on recycle mixing point:

$$n_1 + n_8 = n_2 \Rightarrow n_1 = 28.24 - 7.83 = 20.36 \text{ mol CH}_3\text{OH fresh feed}$$

Summary of requested material balance results:

$$n_1 = 20.4 \text{ mol CH}_3\text{OH}(l) \text{ fresh feed}$$

$$n_2 = 75.9 \text{ mol product solution}$$

$$n_3 = 7.88 \text{ mol CH}_3\text{OH}(l) \text{ recycle}$$

$$n_4 = 37.5 \text{ mol absorber off - gas}$$

Waste heat boiler:

Refs: HCHO$(v, 145°\text{C})$, CH$_3$OH$(v, 145°\text{C})$; N$_2$, O$_2$, H$_2$, H$_2$O(v) at 25°C for product gas, H$_2$O$(l, \text{triple point})$ for boiler water

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$		
HCHO	19.9	22.55	19.9	0		$\left.\begin{array}{}\\\\\end{array}\right\} \hat{H} = \int_{145}^{T} C_p dT$
CH$_3$OH	8.34	32.02	8.34	0	n (mol)	
N$_2$	30.3	17.39	30.3	3.51		
O$_2$	0.83	18.41	0.83	3.60	$\hat{H}$ (kJ/mol)	
H$_2$	5.0	16.81	5.0	3.47		$\left.\begin{array}{}\\\\\end{array}\right\} \hat{H} = \bar{C}_p(T)[T - 25]$
H$_2$O	35.6	20.91	35.6	4.09		
H$_2$O (boiler)	m_{w1}	566.2	m_{w1}	2726.32	m (kg) $\hat{H}$ (kJ/kg)	$\left.\begin{array}{}\\\end{array}\right\} \hat{H}$ from steam tables

E.B. $\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0 \Rightarrow -1814 + 2160 m_{w1} = 0 \Rightarrow m_{w1} = 0.84 \text{ kg 3.1 bar steam}$

8.68 (cont'd)

<u>Gas cooler:</u> Same refs. as above for product gas, $H_2O(l, 30°C)$ for cooling water

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
HCHO	19.9	0	19.9	−1.78	
CH_3OH	8.34	0	8.34	−2.38	n (mol)
N_2	30.3	3.51	30.3	2.19	$\hat{H}$ (kJ/mol)
O_2	0.83	3.60	0.83	2.24	
H_2	5.0	3.47	5.0	2.16	
H_2O	35.6	4.09	35.6	2.54	
H_2O (coolant)	m_{w2}	0	m_{w2}	62.76	m (kg) $\hat{H}$ (kJ/kg)

$$\hat{H} = 4.184 \frac{kJ}{kg \cdot °C}(T - 30)°C$$

<u>E.B.</u> $\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0 \Rightarrow -158.1 + 62.6m_{w2} = 0 \Rightarrow m_{w2} = \underline{\underline{2.52 \text{ kg cooling water}}}$

<u>Condenser:</u> CH_3OH condensed $= n_8 + 2.5n_8 = (3.5)(7.88) = 27.58$ mol CH_3OH condensed

<u>E.B.:</u> $Q = -n\Delta \hat{H}_v(1 \text{ atm}) = -(27.58 \text{ mol})(35.27 \text{ kJ/mol})$
$= \underline{\underline{-973 \text{ kJ}}}$ (transferred from condenser)

b. $\dfrac{3.6 \times 10^4 \text{ tonne / y}}{} \left| \dfrac{10^6 \text{ g}}{1 \text{ metric ton}} \right| \dfrac{1 \text{ yr}}{350 \text{ d}} \left| \dfrac{1 \text{ d}}{24 \text{ h}} \right. = 4.286 \times 10^6$ g/h product soln

$\left. \begin{array}{l} (0.37)(4.286 \times 10^6) = 1.586 \times 10^6 \text{ g HCHO/h} \Rightarrow 5.281 \times 10^4 \text{ mol HCHO/h} \\ \Rightarrow (0.01)(4.286 \times 10^6) = 4.286 \times 10^6 \text{ g CH}_3\text{OH/h} \Rightarrow 1338 \text{ mol CH}_3\text{OH/h} \\ (0.62)(4.286 \times 10^6) = 2.657 \times 10^6 \text{ g H}_2\text{O/h} \Rightarrow 1.475 \times 10^5 \text{ mol H}_2\text{O/h} \end{array} \right\}$

$\Rightarrow 2.016 \times 10^5 \text{ mol/h} \Rightarrow$ Scale factor $= \dfrac{2.016 \times 10^5 \text{ mol/h}}{75.9 \text{ mol}} = \underline{\underline{2657 \text{ h}^{-1}}}$

8.69 (a) For 24°C and 50% relative humidity, from Figure 8.4-1,
Absolute humidity = $\underline{\underline{0.0093 \text{ kg water / kg DA}}}$, Humid volume ≈ $\underline{\underline{0.856 \text{ m}^3 \text{ / kg DA}}}$
Specific enthalpy = (48 - 0.2) kJ / kg DA = $\underline{\underline{47.8 \text{ kJ / kg DA}}}$, Dew point = $\underline{\underline{13°C}}$, $T_{wb} = \underline{\underline{17°C}}$

(b) $\underline{\underline{24°C}}$ (T_{db})

(c) $\underline{\underline{13°C}}$ (Dew point)

(d) Water evaporates, causing your skin temperature to drop. $T_{skin} \approx \underline{\underline{13°C}}$ (T_{wb}). At 98%

R.H. the rate of evaporation would be lower, T_{skin} would be closer to $T_{ambient}$, and you
would not feel as cold.

8.70 $V_{room} = 141 \text{ ft}^3$. DA = dry air.

$$m_{DA} = \frac{140 \text{ ft}^3}{} \left| \frac{\text{lb - mol} \cdot {}^\circ \text{R}}{0.7302 \text{ ft}^3 \cdot \text{atm}} \right| \frac{29 \text{ lb}_m \text{ DA}}{\text{lb - mol}} \left\| \frac{1 \text{ atm}}{550 \text{ }^\circ \text{R}} = 10.1 \text{ lb}_m \text{ DA} \right.$$

$$h_a = \frac{0.205 \text{ lb}_m \text{ H}_2\text{O}}{10.1 \text{ lb}_m \text{ DA}} = 0.0203 \text{ lb}_m \text{ H}_2\text{O} / \text{lb}_m \text{ DA}$$

From the psychrometric chart, $T_{db} = 90^\circ$ F, $h_a = 0.0903$

$$\Downarrow$$

$\underline{\underline{h_r = 67\%}}$ $\underline{\underline{T_{wb} = 80.5^\circ \text{ F}}}$ $\underline{\underline{\hat{V} = 14.3 \text{ ft}^3 / \text{lb}_m \text{ DA}}}$

$\underline{\underline{T_{dew \ point} = 77.3^\circ \text{ F}}}$ $\underline{\underline{\hat{H} = 44.0 - 0.11 \cong 43.9 \text{ Btu} / \text{lb}_m}}$

8.71

$\left. \begin{array}{l} T_{db} = 35^\circ \text{C} \\ T_{ab} = 27^\circ \text{C} \end{array} \right\} \Rightarrow \underline{\underline{h_r = 55\%}} \quad \underline{\underline{\text{He wins}}}$

8.72 a. $T_{db} = 40^\circ \text{C}$, $T_{dew \ point} = 20^\circ \text{C}$ $\overset{\text{Fig. 8.4-1}}{\Rightarrow}$ $\underline{\underline{\begin{array}{l} h_r = 33\%, h_a = 0.0148 \text{ kg H}_2\text{O/kg dry air} \\ T_{wb} = 25.5^\circ \text{C} \end{array}}}$

b. Mass of dry air: $m_{da} = \frac{2.00 \text{ L}}{} \left| \frac{1 \text{ m}^3}{10^3 \text{ L}} \right| \frac{1 \text{ kg dry air}}{0.92 \text{ m}^3} = 2.2 \times 10^{-3} \text{ kg dry air}$

$\uparrow$ from Fig. 8.4-1

Mass of water: $\frac{2.2 \times 10^{-3} \text{ kg dry air}}{} \left| \frac{0.0148 \text{ kg H}_2\text{O}}{1 \text{ kg dry air}} \right| \frac{10^3 \text{ g}}{1 \text{ kg}} = \underline{\underline{0.033 \text{ g H}_2\text{O}}}$

c. $\hat{H}(40^\circ\text{C}, \ 33\% \text{ relative humidity}) \approx (78.0 - 0.65) \text{ kJ/kg dry air} = 77.4 \text{ kJ/kg dry air}$

$\hat{H}(20^\circ\text{C}, \ \text{saturated}) \approx 57.5 \text{ kJ/kg dry air}$ (both values from Fig. 8.4-1)

$\Delta H_{40 \to 20} = \frac{2.2 \times 10^{-3} \text{ kg dry air}}{} \left| \frac{(57.5 - 77.4) \text{ kJ}}{\text{kg dry air}} \right| \frac{10^3 \text{ J}}{1 \text{ kJ}} = \underline{\underline{-44 \text{ J}}}$

d. Energy balance: closed system

$n = \frac{2.2 \times 10^{-3} \text{ kg dry air}}{} \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \frac{1 \text{ mol}}{29 \text{ g}} + \frac{0.033 \text{ g H}_2\text{O}}{} \left| \frac{1 \text{ mol}}{18 \text{ g}} = 0.078 \text{ mol} \right.$

$Q = \Delta U = n\Delta \hat{U} = n(\Delta \hat{H} - R\Delta T) = \Delta H - nR\Delta T$

$= -44 \text{ J} - \frac{0.078 \text{ mol}}{} \left| \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \right| \frac{(20 - 40)^\circ \text{C}}{} \left| \frac{1 \text{ K}}{1^\circ \text{C}} = \underline{\underline{-31 \text{ J}}}(23 \text{ J transferred from the air}) \right.$

8.73 **(a)** $\dfrac{400 \text{ kg}}{\text{min}} \left| \dfrac{2.44 \text{ kg water}}{97.56 \text{ kg air}} \right. = \underline{\underline{10.0 \text{ kg water evaporates}/\text{min}}}$

(b) $h_a = \dfrac{10 \text{ kg H}_2\text{O}/\text{min}}{400 \text{ kg dry air}/\text{min}} = 0.025 \text{ kg H}_2\text{O}/\text{kg dry air}, \ T_{db} = 50°\text{C}$

$\xRightarrow{\text{Fig. 8.4-1}} \hat{H} = (116 - 1.1) = 115 \text{ kJ}/\text{kg dry air}, \ T_{wb} = 33°\text{C}, \ h_r = 32\%, \ T_{\text{dew point}} = 28.5°\text{C}$

(c) $T_{db} = 10°\text{C}$, saturated $\Rightarrow h_a = 0.0077 \text{ kg H}_2\text{O}/\text{kg dry air}, \ \hat{H} = 29.5 \text{ kJ}/\text{kg dry air}$

(d) $\dfrac{400 \text{ kg dry air}}{\text{min}} \left| \dfrac{(0.0250 - 0.0077) \text{ kg H}_2\text{O}}{\text{kg dry air}} \right. = \underline{\underline{6.92 \text{ kg H}_2\text{O}/\text{min condense}}}$

References: Dry air at $0°\text{C}$, $\text{H}_2\text{O}(l)$ at $0°\text{C}$

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	400	115	400	29.5	$\dot{m}_{\text{air}}$ in kg dry air/min, $\dot{m}_{\text{H}_2\text{O}}$ in kg/min
$\text{H}_2\text{O}(l)$	—	—	6.92	42	$\hat{H}_{\text{air}}$ in kJ/kg dry air, $\hat{H}_{\text{H}_2\text{O}}$ in kJ/kg

$\text{H}_2\text{O}(l, 0°\text{C}) \rightarrow \text{H}_2\text{O}(l, 20°\text{C})$:

$\hat{H} = \dfrac{75.4 \text{ J}}{\text{mol}\cdot°\text{C}} \left| \dfrac{1 \text{ mol}}{18 \text{ g}} \right| \dfrac{(10-0)°\text{C}}{} \left| \dfrac{1 \text{ kJ}}{10^3 \text{ J}} \right| \dfrac{10^3 \text{ g}}{1 \text{ kg}} = 42 \text{ kJ}/\text{kg}$

$Q = \Delta H = \displaystyle\sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \dfrac{-34027.8 \text{ kJ}}{\text{min}} \left| \dfrac{1 \text{ min}}{60 \text{ s}} \right| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-565 \text{ kW}}}$

(e) T>50°C, because the heat required to evaporate the water would be transferred from the air, causing its temperature to drop. To calculate $(T_{\text{air}})_{\text{in}}$, you would need to know the flow rate, heat capacity and temperature change of the solids.

8.74 **a.** Outside air: $T_{db} = 87°\text{F}, \ h_r = 80\% \Rightarrow h_a = 0.0226 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.}$,

$\hat{H} = 45.5 - 0.01 = 45.5 \text{ Btu}/\text{lb}_m \text{ D.A.}$

Room air: $T_{db} = 75°\text{F}, \ h_r = 40\% \Rightarrow h_a = 0.0075 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.}$,

$\hat{H} = 26.2 - 0.02 = 26.2 \text{ Btu}/\text{lb}_m \text{ D.A.}$

Delivered air: $T_{db} = 55°\text{F}, \ h_a = 0.0075 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.}$

$\Rightarrow \hat{H} = 21.4 - 0.02 = 21.4 \text{ Btu}/\text{lb}_m \text{ D.A.}, \ \hat{V} = 13.07 \text{ ft}^3/\text{lb}_m \text{ D.A.}$

Dry air delivered: $\dfrac{1,000 \text{ ft}^3}{\text{min}} \left| \dfrac{1 \text{ lb}_m \text{ D.A.}}{13.07 \text{ ft}^2} \right. = 76.5 \text{ lb}_m \text{ D.A.}/\text{min}$

H_2O condensed:

$\dfrac{76.5 \text{ lb}_m \text{ D.A.}}{\text{min}} \left| \dfrac{(0.0226 - 0.0075) \text{ lb}_m \text{ H}_2\text{O}}{\text{lb}_m \text{ D.A.}} \right. = \underline{\underline{1.2 \text{ lb}_m \text{ H}_2\text{O}/\text{min condensed}}}$

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 $\Rightarrow \underline{T = 49°\,F}$
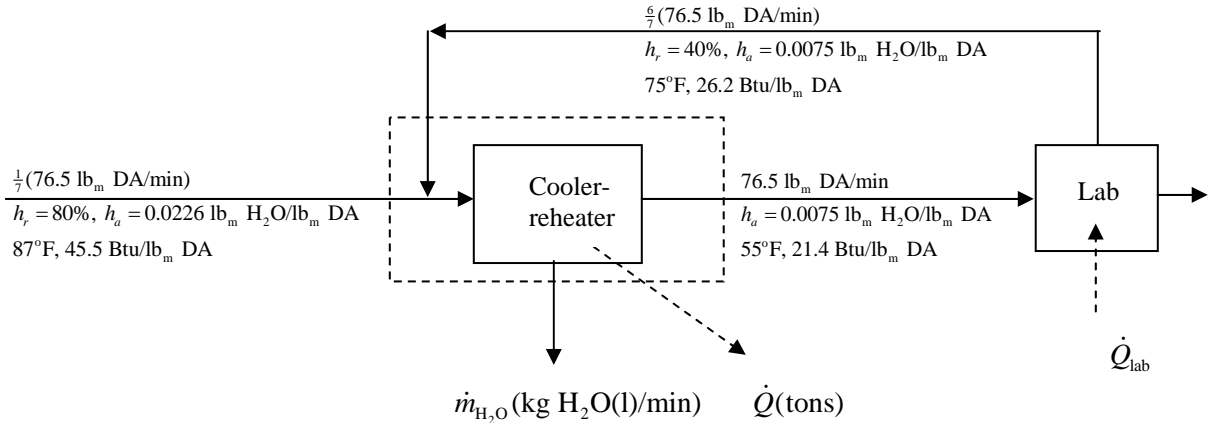
References: Same as Fig. 8.4-2 [including $H_2O(l, 32°\,F)$]

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

$$\dot{m}_{H_2O}\,(\text{kg } H_2O(l)/\text{min}) \qquad \dot{Q}(\text{tons})$$

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

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

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

8.74 (cont'd)

Energy balance on cooler-reheater

<u>References</u>: Same as Fig. 8.4-2 [including $H_2O(l, 32^oF)$]

Substance	$\dot{m}_{in}$	$\hat{H}_{in}$	$\dot{m}_{out}$	$\hat{H}_{out}$	
Fresh air feed	10.93	45.5	—	—	$\dot{m}_{DA}$ in lb_m dry air/min
Recirculated air feed	65.57	26.2	—	—	$\hat{H}_{air}$ 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

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

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

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 <u>Basis</u>: 1 kg wet chips. DA = dry air, DC = dry chips

Outlet air: T_{db}=38°C, T_{wb}=29°C
m_{2a} (kg DA)
m_{2w} [kg H_2O(v)]

Inlet air: 11.6 m^3(STP), T_{db}=100°C
m_{1a} (kg DA)

1 kg wet chips, 19°C
0.40 kg H_2O(l)/kg
0.60 kg DC/kg

m_{3c} (kg dry chips)
m_{3w} [kg H_2O(l)]
T (^{o}C)
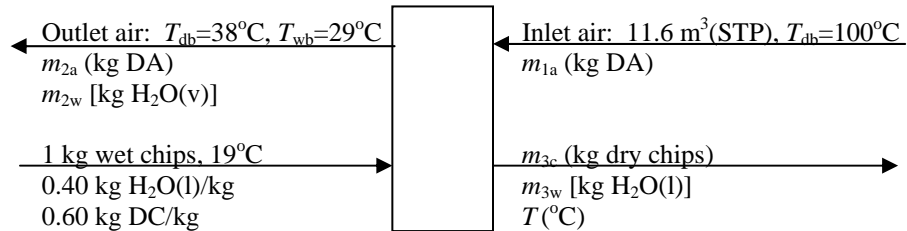
(a) <u>Dry air:</u> $m_{1a} = \dfrac{11.6 \text{ m}^3(\text{STP}) \text{ DA}}{}\left|\dfrac{1 \text{ kmol}}{22.4 \text{ m}^3(\text{STP})}\right|\dfrac{29.0 \text{ kg}}{1 \text{ kmol}} = 15.02 \text{ kg DA} = m_{2a}$

<u>Outlet air:</u>

$$\left(T_{db} = 38°C, T_{wb} = 29°C\right) \xrightarrow{\text{Fig. 8.4-1}} \hat{H}_2 = (95.3 - 0.48) = \underline{\underline{94.8 \frac{\text{kJ}}{\text{kg DA}}}} \quad h_{a_2} = \underline{\underline{0.0223 \frac{\text{kg } H_2O}{\text{kg DA}}}}$$

<u>Water in outlet air:</u> $m_{2w} = h_{a_2}m_{2a} = 0.0223(15.02) = \underline{\underline{0.335 \text{ kg } H_2O}}$

(b) <u>H_2O balance:</u> $\underline{0.400 \text{ kg}} = 0.335 \text{ kg} + m_{3w} \Rightarrow m_{3w} = 0.065 \text{ kg } H_2O$

8.75 (cont'd)

Moisture content of exiting chips:

$$\frac{0.065 \text{ kg water}}{0.600 \text{ kg dry chips} + 0.065 \text{ kg water}} \times 100\% = 9.8\% < 15\% \therefore \text{meets design specification}$$

(c) References: Dry air, $H_2O(l)$, dry chips @ 0°C.

substance	m_{in}	$\hat{H}_{in}$	m_{out}	$\hat{H}_{out}$	
Air	15.02	100.2	15.02	94.8	m_{air} in kg DA, $\hat{H}_{air}$ in kJ/kg DA
$H_2O(l)$	0.400	79.5	0.065	$4.184T$	m in kg DC, $\hat{H}_{in}$ in kJ/kg DC
dry chips	0.600	39.9	0.6	$2.10T$	

Energy Balance:

$$\Delta H = \sum m_{out}\hat{H}_{out} - \sum m_{in}\hat{H}_{in} = 0 \Rightarrow -136.8 + 1.532T = 0 \Rightarrow \underline{\underline{T = 89.3°C}}$$

8.76 a. $T_{db} = 45°C$
$h_r = 10\%$ $\xrightarrow{\text{Fig. 8.4-1}}$ $T_{as} = T_{wb} = \underline{\underline{21.0°C}}$ $h_a = 0.0059$ kg H_2O/kg DA

b. $T_{wb} = 21.0°C$
$h_r = 60\%$ $\xrightarrow{\text{Fig. 8.4-1}}$ $T_{db} = \underline{\underline{26.8°C}}$ $h_a = 0.0142$ kg H_2O/kg DA

$$\underline{H_2O \text{ added:}} \quad \frac{15 \text{ kg air}}{\text{min}} \left| \frac{1 \text{ kg D.A.}}{1.0059 \text{ kg air}} \right| \frac{(0.0142 - 0.0059) \text{ kg } H_2O}{1 \text{ kg D.A.}} = \underline{\underline{0.12 \text{ kg } H_2O/\text{min}}}$$

8.77

Inlet air: $\left.\begin{array}{l} T_{db} = 50°C \\ T_{dew pt.} = 4°C \end{array}\right\}$ $\xrightarrow{\text{Fig. 8.4-1}}$ $\begin{array}{l} \hat{V} = 0.92 \text{ m}^3/\text{kg D.A.}, \ T_{wb} = 22°C \\ \underline{\underline{h_a = 0.0050 \text{ kg } H_2O/\text{kg D.A.}}} \end{array}$

$$\frac{11.3 \text{ m}^3}{\text{min}} \left| \frac{1 \text{ kg D.A.}}{0.92 \text{ m}^3} \right. = \underline{\underline{12.3 \text{ kg D.A./min}}}$$

Outlet air: $T_{wb} = T_{as} = 22°C$
saturated $\Rightarrow \underline{\underline{T = 22°C}}$ $h_a = 0.0165$ kg H_2O/kg D.A.

$$\underline{\text{Evaporation:}} \quad \frac{12.3 \text{ kg D.A.}}{\text{min}} \left| \frac{(0.0165 - 0.0050) \text{ kg } H_2O}{\text{kg D.A.}} \right. = \underline{\underline{0.14 \text{ kg } H_2O/\text{min}}}$$

8.78 a.

$$\left.\begin{array}{l} T_{db} = 45°C \\ T_{dew\ point} = 4°C \end{array}\right\} \xrightarrow[\text{Fig. 8.4-1}]{} \begin{array}{l} (h_a)_{in} = 0.0050\ \text{kg H}_2\text{O/kg D.A.} \\ T_{wb} = 20.4°C,\ \hat{V} = 0.908\ \text{m}^3/\text{kg D.A.} \end{array}$$

$$T_{wb} = T_{as} = 20.4°C,\ \text{saturated} \Rightarrow (h_a)_{out} = 0.0151\ \text{kg H}_2\text{O/kg D.A.}$$

b. Basis: 1 kg entering sugar (S) solution

m_1 (kg D.A.) 0.0050 kg H$_2$O/kg DA		m_1 (kg D.A.) 0.0151 kg H$_2$O(v)/kg
1 kg 0.05 kg S/kg 0.95 kg H$_2$O/kg		m_2 (kg) 0.20 kg S/kg 0.80 kg H$_2$O/kg
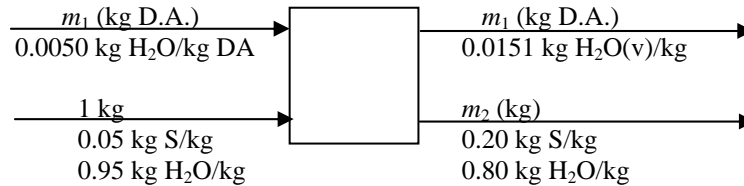
Sugar balance: $(0.05)(1) = (0.20)m_2 \Rightarrow m_2 = 0.25$ kg

Water balance: $(m_1)(0.0050) + (1)(0.95) = (m_1)(0.0151) + (0.25)(0.80)$

$$\Rightarrow \left\{ \begin{array}{l} m_1 = 74\ \text{kg dry air} \\[1mm] V = \dfrac{74\ \text{kg dry air}}{} \left| \dfrac{0.908\ \text{m}^3}{1\ \text{kg D.A.}} = 67\ \text{m}^3 \right. \end{array} \right.$$

8.79
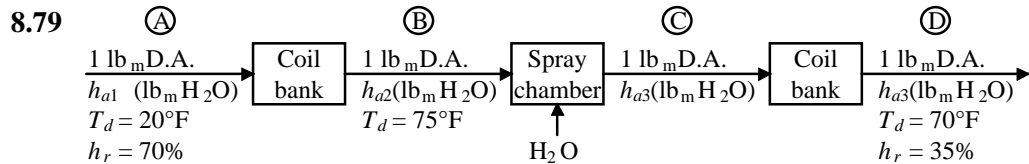
<u>Inlet air (A):</u> $\left.\begin{array}{l} T_{db} = 20°\text{F} \\ h_r = 70\% \end{array}\right\} \xrightarrow[\text{Fig. 8.4-2}]{} \begin{array}{l} h_{a1} \approx 0.0017\ \text{lb}_m\ \text{H}_2\text{O/lb}_m\ \text{D.A.} \\ \hat{V} \approx 12.2\ \text{ft}^3/\text{lb}_m\ \text{D.A.} \end{array}$

<u>Outlet air (D):</u> $\left.\begin{array}{l} T_{db} = 70°\text{F} \\ h_r = 35\% \end{array}\right\} \xrightarrow[\text{Fig. 8.4-2}]{} h_{a3} = 0.0054\ \text{lb}_m\ \text{H}_2\text{O/lb}_m\ \text{D.A.}$

a. <u>Inlet of spray chamber (B):</u> $\left.\begin{array}{l} h_a = 0.0017\ \text{lb}_m\ \text{H}_2\text{O/lb}_m\ \text{D.A.} \\ T_{db} = 75°\text{F} \end{array}\right\} \Rightarrow T_{wb} = 49.5°\text{F}$

The state of the air at (C) must lie on the same adiabatic saturation curve as does the state at (B), or $T_{wb} = 49.5°\text{F}$. Thus,

<u>Outlet of spray chamber (C):</u> $\left.\begin{array}{l} h_a = 0.0054\ \text{lb}_m\ \text{H}_2\text{O/lb}_m\ \text{D.A.} \\ T_{wb} = 49.5°\text{F} \end{array}\right\} \Rightarrow h_r = 52\%$

At point C, $T_{db} = 58.5°\text{F}$

b.
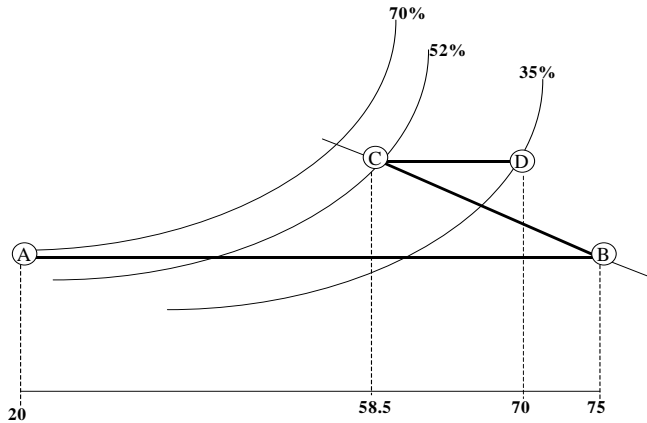
$$\frac{(h_{a3} - h_{a1})\ \text{lb}_m\ \text{H}_2\text{O evaporate}}{\text{lb}_m\ \text{DA}} \left| \frac{\text{lb}_m\ \text{DA}}{\hat{V}_A\left(\text{ft}^3\ \text{inlet air}\right)} = \frac{(0.0054 - 0.0017)}{12.2} = 3.0 \times 10^{-4}\ \frac{\text{lb}_m\ \text{H}_2\text{O}}{\text{ft}^3\ \text{air}} \right.$$
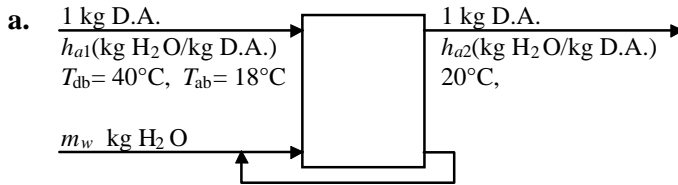
8.79 (cont'd)

c. $Q_{BA} = \Delta H = \hat{H}_B - \hat{H}_A \cong \dfrac{(20 - 6.4) \text{ Btu / lb}_m \text{ dry air}}{12.2 \text{ ft}^3 \text{ / lb}_m \text{ dry air}} = \underline{\underline{1.1 \text{ Btu / ft}^3}}$

$Q_{DC} = \Delta H = \hat{H}_D - \hat{H}_C \cong \dfrac{(23 - 20) \text{ Btu / lb}_m \text{ dry air}}{12.2 \text{ ft}^3 \text{ / lb}_m \text{ dry air}} = \underline{\underline{0.25 \text{ Btu / ft}^3}}$

d.

8.80 <u>Basis</u>: 1 kg D.A.

a.

<u>Inlet air:</u> $\begin{aligned} T_{db} &= 40°\,C \\ T_{wb} &= 18°\,C \end{aligned} \Rightarrow h_{a1} = 0.0039 \text{ kg } H_2O/\text{kg D.A.}$

<u>Outlet air:</u> $\begin{aligned} T_{db} &= 20°\,C \\ T_{wb} &= 18°\,C \ (\text{adiabatic humidification}) \end{aligned} \Rightarrow h_{a2} = 0.0122 \text{ kg } H_2O/\text{kg D.A.}$

<u>Overall H_2O balance:</u> $m_w + (1)(h_{a1}) = (1)(h_{a2}) \Rightarrow m_n = (0.0122 - 0.0039) \text{kg } H_2O/\text{kg D.A.}$

$ = \underline{\underline{0.0083 \text{ kg } H_2O/\text{kg D.A.}}}$

b.
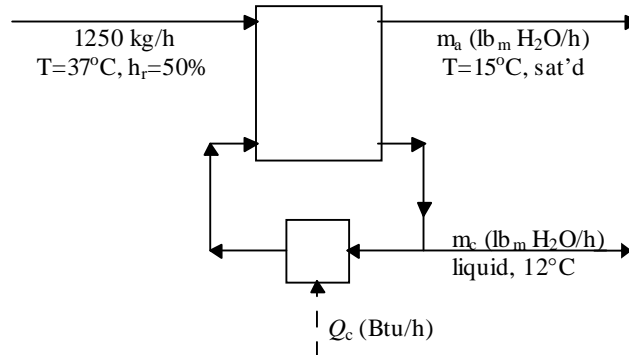
8.80 (cont'd)

Inlet air: $\left.\begin{array}{l} T_{db} = 37°C \\ h_r = 50\% \end{array}\right\}$ $\xrightarrow{\text{Fig. 8.4-1}}$ $\left\{\begin{array}{l} h_{a1} = 0.0198 \text{ kg } H_2O/\text{kg DA} \\ \hat{H}_1 = (88.5 - 0.5) \text{ kJ/kg DA} = 88.0 \text{ kJ/kg DA} \end{array}\right.$

Moles dry air: $\dot{m}_a = \dfrac{1250 \text{ kg}}{h} \left| \dfrac{1 \text{ kg DA}}{1.0198 \text{ kg}} \right. = 1226 \text{ kg DA/h}$

Outlet air: $T_{db} = 15°C$, sat'd $\xrightarrow{\text{Fig. 8.4-1}}$ $\left\{\begin{array}{l} h_a = 0.0106 \text{ kg } H_2O/\text{kg DA} \\ \hat{H}_2 = 42.1 \text{ kJ/kg DA} \end{array}\right.$

Overall water balance $\Rightarrow \dot{m}_c = \dfrac{1226 \text{ kg DA}}{h} \left| \dfrac{(0.0198 - 0.0106) \text{ kg } H_2O}{\text{kg DA}} \right.$

$= 11.3 \text{ kg } H_2O/h \text{ withdrawn}$

Reference states for enthalpy calculations: $H_2O(l)$, dry air at 0°C. $(C_p)_{H2O(l)} = 4.184 \dfrac{\text{kJ}}{\text{kg} \cdot °C}$

$H_2O(l, 12°C)$: $\hat{H} = \int_0^{12} C_p dT = 50.3 \text{ kJ / kg}$

Overall system energy balance:

$\dot{Q}_c = \Delta\dot{H} = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i$

$= \left[\dfrac{11.3 \text{ kg } H_2O}{h} \left| \dfrac{50.3 \text{ kJ}}{\text{kg } H_2O} \right. + \dfrac{1226 \text{ kg DA}}{h} \left| \dfrac{(42.1 - 88) \text{ kJ}}{\text{kg DA}} \right. \right] \left(\dfrac{1 \text{ h}}{3600 \text{ s}} \right) \left(\dfrac{1 \text{ kW}}{1 \text{ kJ / s}} \right)$

$= -15.5 \text{ kW}$

8.81 $\Delta H = \dfrac{400 \text{ mol } NH_3}{} \left| \dfrac{-78.2 \text{ kJ}}{\text{mol } NH_3} \right. = -31{,}280 \text{ kJ}$

8.82 a. $HCl(g, 25°C)$, $H_2O(l, 25°C) \rightarrow HCl(25°C, r = 5)$.

$\Delta\hat{H} = \Delta\hat{H}_s(25°C, r = 5) \xrightarrow{\text{Table B.11}} \Delta\hat{H} = -64.05 \text{ kJ/mol HCl}$

b. $HCl(aq, r = \infty) \rightarrow HCl(r = 5)$, $H_2O(l)$

$\Delta\hat{H} = \Delta\hat{H}_s(25°C, n = 5) - \Delta\hat{H}_s(25°C, n = \infty)$

$= (-64.05 + 75.14) \text{ kJ/mol HCl} = 11.09 \text{ kJ / mol HCl}$

8.83 <u>Basis:</u> 100 mol solution $\Rightarrow$ 20 mol NaOH, 80 mol H_2O

$$\Rightarrow r = \frac{80 \text{ mol } H_2O}{20 \text{ mol NaOH}} = 4.00 \text{ mol } H_2O/\text{mol NaOH}$$

<u>Refs:</u> NaOH(s), $H_2O(l)$ @ 25°C

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
NaOH(s)	20.0	0.0	–	–	n in mol
$H_2O(l)$	80.0	0.0	–	–	$\hat{H}$ in kJ/mol
NaOH$(r = 4.00)$	–	–	20.0	–34.43	$\leftarrow n$ in mol NaOH

$\hat{H}(\text{NaOH}, r = 4.00) = -34.43 \text{ kJ/mol NaOH}$ (Table B.11)

$$\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = (20)(-34.43) = \frac{-688.6 \text{ kJ}}{} \left| \frac{9.486 \times 10^{-4} \text{ Btu}}{10^{-3} \text{ kJ}} \right. = -653.2 \text{ Btu}$$

$$Q = \frac{-653.2 \text{ Btu}}{[20.0(40.00) + 80.0(18.01)]g} \left| \frac{10^3 \text{ g}}{2.20462 \text{ lb}_m} \right. = \underline{\underline{-132.3 \text{ Btu/lb}_m}} \text{ product solution}$$

8.84 <u>Basis: 1 liter solution</u>

$$n_{H_2SO_4} = \frac{1 \text{ L}}{} \left| \frac{8 \text{ g-eq}}{L} \right| \frac{1 \text{ mol}}{2 \text{ g-eq}} = 4 \text{ mol } H_2SO_4 \times \left(\frac{0.09808 \text{ kg}}{1 \text{ mol}} \right) = 0.392 \text{ kg } H_2SO_4$$

$$m_{total} = \frac{1 \text{ L}}{} \left| \frac{1.230 \text{ kg}}{L} \right. = 1.230 \text{ kg solution}$$

$$n_{H_2O} = \frac{(1.230 - 0.392) \text{kg } H_2O}{} \left| \frac{1000 \text{ mol } H_2O}{18.02 \text{ kg } H_2O} \right. = 46.5 \text{ mol } H_2O$$

$$\Rightarrow r = \frac{n_{H_2O}}{n_{H_2SO_4}} = \frac{46.49 \text{ mol } H_2O}{4 \text{ mol } H_2SO_4} = 11.6 \frac{\text{mol } H_2O}{\text{mol } H_2SO_4}$$

$$H_2SO_4\left(aq, r = \infty, 25°C\right) \rightarrow H_2SO_4\left(aq, r = 11.6, 25°C\right) + H_2O\left(l, 25°C\right)$$
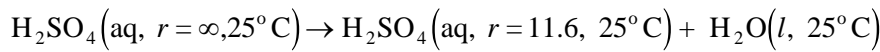
$$\Delta\hat{H}_1 = \Delta\hat{H}_s(r = 11.6) - \Delta\hat{H}_s(r = \infty) \overset{\text{Table B.11}}{=} (-67.6 + 96.19) = 28.6 \frac{\text{kJ}}{\text{mol } H_2SO_4}$$

$$\hat{H}(H_2SO_4, r = 11.6, 60°C) = \frac{\left[n_{H_2SO_4} \Delta H_1 + m \int_{25}^{60} C_p dT \right] \text{kJ}}{n_{H_2SO_4} (\text{mol } H_2SO_4)}$$

$$= \frac{1}{4 \text{ mol } H_2SO_4} \left\{ \frac{4 \text{ mol } H_2SO_4}{} \left| \frac{28.6 \text{ kJ}}{\text{mol } H_2SO_4} + \frac{1.230 \text{ kg}}{} \right| \frac{3.00 \text{ kJ}}{\text{kg} \cdot °C} \left| \frac{(60 - 25)°C}{} \right. \right\}$$

$$= \underline{\underline{60.9 \text{ kJ/mol } H_2SO_4}}$$

8.85 $2 \text{ mol } H_2SO_4 = 0.30(2.00 + n_{H_2O}) \Rightarrow n_{H_2O} = 4.67 \text{ mol } H_2O \Rightarrow r = \dfrac{4.67}{2} = 2.33 \dfrac{\text{mol } H_2O}{\text{mol } H_2SO_4}$

    a. For this closed constant pressure system,

$$Q = \Delta H = n_{H_2SO_4} \Delta \hat{H}_s(25°C, \ r = 2.33) = \frac{2 \text{ mol } H_2SO_4}{} \left| \frac{-44.28 \text{ kJ}}{\text{mol } H_2SO_4} \right| = \underline{\underline{-88.6 \text{ kJ}}}$$
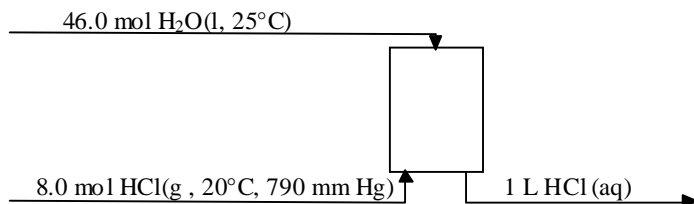
    b. $m_{\text{solution}} = \dfrac{2 \text{ mol } H_2SO_4}{} \left| \dfrac{98.08 \text{ g } H_2SO_4}{\text{mol}} + \dfrac{4.67 \text{ mol } H_2O}{} \right| \dfrac{18.0 \text{ g } H_2O}{\text{mol}} = 280.2 \text{ g}$

$$\Delta H = 0 \Rightarrow n_{H_2SO_4} \Delta \hat{H}_s(25°C, \ r = 2.33) + m \int_{25}^{T} C_p \, dT = 0$$

$$-88.6 \text{ kJ} + \frac{(280.6 + 150)\text{g}}{} \left| \frac{3.3 \text{ J}}{\text{g} \cdot °C} \right| \frac{(T - 25)°C}{} \left| \frac{1 \text{ kJ}}{1000 \text{ J}} = 0 \Rightarrow \underline{\underline{T = 87°C}} \right.$$

8.86 a.

Basis: $\dfrac{1 \text{ L product solution}}{} \left| \dfrac{1.12(10^3 \text{ g})}{L} = 1120 \text{ g solution} \right.$

$\dfrac{1 \text{ L}}{} \left| \dfrac{8 \text{ mol HCl}}{L} \right| \dfrac{36.47 \text{ g HCl}}{\text{mol HCl}} = 292 \text{ g HCl}$

$1120 \text{ g} - 292 \text{ g} = 828 \text{ g } H_2O$

$\dfrac{828 \text{ g } H_2O}{} \left| \dfrac{\text{mol}}{18.0 \text{ g}} = 46.0 \text{ mol } H_2O \right.$

$n = \dfrac{46.0 \text{ mol } H_2O}{8.0 \text{ mol HCl}} = 5.75 \text{ mol } H_2O/\text{mol HCl}$

Assume all HCl is absorbed

Volume of gas:

$\dfrac{8 \text{ mol}}{} \left| \dfrac{293 \text{ K}}{273 \text{ K}} \right| \dfrac{760 \text{ mm Hg}}{790 \text{ mm Hg}} \left| \dfrac{22.4 \text{ L (STP)}}{\text{mol}} = \underline{\underline{185 \text{ liter (STP) gas feed/L HCl solution}}} \right.$

    b. Ref: 25°C

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
$H_2O(l)$	46.0	0.0	–	–	n in mol
$HCl(g)$	8.0	–0.15	–	–	$\hat{H}$ in kJ/mol
$HCl(n = 5.75)$	–	–	8.0	–59.07	

8.86 (cont'd)

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

$$=-64.87\ \text{kJ/mol}+\frac{\left|\ 1120\ \text{g}\ \right|\ 0.66\ \text{cal}\ \left|\ (40-25)°\text{C}\ \right|\ 4.184\ \text{J}\ \right|\ \text{kJ}}{8\ \text{mols}\ \left|\qquad\quad\right|\ \text{g·°C}\ \left|\qquad\qquad\right|\ \text{cal}\ \right|\ 10^3\ \text{J}}$$

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

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

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

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

$$-0.15=\hat{H}=-64.87+\frac{\left|\ 1120\ \text{g}\ \right|\ 0.66\ \text{cal}\ \left|\ (T-25)°\text{C}\ \right|\ 4.184\ \text{J}\ \right|\ 1\ \text{kJ}}{8\ \text{mol}\ \left|\ \text{g·°C}\ \right|\qquad\qquad\ \left|\ \text{cal}\ \right|\ 1000\ \text{J}}$$

$$\underline{\underline{T=192\ °\text{C}}}$$

8.87 Basis: Given solution feed rate

$$
\begin{array}{ll}
\dot{n}_a\ (\text{mol air/min}) & \dot{n}_a\ (\text{mol air/min})\\
200°\text{C, 1.1 bars} & \dot{n}_1\ (\text{mol }H_2O(\text{v})/\text{min})\\
 & \text{saturated @ 50°C, 1 atm}\\
150\ \text{mol/min solution} & \\
0.001\ \text{NaOH} & \dot{n}_2\ (\text{mol/min})\ @\ 50°\text{C}\\
0.999\ H_2O & 0.05\ \text{NaOH}\\
25°\text{C} & 0.95\ H_2O
\end{array}
$$
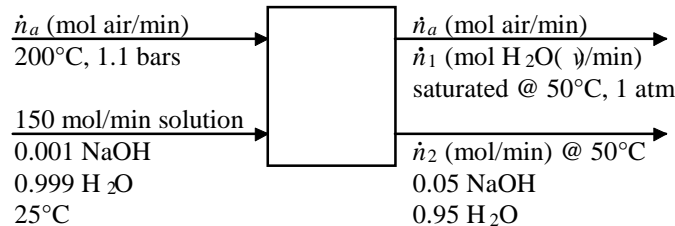
NaOH balance: $(0.001)(150)=0.05\dot{n}_2\Rightarrow\dot{n}_2=3.0\ \text{mol/min}$

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

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

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

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

0.1% solution @ 25°C: $r=\dfrac{999\ \text{mol }H_2O}{1\ \text{mol NaOH}}\overset{\text{Table B.11}}{\Rightarrow}\Delta\hat{H}_s(25°\text{C})=-42.47\ \text{kJ/mol NaOH}$

5% solution @ 50°C: $r=\dfrac{95\ \text{mol }H_2O}{5\ \text{mol NaOH}}=\dfrac{19\ \text{mol }H_2O}{\text{mol NaOH}}\Rightarrow\Delta\hat{H}_s(25°\text{C})=-42.81\dfrac{\text{kJ}}{\text{mol NaOH}}$

Solution mass: $m=\dfrac{\left|\ 1\ \text{mol NaOH}\ \right|\ 40.0\ \text{g}}{\left|\qquad\qquad\right|\ 1\ \text{mol}}+\dfrac{\left|\ 19\ \text{mol }H_2O\ \right|\ 18.0\ \text{g}}{\left|\qquad\qquad\right|\ 1\ \text{mol}}=382\ \dfrac{\text{g solution}}{\text{mol NaOH}}$

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

$$=-42.81\frac{\text{kJ}}{\text{mol NaOH}}+\frac{\left|\ 382\ \text{g}\ \right|\ 4.184\ \text{J}\ \left|\ (50-25)°\text{C}\ \right|\ 1\ \text{kJ}}{\text{mol NaOH}\ \left|\ 1\ \text{g·°C}\ \right|\qquad\qquad\ \left|\ 10^3\ \text{J}\right.}=-2.85\ \text{kJ}$$

8.87 (cont'd)

Air @ 200°C: Table B.8 $\Rightarrow \hat{H} = 5.15$ kJ/mol

Air (dry) @ 50°C: Table B.8 $\Rightarrow \hat{H} = 0.73$ kJ/mol

$H_2O(v, 50°C)$: Table B.5 $\Rightarrow \hat{H} = \dfrac{(2592 - 104.8) \text{ kJ}}{\text{kg}} \left| \dfrac{1 \text{ kg}}{10^3 \text{ g}} \right| \dfrac{18.0 \text{ g}}{1 \text{ mol}} = 44.81$ kJ/mol

substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
$NaOH(aq)$	0.15	−42.47	0.15	−2.85	$\dot{n}$ in mol/min
$H_2O(v)$	–	–	147	44.81	$\hat{H}$ in kJ/mol
Dry air	1061	5.15	1061	0.73	

$\underset{(\text{neglect } \Delta E_n)}{\underline{\text{Energy balance:}}}$ $\dot{Q} = \Delta\dot{H} = \sum\limits_{out} n_i \hat{H}_i - \sum\limits_{in} n_i \hat{H}_i = \underline{\underline{1900 \text{ kJ/min}}}$ transferred to unit

8.88 a. Basis: 1 L 4.00 molar H_2SO_4 solution (S.G. = 1.231)

$\dfrac{1 \text{ L}}{} \left| \dfrac{1231 \text{ g}}{\text{L}} \right| = 1231 \text{ g} \Rightarrow \dfrac{4.00 \text{ mol } H_2SO_4}{} = \underline{\underline{392.3 \text{ g } H_2SO_4}} \Rightarrow \dfrac{1231 - 392.3 = \underline{\underline{838.7 \text{ g } H_2O}}}{= 46.57 \text{ mol } H_2O}$

$\Rightarrow r = 11.64 \text{ mol } H_2O / \text{mol } H_2SO_4 \xrightarrow{\text{Table B.11}} \Delta\hat{H}_s = -67.6 \text{ kJ} / \text{mol } H_2SO_4$

Ref: $H_2O(l, 25°C), H_2SO_4(25°C)$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
$H_2O(l)$	46.57	$0.0754(T - 25)$	–	–	n in mol
$H_2SO_4(l)$	4.00	0	–	–	$\hat{H}$ in kJ/mol
$H_2SO_4(25°C, n = 11.64)$	–	–	4.00	−67.6	

$Q = \Delta H = 0 = 4.00(-67.6) - 46.57(0.0754)(T - 25) \Rightarrow \underline{\underline{T = -52°C}}$

(The water would not be liquid at this temperature ⇒ impossible alternative!)

b. Ref: $H_2O(l, 25°C), H_2SO_4(25°C)$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
$H_2O(l)$	n_l	$0.0754(0 - 25)$	–	–	n in mols
$H_2O(s)$	n_s	$-6.01 + 0.0754(0 - 25)$	–	–	$\hat{H}$ in kJ/mol
$H_2SO_4(l)$	4.00	0	–	–	
$H_2SO_4(25°C, n = 11.64)$			4.00	−67.61	

$\Delta\hat{H}_m \underset{\underset{\text{Table B.1}}{\uparrow}}{(H_2O, 0°C)} = 6.01$ kJ/mol

$\left.\begin{array}{l} n_\ell + n_s = 46.57 \\ \Delta H = 0 = 4.00(-67.61) - n_l(-1.885) - (46.57 - n_l)(-7.895) \end{array}\right\} \Rightarrow \begin{array}{l} n_l = 16.18 \text{ mol liquid } H_2O \\ n_s = 30.39 \text{ mol ice} \end{array}$

$\Rightarrow \underline{\underline{291.4 \text{ g } H_2O(\ell) + 547.3 \text{ g } H_2O(s) @ 0°C}}$

8.89 $P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

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

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

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

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

$\begin{array}{l} \text{1 lb}_m\text{solution, 125°F} \\ \left(\begin{array}{l} 0.3867 \text{ lb}_m\text{H}_3\text{PO}_4 \\ 0.6133 \text{ lb}_m\text{H}_2\text{O} \end{array} \right) \end{array}$ → [box] → $m_1 (\text{lb}_m H_2O(v)), \ T, \ 3.7 \text{ psia}$

$m_2 (\text{lb}_m \text{ solution}), T$
$\left(\begin{array}{l} 0.5800 \text{ lb}_m\text{H}_3\text{PO}_4/\text{lb}_m \\ 0.4200 \text{ lb}_m\text{H}_2\text{O}/\text{lb}_m \end{array} \right)$
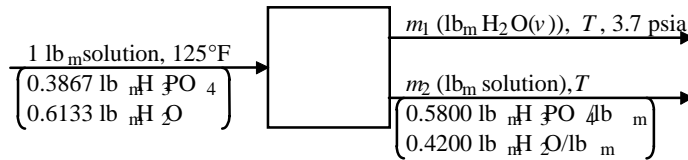
<u>H_3PO_4 balance:</u> $0.3867 = 0.5800m_2 \Rightarrow m_2\, 0.667 \text{ lb}_m \text{ solution}$

<u>Total balance:</u> $1 = m_1 + m_2 \Rightarrow m_1 = 0.3333 \text{ lb}_m\, H_2O(r)$

<u>Evaporation ratio:</u> $0.3333 \text{ lb}_m\, H_2O(v)/\text{lb}_m \text{ feed solution}$

c. <u>Condensate:</u>

$P = 3.7 \text{ psia } (0.255 \text{ bar})$

$\overset{\text{Table B.6}}{\Rightarrow} T_{sat} = 65.4°C = 149°F, \ V_{liq} = \dfrac{0.00102 \text{ m}^3}{\text{kg}} \left| \dfrac{35.3145 \text{ ft}^3 / \text{m}^3}{2.205 \text{ lb}_m / \text{kg}} \right. = 0.0163 \dfrac{\text{ft}^3}{\text{lb}_m\, H_2O(l)}$

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

$\dot{V} = \dfrac{46.3 \text{ lb}_m}{\text{min}} \left| \dfrac{0.0163 \text{ ft}^3}{\text{lb}_m} \right| \dfrac{7.4805 \text{ gal}}{\text{ft}^3} = 5.65 \text{ gal condensate / min}$

<u>Heat of condensation process:</u>

$46.3 \text{lb}_m\, H_2O(v)/\text{min}$
$(149+37)°F, 3.7 \text{ psia}$ → [box] → $46.3 \text{lb}_m\, H_2O(l)/\text{min}$
$149°F, 3.7 \text{ psia}$
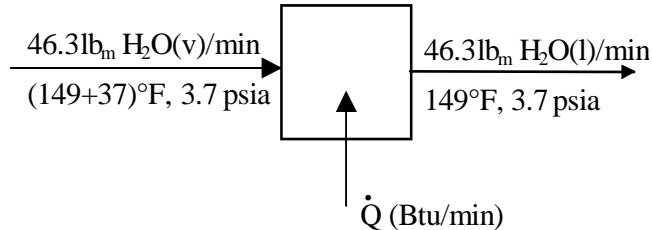
$\dot{Q}$ (Btu/min)

8.89 (cont'd)

$$\text{Table B.6} \Rightarrow \begin{cases} \hat{H}_{H_2O(v)}(186^\circ\text{F}=85.6^\circ\text{C}) = (2652 \text{ kJ}/\text{kg})\left(0.4303\frac{\text{Btu}/\text{lb}_m}{\text{kJ}/\text{kg}}\right) = 1141 \text{ Btu}/\text{lb}_m \\[3em] \hat{H}_{H_2O(l)}(149^\circ\text{F}=65.4^\circ\text{C}) = (274 \text{ kJ}/\text{kg})(0.4303) = 118 \text{ Btu}/\text{lb}_m \end{cases}$$

$$\dot{Q} = \dot{m}\Delta\hat{H} = (46.3\ \frac{\text{lb}_m}{\text{min}})\left[(118-1141)\frac{\text{Btu}}{\text{lb}_m}\right] = -47,360 \text{ Btu}/\text{min}$$

$$\Rightarrow \underline{\underline{4.74 \times 10^4\ \text{Btu/min available at } 149^\circ\text{F}}}$$

d. <u>Refs:</u> $H_3PO_4(l)$, $H_2O(l)$ @ 77°F

substance	m_{in}	$\hat{H}_{in}$	m_{out}	$\hat{H}_{out}$	
$H_3PO_4(28\%)$	1.00	13.95	–	–	m in lb_m
$H_3PO_4(42\%)$	–	–	0.667	34.13	$\hat{H}$ in Btu/lb_m
$H_2O(v)$	–	–	0.3333	1099	

$$\underline{\hat{H}(H_3PO_4,\ 28\%)} = \frac{-5040 \text{ Btu}}{\text{lb-mole } H_3PO_4}\left|\frac{1 \text{ lb-mole } H_3PO_3}{98.00 \text{ lb}_m \text{ } H_3PO_4}\right|\frac{0.3867 \text{ lb}_m \text{ } H_3PO_4}{1.00 \text{ lb}_m \text{ soln}}$$

$$+ \frac{0.705 \text{ Btu}}{\text{lb}_m \cdot ^\circ\text{F}}\left|\frac{(125-77)^\circ\text{F}}{}\right| = 13.95\ \text{Btu/lb}_m \text{ soln}$$

$$\underline{\hat{H}(H_3PO_4,\ 42\%)} = \frac{-5040 \text{ Btu}}{\text{lb-mole } H_3PO_4}\left|\frac{1 \text{ lb-mole } H_3PO_4}{98.00 \text{ lb}_m \text{ } H_3PO_4}\right|\frac{0.5800 \text{ lb}_m \text{ } H_3PO_4}{1.00 \text{ lb}_m \text{ sol.}}$$

$$+ \frac{0.705 \text{ Btu}}{\text{lb}_m \cdot ^\circ\text{F}}\left|\frac{(186.7-77)^\circ\text{F}}{}\right| = 34.13\ \text{Btu/lb}_m \text{ soln}$$

$$\hat{H}(H_2O) = \hat{H}(3.7\text{psia},\ 186^\circ\text{F}) - \hat{H}(l,\ 77^\circ\text{F}) = (2652-104.7)\ \text{kJ/kg} \Rightarrow 1096\ \text{Btu/lb}_m$$

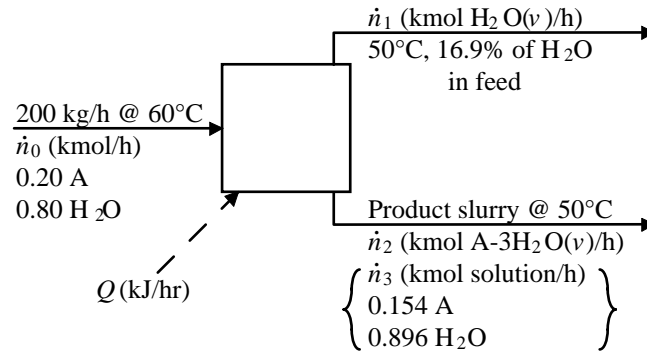At 27.6 psia (=1.90 bar), Table B.6 $\Rightarrow \Delta\hat{H}_v = 2206 \text{ kJ}/\text{kg} = 949 \text{ Btu}/\text{lb}_m$

$$\Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 375 \text{ Btu} = m_{steam}\Delta\hat{H}_v \Rightarrow m_{steam} = \frac{375 \text{ Btu}}{949 \text{ Btu}/\text{lb}_m} = 0.395 \text{ lb}_m \text{ steam}$$

$$\Rightarrow \frac{0.395 \text{ lb}_m \text{ steam}}{\text{lb}_m \text{ } 28\% \text{ } H_3PO_4}\left|\frac{100 \times 2000 \text{ lb}_m \text{ } H_3PO_4}{\text{day}}\right|\frac{1 \text{ day}}{24 \text{ h}} = \underline{\underline{3292 \text{ lb}_m \text{ steam}/\text{h}}}$$

$$\Rightarrow \frac{3292 \text{ lb}_m \text{ steam}}{(46.3 \times 60) \text{ lb}_m \text{ } H_2O \text{ evaporated}/\text{h}} = \underline{\underline{1.18\ \frac{\text{lb}_m \text{ steam}}{\text{lb}_m \text{ } H_2O \text{ evaporated}}}}$$

8.90 <u>Basis: 200 kg/h feed solution.</u> $A = NaC_2H_3O_2$

a. <u>Average molecular weight of feed solution:</u> $\overline{M} = 0.200 M_A + 0.800 M_{H_2O}$

$$= (0.200)(82.0) + (0.800)(18.0) = 30.8 \text{ kg/k}$$

<u>Molar flow rate of feed:</u> $n_0 = \dfrac{200 \text{ kg}}{h} \left| \dfrac{1 \text{ kmol}}{30.8 \text{ kg}} \right. = \underline{\underline{6.49 \text{ kmol/h}}}$

b. <u>16.9% evaporation</u> $\Rightarrow n_1 = (0.169)(0.80)(6.49 \text{ kmol/h}) = 0.877 \text{ kmol } H_2O(v)/h$

<u>A balance:</u> $(0.20)(6.49 \text{ kmol/h}) \underset{\Downarrow}{=} \dfrac{n_2(\text{kmol } A \cdot 3 H_2O)}{h} \left| \dfrac{1 \text{ mole } A}{1 \text{ mole } A \cdot 3 H_2O} \right. + 0.154 n_3$

$$\Rightarrow n_2 + 0.154 n_3 = 1.30 \qquad\qquad (1)$$

<u>H_2O balance:</u> $(0.80)(6.49 \text{ kmol/h}) = 0.877 + \dfrac{n_2(\text{kmol } A \cdot 3 H_2O)}{h} \left| \dfrac{3 \text{ moles } H_2O}{1 \text{ mole } A \cdot 3 H_2O} \right.$

$$+ 0.846 n_3 \Rightarrow 3n_2 + 0.846 n_3 = 4.315 \qquad\qquad (2)$$

<u>Solve (1) and (2) simultaneously</u> $\Rightarrow$ $n_2 = 1.13 \text{ kmol } A \cdot 3H_2O(s)/h$

$$n_3 = 1.095 \text{ kmol solution/h}$$

<u>Mass flow rate of crystals</u>

$$\dfrac{1.13 \text{ kmol } A \cdot 3H_2O}{h} \left| \dfrac{136 \text{ kg } A \cdot 3H_2O}{1 \text{ kmol}} \right. = \underline{\underline{\dfrac{154 \text{ kg } NaC_2H_3O_2 \cdot 3H_2O(s)}{h}}}$$

<u>Mass flow rate of product solution</u>

$$\dfrac{200 \text{ kg feed}}{h} - \dfrac{154 \text{ kg crystals}}{h} - \dfrac{(0.877)(18.0) \text{kg } H_2O(v)}{h} = \underline{\underline{30 \text{ kg solution/h}}}$$

c. <u>References for enthalpy calculations:</u> $NaC_2H_3O_2(s), H_2O(l) @ 25°C$

<u>Feed solution:</u> $n\hat{H} = n_A \Delta\hat{H}_s(25°C) + m\displaystyle\int_{25}^{60} C_p dT$ (form solution at $25°C$, heat to $60°C$)

$$n\hat{H} = \dfrac{(0.20)6.49 \text{ kmol } A}{h} \left| \dfrac{-1.71 \times 10^4 \text{ kJ}}{\text{kmol } A} \right. + \dfrac{200 \text{ kg}}{hr} \left| \dfrac{3.5 \text{ kJ}}{\text{kg·°C}} \right| \dfrac{(60-25)°C}{} = 2300 \text{ kJ/h}$$

8.90 (cont'd)

Product solution: $n\hat{H} = n_A \Delta \hat{H}_s (25°C) + m\int_{25}^{50} C_p dT$

$$= \frac{(0.154)1.095 \text{ kmol } A}{h} \left| \frac{-1.71 \times 10^4 \text{ kJ}}{\text{kmol } A} + \frac{30 \text{ kg}}{h} \right| \frac{3.5 \text{ kJ}}{\text{kg} \cdot °C} \left| \frac{(50-25)°C}{} \right.$$

$$= -259 \text{ kJ/h}$$

Crystals: $n\hat{H} = n_A \Delta \hat{H}_{hydration} + m\int_{25}^{50} C_p dT$ (hydrate at $25°C$, heat to $50°C$)

$$= \frac{1.13 \text{ kmol } A \cdot 3H_2O(s)}{h} \left| \frac{-3.66 \times 10^4 \text{ kJ}}{\text{kmol}} + \frac{154 \text{ kg}}{h} \right| \frac{1.2 \text{ kJ}}{\text{kg} \cdot °C} \left| \frac{(50-25)°C}{} \right.$$

$$= -36700 \text{ kJ/h}$$

$H_2O(v, 50°C)$: $n\Delta H = n\left[\Delta \hat{H}_v + \int_{25}^{50} C_p dT \right]$ (vaporize at $25°C$, heat to $50°C$)

$$= \frac{0.877 \text{ kmol } H_2O}{h} \left| \frac{\left[4.39 \times 10^4 + (32.4)(50-25) \right] \text{kJ}}{} \right. = 39200 \text{ kJ/h}$$

Energy balance: $Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \left[(-259 - 36700 + 39200) - (2300) \right] \text{ kJ/h}$
(neglect ΔE_R)

$$= \underline{\underline{-60 \text{ kJ/h}}} \quad \text{(Transfer heat from unit)}$$

8.91 $\dfrac{50 \text{ mL } H_2SO_4}{} \left| \dfrac{1.834 \text{ g}}{\text{mL}} \right. = 91.7 \text{ g } H_2SO_4 \Rightarrow 0.935 \text{ mol } H_2SO_4$

$\dfrac{84.2 \text{ mL } H_2O(l)}{} \left| \dfrac{1.00 \text{ g}}{\text{mL}} \right. = 84.2 \text{ g } H_2O(l) \Rightarrow 4.678 \text{ mol } H_2O(l)$
$\Rightarrow r = 5.00 \text{ mol } H_2O/\text{mol } H_2SO_4$

Ref: H_2O, H_2SO_4 @ 25 °C

$\hat{H}(H_2O(l), 15°C) = [0.0754 \text{ kJ} / (\text{mol} \cdot ° C)](15-25)°C = -0.754 \text{ kJ} / \text{mol}$

$\hat{H}(H_2SO_4, r = 5.00) = -58.03 \dfrac{\text{kJ}}{\text{mol}} + \dfrac{(91.7 + 84.2) \text{ g}}{0.935 \text{ mol } H_2SO_4} \left| \dfrac{2.43 \text{ J}}{\text{g} \cdot °C} \right| \dfrac{(T-25)°C}{} \left| \dfrac{1 \text{ kJ}}{10^3 \text{ J}} \right.$

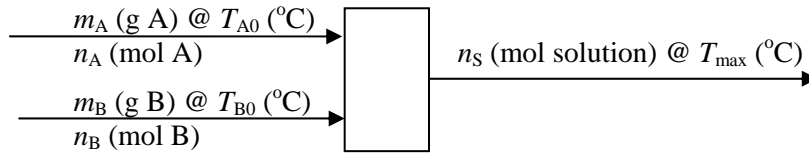$$= (-69.46 + 0.457T)(\text{kJ} / \text{mol } H_2SO_4)$$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
$H_2O(l)$	4.678	–0.754	—	—	n in mol
H_2SO_4	0.935	0.0	—	—	$\hat{H}$ in kJ/mol
$H_2SO_4(r = 4.00)$	—	—	0.935	$(-69.46 + 0.457T)$	n (mol H_3SO_4)

Energy Balance: $\Delta H = 0 = 0.935(-69.46 + 0.457T) - 4.678(-0.754) \Rightarrow \underline{T = 144 °C}$

Conditions: Adiabatic, negligible heat absorbed by the solution container.

8.92 a.

m_A (g A) @ T_{A0} (°C)
n_A (mol A)

m_B (g B) @ T_{B0} (°C)
n_B (mol B)

n_S (mol solution) @ T_{max} (°C)

Refs: A(l), B(l) @ 25 °C

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
A	n_A	$\hat{H}_A$	—	—
B	n_B	$\hat{H}_B$	—	—
S	—	—	n_A	$\hat{H}_S$ (J/mol A)

n in mol

$\hat{H}$ in J / mol

Moles of feed materials: n_A (mol A) $= \dfrac{m_A \text{ (g A)}}{M_A \text{ (g A / mol A)}}$, $n_B = \dfrac{m_B}{M_B}$

Enthalpies of feeds and product

$$\hat{H}_A = m_A C_{pA}(T_{A0} - 25°\text{C}),\ \hat{H}_B = m_B C_{pB}(T_{B0} - 25°\text{C})$$

$$r \text{ (mol B/mol A)} = n_B / n_A = \frac{m_B / M_B}{m_A / M_A}$$

$$\hat{H}_S \left(\frac{\text{J}}{\text{mol A}}\right) = \frac{1}{n_A \text{ (mol A)}}\left[\begin{array}{l} n_A \text{ (mol A)} \times \Delta\hat{H}_m(r)\left(\dfrac{\text{J}}{\text{mol A}}\right) \\[6pt] +\ (m_A + m_B)(\text{g soln}) \times C_{ps}\left(\dfrac{\text{J}}{\text{g soln} \cdot °\text{ C}}\right) \times (T_{max} - 25)(°\text{C}) \end{array}\right]$$

$$\Rightarrow \hat{H}_S = \frac{1}{n_A}\left[n_A \Delta\hat{H}_m(r) + (m_A + m_B)C_{ps}(T_{max} - 25)\right]$$

Energy balance

$$\Delta H = n_A \hat{H}_S - n_A \hat{H}_A - n_B \hat{H}_B = 0$$

$$\Rightarrow \frac{m_A}{M_A}\Delta\hat{H}_m(r) + (m_A + m_B)C_{ps}(T_{max} - 25) - m_A C_{pA}(T_{A0} - 25) - m_B C_{pB}(T_{B0} - 25) = 0$$

$$\Rightarrow T_{max} = 25 + \frac{m_A C_{pA}(T_{A0} - 25) + m_B C_{pB}(T_{B0} - 25) - \dfrac{m_A}{M_A}\Delta\hat{H}_m(r)}{(m_A + m_B)C_{ps}}$$

Conditions for validity: Adiabatic mixing; negligible heat absorbed by the solution container, negligible dependence of heat capacities on temperature between 25°C and T_{A0} for A, 25°C and T_{B0} for B, and 25°C and T_{max} for the solution.

b. $m_A = 100.0$ g $M_A = 40.00$ $T_{A0} = 25°$C $C_{pA} = ?(\text{irrelevant})$ $\left.\begin{array}{l}\\\\\end{array}\right\} \Rightarrow r = 5.00 \ \dfrac{\text{mol H}_2\text{O}}{\text{mol NaOH}}$

$m_B = 225.0$ g $M_B = 18.01$ $T_{B0} = 40°$C $C_{pB} = 4.18$ J/(g·°C)

$C_{ps} = 3.35$ J/(g·°C) $\Delta\hat{H}_m(n = 5.00) = -37,740$ J/mol A $\Rightarrow \underline{\underline{T_{max} = 125°\text{C}}}$

**8.93** <u>Refs:</u> Sulfuric acid and water @ 25 °C

b.

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
H_2SO_4	1	$M_A C_{pA}(T_0 - 25)$	—	—	n in mol
H_2O	r	$M_w C_{pw}(T_0 - 25)$	—	—	$\hat{H}$ 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)	

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

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

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

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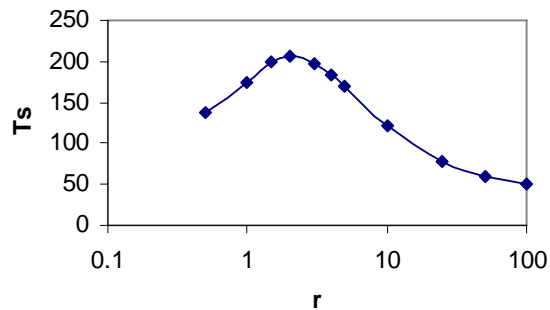
d. Some heat would be lost to the surroundings, leading to a lower final temperature.

8.94 a. <u>Ideal gas equation of state</u> $n_{A0} = P_0 V_g / RT_0$ (1)

<u>Total moles of B:</u> $n_{B0}(\text{mol B}) = \dfrac{V_l(\text{L}) \times \left(SG_B \times 1\,\text{kg / L}\right)\left(10^3\,\text{g / kg}\right)}{M_B\,(\text{g / mol B})}$ (2)

<u>Total moles of A:</u> $n_{Ao} = n_{Av} + n_{Al}$ (3)

<u>Henry's Law:</u> $r\left(\dfrac{\text{mol A(l)}}{\text{mol B}}\right) = k_s p_A \Rightarrow \dfrac{n_{Al}}{n_{B0}} = \left(c_0 + c_1 T\right) \dfrac{n_{Av} RT}{V_g}$ (4)

Solve (3) and (4) for n_{Al} and n_{Av}.

$$n_{Al} = \frac{\dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)}{\left[1 + \dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)\right]}$$ (5)

$$n_{Av} = \frac{n_{Ao}}{\left[1 + \dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)\right]}$$ (6)

<u>Ideal gas equation of state</u>

$$P = \frac{n_{Av}RT}{V_g} \overset{(6)}{=} \frac{n_{A0}RT}{V_g + n_{B0}RT\left(c_0 + c_1 T\right)}$$ (7)

<u>Refs:</u> $A(g), B(l)$ @ 298 K

substance	n_{in}	$\hat{U}_{\text{in}}$	n_{eq}	$\hat{U}_{\text{eq}}$
$A(g)$	n_{Ao}	$M_A C_{vA}\left(T_0 - 298\right)$	n_{Av}	$M_A C_{vA}\left(T - 298\right)$
$B(l)$	n_{B0}	$M_B C_{vB}\left(T_0 - 298\right)$	—	—
Solution	—	—	n_{Al}	$\hat{U}_1$ (kJ/mol A)

n in mol
$\hat{U}$ in kJ/mol

$$\hat{U}_1 = \Delta \hat{U}_s + \frac{1}{n_{Al}}\left(n_{Al} M_A + n_{B0} M_B\right)C_{vs}\left(T - 298\right)$$

<u>E.B.:</u> $\Delta U = 0 = \displaystyle\sum_{\text{out}} n_i \hat{U}_i - \sum_{\text{in}} n_i \hat{U}_i$

$$0 = \left(n_{Av} C_{vA} + \left(n_{Al} M_A + n_B M_B\right)C_{vs}\right)\left(T - 298\right) + n_{Al}\Delta\hat{U}_s - \left(n_{Ao} C_{vA} + n_B C_{vB}\right)\left(T_0 - 298\right)$$

$$\underline{\underline{\Rightarrow T = 298 + \frac{n_{Al}\left(-\Delta\hat{U}_s\right) + \left(n_{Ao} C_{vA} + n_B C_{vB}\right)\left(T_0 - 298\right)}{n_{Av} C_{vA} + \left(n_{Al} M_A + n_B M_B\right)C_{vs}}}}$$

8.94 (cont'd)

b.

Vt	MA	CvA	MB	CvB	SGB	c0	c1	Dus	Cvs
20.0	47.0	0.831	26.0	3.85	1.76	0.00154	-1.60E-06	-174000	3.80

Vl	T0	P0	Vg	nB0	nA0	T	nA(v)	nA(l)	P	Tcalc
3.0	300	1.0	17.0	203.1	0.691	301.4	0.526	0.164	0.8	301.4
3.0	300	5.0	17.0	203.1	3.453	307.0	2.624	0.828	3.9	307.0
3.0	300	10.0	17.0	203.1	6.906	313.9	5.234	1.671	7.9	313.9
3.0	300	20.0	17.0	203.1	13.811	327.6	10.414	3.397	16.5	327.6
3.0	330	1.0	17.0	203.1	0.628	331.3	0.473	0.155	0.8	331.3
3.0	330	5.0	17.0	203.1	3.139	336.4	2.359	0.779	3.8	336.4
3.0	330	10.0	17.0	203.1	6.278	342.8	4.709	1.569	7.8	342.8
3.0	330	20.0	17.0	203.1	12.555	355.3	9.381	3.174	16.1	355.3

c.

```
C*      REAL R, NB, T0, P0, VG, C, D, DUS, MA, MB, CVA, CVB, CVS
        REAL NA0, T, DEN, P, NAL, NAV, NUM, TN
        INTEGER K
        R = 0.08206
  1     READ (5, *) NB
        IF (NB.LT.0) STOP
        READ (1, *) T0, P0, VG, C, D, DUS, MA, MB, CVA, CVB, CVS
        WRITE (6, 900)
        NA0 = P0 * VG/R/T0
        T = 1.1 * T0
        K = 1
  10    DEN = VG/R/T/NB + C + D * T
        P = NA0/NB/DEN
        NAL = (C + D * T) * NA0/DEN
        NAV = VG/R/T/NB * NA0/DEN
        NUM = NAL * (–DUS) + (NA0 * CVA + NB * CVB) * (TO – 298)
        DEN = NAV * CVA + (NAL * MA + NB * MB) * CVS
        TN = 298 + NUM/DEN
        WRITE (6, 901) T, P, NAV, NAL, TN
        IF (ABS(T – TN).LT.0.01) GOTO 20
        K = K + 1
        T = TN
        IF (K.LT.15) GOTO 10
        WRITE (6, 902)
        STOP
  20    WRITE (6, 903)
        GOTO 1
  900   FORMAT ('T(assumed)    P    Nav    Nal    T(calc.)'/
      *         '    (K)    (atm) (mols) (mols)    (K)')
  901   FORMAT (F9.2, 2X, F6.3, 2X, F7.3, 2X, F7.3, 2X, F7.3, 2)
  902   FORMAT (' ***  DID NOT CONVERGE  ***')
  903   FORMAT ('CONVERGENCE'/)
        END
$ DATA
     300
     291        10.0        15.0        1.54E–3        –2.6E–6        –74
     35.0       18.0        0.0291       0.0754        4.2E–03
```

8.94 (cont'd)

300					
291	50.0	15.0	1.54E–3	–2.6E–6	–74
35.0	18.0	0.0291	0.0754	4.2E–03	
–1					

Program Output

T (assumed) (K)	P (atm)	Nav (mols)	Nal (mols)	T(calc.) (K)
321.10	8.019	4.579	1.703	296.542
296.54	7.415	4.571	1.711	296.568
296.57	7.416	4.571	1.711	<u>296.568</u>

Convergence

T (assumed) (K)	P (atm)	Nav (mols)	Nal (mols)	T(calc.) (K)
320.10	40.093	22.895	8.573	316.912
316.91	39.676	22.885	8.523	316.942
316.94	39.680	22.885	8.523	<u>316.942</u>

8.95

a.
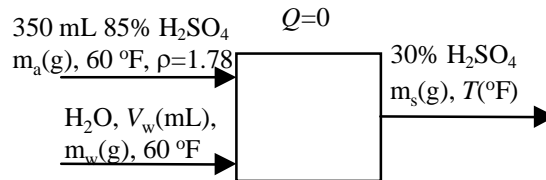
$$V_w = \frac{350 \text{ mL feed}}{} \left| \frac{1.78 \quad \text{g}}{1 \text{ mL feed}} \right| \frac{[0.85(70/30) - 0.15] \text{ g } H_2O \text{ added}}{\text{g feed}} \left| \frac{1 \text{ mL water}}{1 \text{ g water}} \right.$$

$$= \underline{\underline{1140 \text{ mL } H_2O}}$$

b. Fig. 8.5-1 $\Rightarrow \hat{H}_a \approx \underline{\underline{-103 \text{ Btu/lb}_m}}$;   Water: $\hat{H}_{water} \approx \underline{\underline{27 \text{ Btu/lb}_m}}$

Mass Balance: $m_p = m_f + m_w = (350 \text{ mL})(1.78 \text{ g/mL}) + (1142 \text{ mL})(1 \text{ g/mL}) = 623 + 1142 = 1765 \text{ g}$

Energy Balance: $\Delta H = 0 = m_p \hat{H}_{product} - m_a \hat{H}_a - m_w \hat{H}_w \Rightarrow \hat{H}_s = \dfrac{m_f \hat{H}_f + m_w \hat{H}_w}{m_p}$

$$\Rightarrow \hat{H}_{product} = \frac{(623)(-103) + (1140)(27)}{1765} = \underline{\underline{-18.9 \text{ Btu/lb}_m}}$$

c. $T(\hat{H} = -18.9 \text{ Btu/lb}_m, 30\%) \approx \underline{\underline{130^\circ \text{F}}}$

d. When acid is added slowly to water, the rate of temperature change is slow: few isotherms are crossed on Fig. 8.5-1 when x_{acid} increases by, say, 0.10. On the other hand, a change from $x_{acid}=1$ to $x_{acid}=0.9$ can lead to a temperature increase of 200°F or more.

8.96 a. 2.30 lb_m 15.0 wt% H_2SO_4

@ 77°F $\Rightarrow \hat{H}_1 = -10$ Btu / lb_m

$\xrightarrow{\text{adiabatic mixing}}$ m_3 (lb_m) 60.0 wt% H_2SO_4 @ T°F, $\hat{H}_3$

m_2 (lb_m) 80.0 wt% H_2SO_4

@ 60°F $\Rightarrow$ $\hat{H}_2 = -120$ Btu / lb_m

Total mass balance: $2.30 + m_2 = m_3$

H_2SO_4 mass balance: $2.30(0.150) + m_2(0.800) = m_3(0.600)$ $\Rightarrow$ $\begin{cases} m_2 = 5.17 \ lb_m \ (80\%) \\ m_3 = 7.47 \ lb_m \ (60\%) \end{cases}$

b. Adiabatic mixing $\Rightarrow Q = \Delta H = 0$

$(7.47)\hat{H}_3 - (2.30)(-10) - (5.17)(-120) = 0 \Rightarrow \hat{H}_3 = -86.1$ Btu / lb_m

$\Downarrow$ Figure 8.5 - 1

$T = 140°$ F

c. $\hat{H}\left(60 \text{ wt\%, } 77°F\right) = -130$ Btu / lb_m

$Q = m_3\left[\hat{H}\left(60 \text{ wt\%, } 77°F\right) - \hat{H}_3\right] = (7.475)(-130 + 86.1) = -328$ Btu

d. Add the concentrated solution to the dilute solution . The rate of temperature rise is much lower (isotherms are crossed at a lower rate) when moving from left to right on Figure 8.5-1.

8.97 a. $x_{NH_3} = 0.30 \xoverset{\text{Fig. 8.5-2}}{=\!=\!=\!\Longrightarrow} y_{NH_3} = 0.96 \ lb_m \ NH_3/lb_m$ vapor, $T = 80°$ F

b. Basis: 1 lb_m system mass $\Rightarrow 0.90 \ lb_m$ liquid $\xrightarrow{x_{NH_3} = 0.30}$ 0.27 lb_m NH_3

0.63 lb_m H_2O

$\Rightarrow 0.10 \ lb_m$ vapor $\xrightarrow{x_{NH_3} = 0.96}$ 0.096 lb_m NH_3

0.004 lb_m H_2O

Mass fractions: $z_{NH_3} = \dfrac{(0.27 + 0.096)lb_m \ NH_3}{1 \ lb_m} = 0.37 \ lb_m \ NH_3/lb_m$

$1 - 0.37 = 0.63 \ lb_m \ H_2O/lb_m$

Enthalpy: $\hat{H} = \dfrac{0.90 \ lb_m \text{ liquid}}{1 \ lb_m} \left|\dfrac{-25 \text{ Btu}}{1 \ lb_m \text{ liquid}}\right. + \dfrac{0.10 \ lb_m \text{ vapor}}{1 \ lb_m}\left|\dfrac{670 \text{ Btu}}{1 \ lb_m \text{ vapor}}\right. = 44 \ Btu/lb_m$

8.98

$T = 140° F$ $\xrightarrow{\text{Fig. 8.5-2}}$ Vapor: 80% NH_3, 20% H_2O

Liquid: 14% NH_3, 86% H_2O
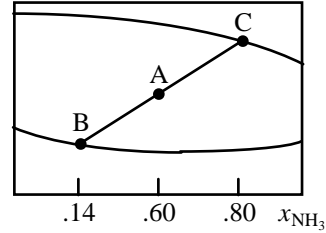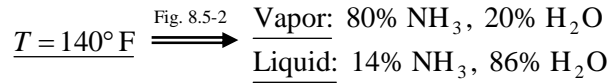
Basis: 250 g system mass

$\Rightarrow m_v$ (g vapor), m_L (g liquid)

Mass Balance: $m_v + m_L = 250$

NH$_3$ Balance: $0.80 m_g + 0.14 m_L = (0.60)(250) \Rightarrow m_v = 175$ g, $m_L = 75g$

$\Longrightarrow$
$\begin{cases} \underline{\text{Vapor:}}\ \ m_{NH_3} = (0.80)(175\ g) = \underline{\underline{140\ g\ NH_3,\ 35\ g\ H_2O}} \\[2mm] \underline{\text{Liquid:}}\ \ m_{NH_3} = (0.14)(75\ g) = \underline{\underline{10.5\ g\ NH_3,\ 64.5\ g\ H_2O\ \text{Liquid}}} \end{cases}$

8.99 Basis: 200 lb$_m$ feed/h

200 lb$_m$/h
0.70 lb$_m$ NH$_3$(aq)/lb$_m$
0.30 lb$_m$ H$_2$O(l)/lb$_m$
$\hat{H}_f = -50$ Btu/lb$_m$

$\dot{m}_v$ (lb$_m$/h)
x_v(lb$_m$ NH$_3$(g)/lb$_m$)
$\hat{H}_v$ (Btu/lb$_m$)

$\dot{m}_l$ (lb$_m$/h)
x_l[lb$_m$ NH$_3$(aq)/lb$_m$]
$\hat{H}_l$ (Btu/lb$_m$)

in equilibrium at 80°F

$\dot{Q}$(Btu/h)
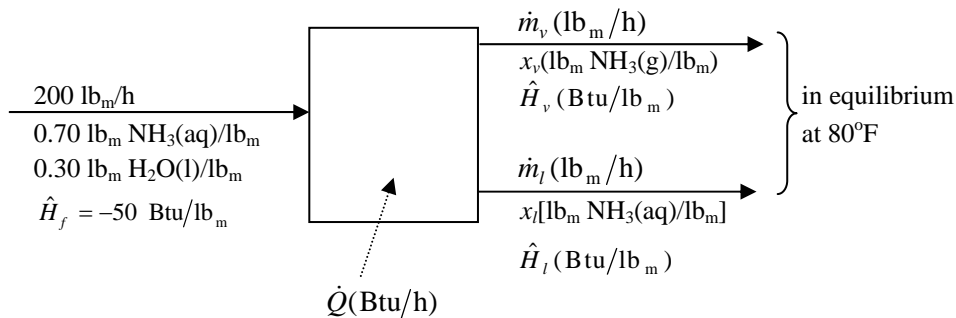
Figure 8.5-2 $\Rightarrow$ Mass fraction of NH$_3$ in vapor: $\underline{\underline{x_v = 0.96\ \text{lb}_m\ NH_3/\text{lb}_m}}$

Mass fraction of NH$_3$ in liquid: $\underline{\underline{x_l = 0.30\ \text{lb}_m\ NH_3/\text{lb}_m}}$

Specific enthalpies: $\hat{H}_v = 650$ Btu/lb$_m$, $\hat{H}_l = -30$ Btu/lb$_m$

Mass balance: $200 = \dot{m}_v + \dot{m}_l$

Ammonia balance: $(0.70)(200) = 0.96\dot{m}_v + 0.30\dot{m}_l$

$\Rightarrow$ $\dot{m}_v = \underline{\underline{120\ \text{lb}_m/\text{h vapor}}}$
$\dot{m}_l = \underline{\underline{80\ \text{lb}_m/\text{h liquid}}}$

Energy balance: Neglect $\Delta \dot{E}_k$.

$$\dot{Q} = \Delta \dot{H} = \sum_{out} \dot{m}_i \hat{H}_i - \dot{m}_f \hat{H}_f = \frac{120\ \text{lb}_m}{h} \left| \frac{650\ \text{Btu}}{\text{lb}_m} + \frac{80\ \text{lb}_m}{h} \right| \frac{-30\ \text{Btu}}{\text{lb}_m} - \frac{200\ \text{lb}_m}{h} \left| \frac{-50\ \text{Btu}}{\text{lb}_m} \right.$$

$$= \underline{\underline{86,000 \frac{\text{Btu}}{h}}}$$

CHAPTER NINE

**9.1** $4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$
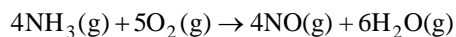
$\Delta \hat{H}_r^o = -904.7 \text{ kJ / mol}$

a. When 4 g-moles of $NH_3(g)$ and 5 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 4 g-moles of NO(g) and 6 g-moles of water vapor at 25°C and 1 atm, the change in enthalpy is -904.7 kJ.

b. Exothermic at 25°C. The reactor must be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the molecular bonds of the reactants is less than the energy released when the product bonds are formed.

c. $2NH_3(g) + \dfrac{5}{2}O_2(g) \rightarrow 2NO(g) + 3H_2O(g)$
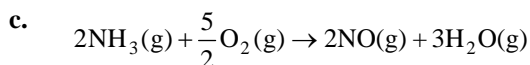
Reducing the stoichiometric coefficients of a reaction by half reduces the heat of reaction by half.

$\Delta \hat{H}_r^o = -\dfrac{904.7}{2} = \underline{\underline{-452.4 \text{ kJ / mol}}}$

d. $NO(g) + \dfrac{3}{2}H_2O(g) \rightarrow NH_3(g) + \dfrac{5}{4}O_2(g)$
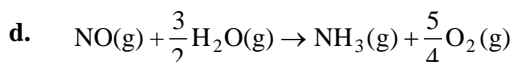
Reversing the reaction reverses the sign of the heat of reaction. Also reducing the stoichiometric coefficients to one-fourth reduces the heat of reaction to one-fourth.

$\Delta \hat{H}_r^o = -\dfrac{(-904.7)}{4} = \underline{\underline{+226.2 \text{ kJ / mol}}}$

e. $\dot{m}_{NH_3} = 340 \text{ g/s}$

$\dot{n}_{NH_3} = \dfrac{340 \text{ g}}{\text{s}} \left| \dfrac{1 \text{ mol}}{17.03 \text{ g}} \right. = 20.0 \text{ mol/s}$

$\dot{Q} = \Delta \dot{H} = \dfrac{\dot{n}_{NH_3} \Delta \hat{H}_r^o}{\nu_{NH_3}} = \dfrac{20.0 \text{ mol } NH_3}{\text{s}} \left| \dfrac{-904.7 \text{ kJ}}{4 \text{ mol } NH_3} \right. = \underline{\underline{-4.52 \times 10^3 \text{ kJ/s}}}$

The reactor pressure is low enough to have a negligible effect on enthalpy.

f. Yes. Pure water can only exist as vapor at 1 atm above 100°C, but in a mixture of gases, it can exist as vapor at lower temperatures.

9.2

$C_9H_{20}(l) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l)$
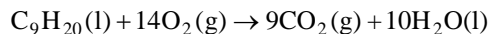
$\Delta \hat{H}_r^o = -6124 \text{ kJ / mol}$

a. When 1 g-mole of $C_9H_{20}(l)$ and 14 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 9 g-moles of $CO_2(g)$ and 10 g-moles of water vapor at 25°C and 1 atm, the change in enthalpy is -6124 kJ.

b. Exothermic at 25°C. The reactor must be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the molecular bonds of the reactants is less than the energy released when the product bonds are formed.

c. $\dot{Q} = \Delta \dot{H} = \dfrac{\dot{n}_{C_9H_{20}} \Delta \hat{H}_r^0}{\nu_{C_9H_{20}}} = \dfrac{25.0 \text{ mol } C_9H_{20}}{\text{s}} \left| \dfrac{-6124 \text{ kJ}}{1 \text{ mol } C_9H_{20}} \right| \dfrac{1 \text{ kW}}{1 \text{ kJ / s}} = \underline{\underline{-1.53 \times 10^5 \text{ kW}}}$

9.2 (cont'd)
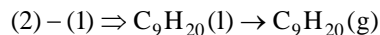
Heat Output $= 1.53 \times 10^5$ kW.
The reactor pressure is low enough to have a negligible effect on enthalpy.

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

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

$C_9H_{20}(l) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l)$ (2)

$\Delta \hat{H}_r^o = -6124 \text{ kJ / mol}$

$(2) - (1) \Rightarrow C_9H_{20}(l) \rightarrow C_9H_{20}(g)$
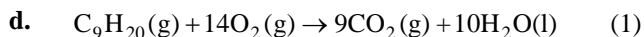
$\Delta \hat{H}_v^o (C_9H_{20}, 25°C) = -6124 \text{ kJ / mol} - (-6171 \text{ kJ / mol}) = \underline{47 \text{ kJ / mol}}$

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.
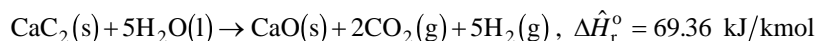
b.

$C_6H_{14}(g) + \dfrac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(g)$ (1) $\Delta \hat{H}_r^o = ?$

$C_6H_{14}(l) + \dfrac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(l)$ (2) $\Delta \hat{H}_2 = \Delta \hat{H}_r^o = -1.791 \times 10^6$ Btu/lb-mole

$C_6H_{14}(g) \rightarrow C_6H_{14}(l)$ (3) $\Delta \hat{H}_3 = -\left(\Delta \hat{H}_v\right)_{C_2H_{14}} = -13,550$ Btu/lb-mole

$H_2O(l) \rightarrow H_2O(g)$ (4) $\Delta \hat{H}_4 = \left(\Delta \hat{H}_v\right)_{H_2O} = 18,934$ Btu/lb-mole
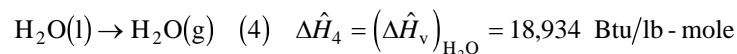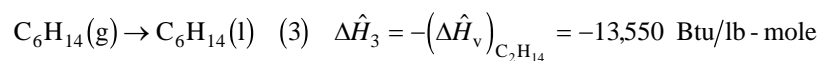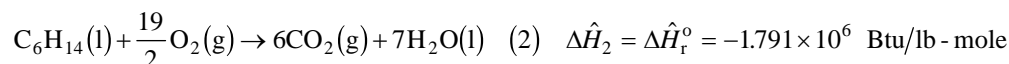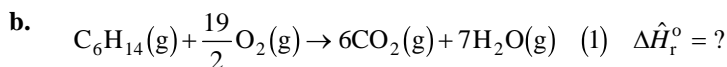
$(1) = (2) + (3) + 7 \times (4) \overset{\text{Hess's law}}{\Rightarrow} \Delta \hat{H}_1 = \Delta \hat{H}_2 + \Delta \hat{H}_3 + 7\Delta \hat{H}_4 = \underline{\underline{-1.672 \times 10^6}}$ Btu/lb-mole

c. $\dot{m} = 120 \text{ lb}_m / s \overset{M_{O_2} = 32.0}{\Rightarrow} \dot{n} = 3.75 \text{ lb-mole / s.}$

$\dot{Q} = \Delta \dot{H} = \dfrac{\dot{n}_{O_2} \Delta \hat{H}_r^o}{v_{O_2}} = \dfrac{3.75 \text{ lb-mole/s}}{9.5} \left| \dfrac{-1.672 \times 10^6 \text{ Btu}}{1 \text{ lb-mole } O_2} \right| = \underline{\underline{-6.60 \times 10^5 \text{ Btu/s}}}$ (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.

$\Delta \hat{U}_r^o = \Delta \hat{H}_r^o - RT \left[\displaystyle\sum_{\substack{\text{gaseous} \\ \text{products}}} v_i - \sum_{\substack{\text{gaseous} \\ \text{reactants}}} v_i \right] = 69.36 \dfrac{\text{kJ}}{\text{mol}} - \dfrac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \left| \dfrac{1 \text{ kJ}}{10^3 \text{ J}} \right| \dfrac{298 \text{ K}}{} \left| \dfrac{(7-0)}{} \right|$

$= \underline{\underline{52.0 \text{ kJ/mol}}}$

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. 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. $N_2(g) + O_2(g) \rightarrow 2NO(g)$, $\Delta\hat{H}_r^o = 2\left(\Delta\hat{H}_f^o\right)_{NO(g)} = 2\left(90.37 \overset{\text{Table B.1}}{\downarrow} \text{kJ/mol}\right) = \underline{\underline{180.74 \text{ kJ/mol}}}$

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. $Na_2SO_4(l) + 4CO(g) \rightarrow Na_2S(l) + 4CO_2(g)$

$$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{Na_2S(l)} + 4\left(\Delta\hat{H}_f^o\right)_{CO_2(g)} - \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(l)} - 4\left(\Delta\hat{H}_f^o\right)_{CO(g)}$$

$$= \left[(-373.2 + 6.7) + (4)(-393.5) - (-1384.5 + 24.3) - 4(-110.52\right] \text{ kJ/mol} = \underline{\underline{-138.2 \text{ kJ/mol}}}$$

9.8 **a.**

$$\Delta \hat{H}^o_{r1} = \left(\Delta \hat{H}^o_f\right)_{C_2H_2Cl_4\,(l)} - \left(\Delta \hat{H}^o_f\right)_{C_2H_4\,(g)} \Rightarrow \left(\Delta \hat{H}^o_f\right)_{C_2H_2Cl_4\,(l)} = -385.76 + 52.28 = \underline{\underline{-333.48}}\ \text{kJ/mol}$$
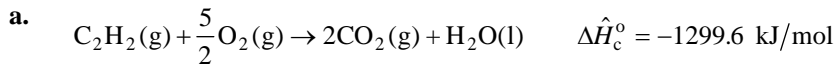
$$\Delta \hat{H}^o_{r2} = \left(\Delta \hat{H}^o_f\right)_{C_2HCl_3\,(l)} + \left(\Delta \hat{H}^o_f\right)_{HCl\,(g)} - \left(\Delta \hat{H}^o_f\right)_{C_2H_2Cl_4\,(l)} = -276.2 - 92.31 + 333.48 = \underline{\underline{-35.03}}\ \text{kJ/mol}$$

b.

Given reaction $= (1) + (2) \Rightarrow -385.76 - 35.03 = \underline{\underline{-420.79}}\ \text{kJ/mol}$

c.

$$\dot{Q} = \Delta \dot{H} = \frac{300\ \text{mol C}_2\text{HCl}_3}{h}\ \left|\ \frac{-420.79\ \text{kJ}}{\text{mol}}\right. = \underline{\underline{-1.26 \times 10^5}}\ \text{kJ/h}\ (= -35\ \text{kW})$$

Heat is evolved.

9.9

a.

$$C_2H_2(g) + \frac{5}{2}O_2(g) \rightarrow 2CO_2(g) + H_2O(l) \qquad \Delta \hat{H}^o_c = -1299.6\ \text{kJ/mol}$$

The enthalpy change when 1 g-mole of $C_2H_2(g)$ and 2.5 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 2 g-moles of $CO_2(g)$ and 1 g-mole of $H_2O(l)$ at 25°C and 1 atm is -1299.6 kJ.

b.

$$\Delta \hat{H}^o_c = 2\left(\Delta \hat{H}^o_f\right)_{CO_2\,(g)} + \left(\Delta \hat{H}^o_f\right)_{H_2O(l)} - \left(\Delta \hat{H}^o_f\right)_{C_2H_2\,(g)}$$

$$\overset{\underset{\text{Table B.1}}{\downarrow}}{=}\ \left[2(-393.5) + (-285.84) - (226.75)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-1299.6}}\ \frac{\text{kJ}}{\text{mol}}$$

c.

(i) $\Delta \hat{H}^o_r = \left(\Delta \hat{H}^o_f\right)_{C_2H_6\,(g)} - \left(\Delta \hat{H}^o_f\right)_{C_2H_2\,(g)}$

$$\overset{\underset{\text{Table B.1}}{\downarrow}}{=}\ \left[(-84.67) - (226.75)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-311.4}}\ \frac{\text{kJ}}{\text{mol}}$$

(ii) $\Delta \hat{H}^o_r = \left(\Delta \hat{H}^o_c\right)_{C_2H_2\,(g)} + 2\left(\Delta \hat{H}^o_c\right)_{H_2\,(g)} - \left(\Delta \hat{H}^o_c\right)_{C_2H_6\,(g)}$

$$\overset{\underset{\text{Table B.1}}{\downarrow}}{=}\ \left[(-1299.6) + 2(-285.84) - (-1559.9)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-311.4}}\ \frac{\text{kJ}}{\text{mol}}$$
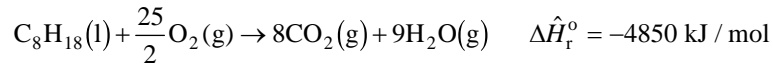
d.

$$C_2H_2(g) + \frac{5}{2}O_2(g) \rightarrow 2CO_2(g) + H_2O(l) \qquad (1)\quad \Delta \hat{H}^o_{c1} = -1299.6\ \text{kJ/mol}$$

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \qquad\qquad\qquad (2)\quad \Delta \hat{H}^o_{c2} = -285.84\ \text{kJ/mol}$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \qquad (3)\quad \Delta \hat{H}^o_{c3} = -1559.9\ \text{kJ/mol}$$
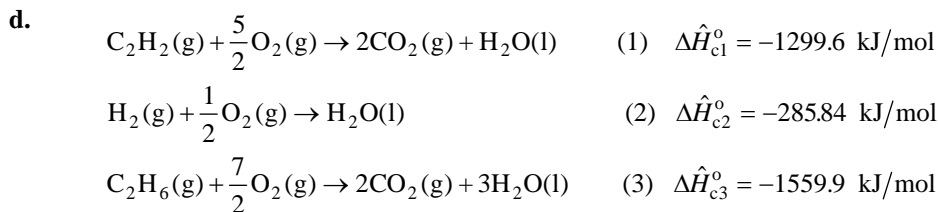
The acetylene dehydrogenation reaction is $(1) + 2 \times (2) - (3)$

$$\overset{\underset{\text{Hess's law}}{\Rightarrow}}{}\ \Delta \hat{H}^o_r = \Delta \hat{H}^o_{c1} + 2 \times \Delta \hat{H}^o_{c2} - \Delta \hat{H}^o_{c3}$$

$$= \left(-1299.6 + 2(-285.84) - (-1559.9)\right)\ \text{kJ/mol}\ = \underline{\underline{-311.4\ \text{kJ / mol}}}$$

9.10

a.

$$C_8H_{18}(l)+\frac{25}{2}O_2(g)\rightarrow 8CO_2(g)+9H_2O(g) \qquad \Delta\hat{H}_r^o = -4850 \text{ kJ / mol}$$

When 1 g-mole of $C_8H_{18}(l)$ and 12.5 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 8 g-moles of $CO_2(g)$ and 9 g-moles of $H_2O(g)$, the change in enthalpy equals -4850 kJ.

b. Energy balance on reaction system (not including heated water):

$$\Delta E_k, \ \Delta E_p, \ W=0 \Rightarrow Q=\Delta U = n(\text{mol } C_8H_{18} \text{ consumed})\Delta\hat{U}_c^o(\text{kJ/mol})$$

$(C_p)_{H_2O(l)}$ from Table B.2 $= 75.4\times 10^{-3}\text{kJ / mol.}^\circ C$

$$-Q = m_{H_2O}(C_p)_{H_2O(l)}\Delta T = \frac{1.00 \text{ kg}}{}\left|\frac{1 \text{ mol}}{18.0\times 10^{-3}\text{kg}}\right.\left|\frac{75.4\times 10^{-3}\text{kJ}}{\text{mol.}^\circ C}\right|\frac{21.34°C}{} = 89.4 \text{ kJ}$$

$$Q=\Delta U \Rightarrow -89.4 \text{ kJ} = \frac{2.01 \text{ g } C_8H_{18} \text{ consumed}}{}\left|\frac{1 \text{ mol } C_8H_{18}}{114.2 \text{ g}}\right|\frac{\Delta\hat{U}_c^o \text{ (kJ)}}{1 \text{ mol } C_8H_{18}}$$

$$\Rightarrow \underline{\underline{\Delta\hat{U}_c^o = -5079 \text{ kJ/mol}}}$$

$$\Delta\hat{H}_c^o = \Delta\hat{U}_c^o + RT\left[\underset{\substack{\text{gaseous}\\\text{products}}}{\sum} \nu_i - \underset{\substack{\text{gaseous}\\\text{reactants}}}{\sum}\nu_i\right]$$

$$=-5079 \text{ kJ/mol} + \frac{8.314 \text{ J}}{\text{mol}\cdot K}\left|\frac{1 \text{ kJ}}{10^3 \text{ J}}\right|\frac{298 \text{ K}}{}\left|(8+9-12.5)\right.$$

$$\Rightarrow \underline{\underline{\Delta\hat{H}_c^o = -5068 \text{ kJ/mol}}}$$

$$\% \text{ difference} = \frac{(-5068)-(-4850)}{|-5068|}\times 100 = -4.3 \text{ \%}$$

c.
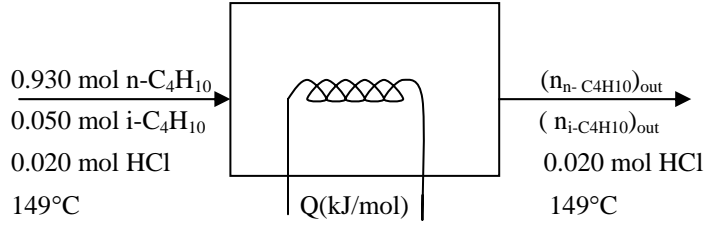
$$\Delta\hat{H}_c^o = 8\left(\Delta\hat{H}_f^o\right)_{CO_2(g)} + 9\left(\Delta\hat{H}_{ff}^o\right)_{H_2O(g)} - \left(\Delta\hat{H}_f^o\right)_{C_8H_{18}(l)}$$

$$\Rightarrow \left(\Delta\hat{H}_f^o\right)_{C_8H_{18}(l)} = \left[8(-393.5)+9(-241.83)+5068\right]\text{kJ/mol} = \underline{\underline{-256.5 \text{ kJ/mol}}}$$

There is no practical way to react carbon and hydrogen such that 2,3,3-trimethylpentane is the only product.

9.11 **a.** $n - C_4H_{10}(g) \rightarrow i - C_4H_{10}(g)$
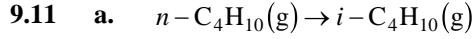
Basis: 1 mol feed gas

$(n_{n-CH_4H_{10}})_{out} = 0.930(1 - 0.400) = \underline{\underline{0.560 \text{ mol}}}$

$(n_{i-CH_4H_{10}})_{out} = 0.050 + 0.930 \times 0.400 = \underline{\underline{0.420 \text{ mol}}}$

$$\xi = \frac{\left|(n_{n-C_4H_{10}})_{out} - (n_{n-C_4H_{10}})_{in}\right|}{\left|\nu_{n-C_4H_{10}}\right|} = \frac{|0.560 - 0.930|}{|1|} = \underline{\underline{0.370 \text{ mol}}}$$

b. $\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{i-C_4H_{10}} - \left(\Delta\hat{H}_f^o\right)_{n-C_4H_{10}} \overset{\text{Table B.1}}{\Longrightarrow} \Delta\hat{H}_r^o = \left[-134.5 - (-124.7)\right] \text{ kJ/mol} = \underline{\underline{-9.8 \text{ kJ/mol}}}$

c. References: $n - C_4H_{10}(g),\ i - C_4H_{10}(g)$ at $25°C$

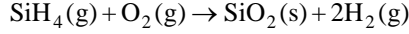| substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	(mol)	(kJ/mol)	(mol)	(kJ/mol)
$n - C_4H_{10}$	1	$\hat{H}_1$	0.600	$\hat{H}_1$
$i - C_4H_{10}$	–	–	0.400	$\hat{H}_2$

$\hat{H}_1 = \left[\int_{25}^{149} \overset{\text{Table B.2}}{\overset{\downarrow}{\hat{C}_p}} dT\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{14.29 \text{ kJ/mol}}}$ $\qquad$ $\hat{H}_2 = \left[\int_{25}^{149} \overset{\text{Table B.2}}{\overset{\downarrow}{\hat{C}_p}} dT\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{14.14 \text{ kJ/mol}}}$

$Q = \Delta H = \xi[\Delta\hat{H}_r^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i] = 0.370\left[-9.8 + (1)(14.142) - (1)(14.287)\right] \text{ kJ}$

$\qquad = \underline{\underline{-3.68 \text{ kJ}}}$

For 325 mol/h fed, $\dot{Q} = \dfrac{-9.8 \text{ kJ}}{1 \text{ mol feed}} \left|\dfrac{325 \text{ mol feed}}{\text{h}}\right| \dfrac{1 \text{ h}}{3600 \text{ s}} \left|\dfrac{1 \text{ kW}}{1 \text{ kJ/s}}\right| = \underline{\underline{-0.90 \text{ kW}}}$

d.

$\Delta\hat{H}_r(149°C) = \dfrac{-3.68 \text{ kJ}}{0.370 \text{ mol}} = \underline{\underline{-9.95 \text{ kJ/mol}}}$

9.12 **a.**

1 m³ at 298K, 3.00 torr → [reactor] → Products at 1375K, 3.00 torr

n_0 (mol)
0.111 mol SiH_4/mol
0.8889 mol O_2/mol

n_1 (mol O_2)
n_2 (mol SiO_2)
n_3 (mol H_2)

$SiH_4(g) + O_2(g) \rightarrow SiO_2(s) + 2H_2(g)$

Ideal Gas Equation of state : $n_o = \dfrac{1\ m^3}{} \left| \dfrac{273\ K}{298\ K} \right| \dfrac{3.00\ torr}{760\ torr} \left| \dfrac{1\ mol}{22.4 \times 10^{-3}\ m^3} \right. = 0.1614$ mol

$n_i = n_{io} + \nu_i \xi$

$\underline{SiH_4}$: $0 = 0.1111(0.1614\ mol) - \xi \Rightarrow \underline{\underline{\xi = 0.0179\ mol}}$

$\underline{O_2}$: $n_1 = 0.8889(0.1614\ mol) - \xi = \underline{\underline{0.1256\ mol\ O_2}}$

$\underline{SiO_2}$: $n_2 = \xi = \underline{\underline{0.0179\ mol\ SiO_2}}$

$\underline{H_2}$: $n_3 = 2\xi = \underline{\underline{0.0358\ mol\ H_2}}$

b. $\Delta \hat{H}_r^o = (\Delta \hat{H}_f^o)_{SiO_2(s)} - (\Delta \hat{H}_f^o)_{SiH_4(g)}$

$= [-851 - (-61.9)]\ kJ/mol = -789.1\ kJ/mol$

References : $SiH_4(g), O_2(g), SiO_2(g), H_2(g)$ at 298 K

Substance	n_{in} (mol/h)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol/h)	$\hat{H}_{out}$ (kJ/mol)
SiH_4	0.0179	0	–	–
O_2	0.1435	0	0.1256	$\hat{H}_1$
SiO_2	–	–	0.0179	$\hat{H}_2$
H_2	–	–	0.0358	$\hat{H}_3$

$O_2(g, 1375K)$: $\hat{H}_1 = \hat{H}_{O_2}(1102^{\circ}C) \overset{\text{Table B.8}}{=} 36.14\ kJ/mol$

$SiO_2(s, 1375K)$: $\hat{H}_2 = \int_{298}^{1375} (C_p)_{SiO_2(s)}\, dT = 79.18\ kJ/mol$

$H_2(g, 1375K)$: $\hat{H}_3 = \hat{H}_{H_2}(1102^{\circ}C) \overset{\text{Table B.8}}{=} 32.35\ kJ/mol$

c. $Q = \Delta H = \xi\, \Delta \hat{H}_r^o + \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = -7.01\ kJ/m^3$ feed

$\dot{Q} = \dfrac{-7.01\ kJ}{m^3} \left| \dfrac{27.5\ m^3}{h} \right| \dfrac{1\ h}{3600\ s} \left| \dfrac{1\ kW}{1\ kJ/s} \right. = \underline{\underline{-0.0536\ kW}}$ (transferred from reactor)

9.13 **a.** $Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(s) + 3CO(g)$, $\Delta\hat{H}_r (77°F) = 2.111 \times 10^5$ Btu/lb-mole

Basis: $\dfrac{2000 \text{ lb}_m \text{ Fe}}{} \left| \dfrac{1 \text{ lb-mole}}{55.85 \text{ lb}_m} \right. = 35.81$ lb-moles Fe produced

53.72 lb-moles CO produced

17.9 lb-moles Fe_2O_3 fed

53.72 lb-moles C fed

17.9 lb-moles Fe_2O_3 (s)
77° F

53.72 lb-moles C
77° F

35.81 lb-moles Fe (l)
2800° F

53.72 lb-moles CO(g)
570° F

Q (Btu/ton Fe)
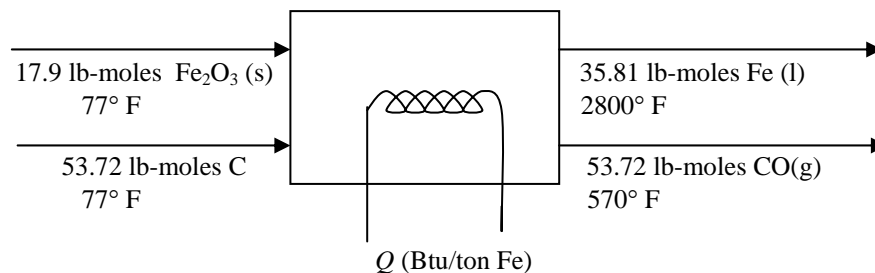
b. References: $Fe_2O_3(s)$, $C(s)$, $Fe(s)$, $CO(g)$ at 77° F

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	(lb-moles)	(Btu/lb-mole)	(lb-moles)	(Btu/lb-mole)
$Fe_2O_3(s,77°F)$	17.91	0	–	–
$C(s,77°F)$	53.72	0	–	–
$Fe(l,2800°F)$	–	–	35.81	$\hat{H}_1$
$CO(g,570°F)$	–	–	53.72	$\hat{H}_2$

$Fe(l,2800°F): \hat{H}_1 = \int_{77}^{2794} (C_p)_{Fe(s)} dT + \Delta\hat{H}_m (2794°F) + \int_{2794}^{2800} (C_p)_{Fe(l)} dT = \underline{\underline{28400}}$ Btu/lb-mole

$CO(g,570°F): \hat{H}_2 = \hat{H}_{CO}(570°F) \underset{\left(\substack{\text{interpolating} \\ \text{from Table B.9}}\right)}{=} \underline{\underline{3486}}$ Btu/lb-mole

c. $Q = \Delta H = \dfrac{n_{Fe}\Delta\hat{H}_r^o}{\nu_{Fe}} + \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i$

$= \dfrac{(35.81)(2.111 \times 10^5)}{2} + (35.81)(28400) + (53.72)(3486) - 0 = \underline{\underline{4.98 \times 10^6}}$ Btu / ton Fe produced
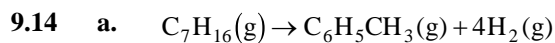
d. Effect of any pressure changes on enthalpy are neglected.

Specific heat of Fe(s) is assumed to vary linearly with temperature from 77°F to 570°F.

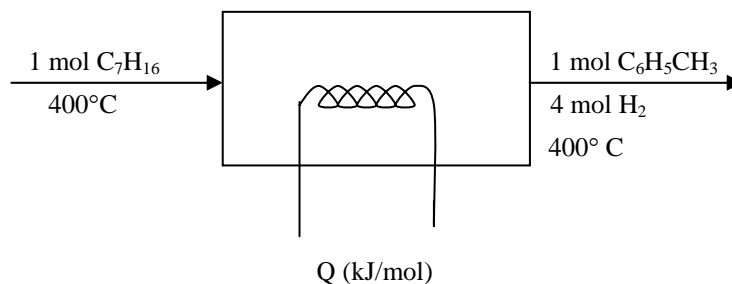Specific heat of Fe(l) is assumed to remain constant with temperature.

Reaction is complete.

No vaporization occurs.

9.14 **a.** $C_7H_{16}(g) \rightarrow C_6H_5CH_3(g) + 4H_2(g)$

<u>Basis</u>: 1 mol C_7H_{16}

$$\text{1 mol } C_7H_{16}$$
$$400°C$$

$$\text{1 mol } C_6H_5CH_3$$
$$\text{4 mol } H_2$$
$$400° \text{ C}$$

Q (kJ/mol)

b. <u>References</u>: $C(s), H_2(g)$ 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	$\hat{H}_3$

$$C_7H_{16}\left(g, 400°C\right): \hat{H}_1 = (\Delta \hat{H}_f^\circ)_{C_7H_{16}(g)} + \left[\int_{25}^{400} \overset{0.2427}{\overset{\downarrow}{C_p}} dT\right]$$

$$= (-187.8 + 91.0) \text{ kJ/mol} = \underline{\underline{-96.8 \text{ kJ/mol}}}$$

$$C_6H_5CH_3\left(g, 400°C\right): \ \hat{H}_2 = (\Delta \hat{H}_f^\circ)_{C_6H_5CH_3(g)} + \left[\int_{25}^{400} \overset{\text{Table B.2}}{\overset{\downarrow}{C_p}} dT\right]$$

$$= (+50 + 60.2) \text{ kJ / mol} = \underline{\underline{110.2 \text{ kJ / mol}}}$$

$$H_2\left(g, 400°C\right): \ \hat{H}_3 = \hat{H}_{H_2}\overset{\text{Table B.8}}{\overset{\downarrow}{(400°C)}} = \underline{\underline{10.89 \text{ kJ/mol}}}$$

c.

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i$$

$$= \left[(1)(110.2) + (4)(10.89) - (1)(-96.8)\right] \text{kJ} = 251 \text{ kJ (transferred to reactor)}$$
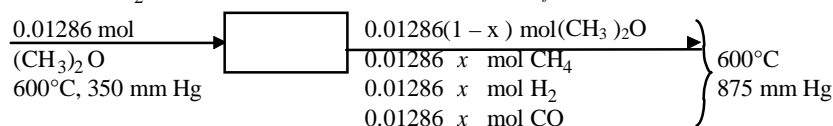
d. $\Delta \hat{H}_r(400°C) = \dfrac{251 \text{ kJ}}{1 \text{ mol } C_7H_{16} \text{ react}} = \underline{\underline{251 \text{ kJ/mol}}}$

9.15 **a.** $(CH_3)_2O(g) \rightarrow CH_4(g) + H_2(g) + CO(g)$
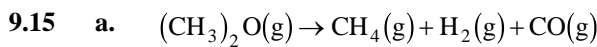
<u>Moles charged:</u> (Assume ideal gas)

$$\frac{2.00 \text{ liters} \mid 273 \text{ K} \mid 350 \text{ mm Hg} \mid}{\mid 873 \text{ K} \mid 760 \text{ mm Hg} \mid} \frac{1 \text{ mol}}{22.4 \text{ liters(STP)}} = 0.01286 \text{ mol } (CH_3)_2O$$

Let x = fraction $(CH_3)_2O$ decomposed (Clearly x<1 since $P_f < 3P_0$)

0.01286 mol		0.01286(1 – x) mol(CH₃)₂O	
(CH₃)₂O		0.01286 x mol CH₄	600°C
600°C, 350 mm Hg		0.01286 x mol H₂	875 mm Hg
		0.01286 x mol CO	

Total moles in tank at $t = 2h = 0.01286[(1-x) + 3x] = 0.01286(1+2x)$ mol

$$\frac{P_f V}{P_0 V} = \frac{n_f RT}{n_0 RT} \Rightarrow \frac{n_f}{n_0} = \frac{P_f}{P_0} \Rightarrow \frac{0.01286(1+2x)}{0.01286} = \frac{875}{350} \Rightarrow x = 0.75 \Rightarrow \underline{\underline{75\% \text{ decomposed}}}$$

b. <u>References:</u> $C(s)$, $H_2(g)$, $O_2(g)$ at $25°C$

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)
$(CH_3)_2O(g)$	0.01286	$\hat{H}_1$	0.25×0.01286	$\hat{H}_1$
$CH_4(g)$	–	–	0.75×0.01286	$\hat{H}_2$
$H_2(g)$	–	–	0.75×0.01286	$\hat{H}_3$
$CO(g)$	–	–	0.75×0.01286	$\hat{H}_4$

$(CH_3)_2O(g,600°C)$: $\hat{H}_1 = (\Delta\hat{H}_f^o)_{(CH_3)_2O} + \left[\int_{298}^{873 \overset{\text{given}}{\downarrow}} C_p dT \right] \frac{J}{mol} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} = (-180.16 \ + \ 62.40) \text{ kJ / mol}$

$$= \underline{\underline{-118 \text{ kJ/mol}}}$$

$CH_4(g,600°C): \hat{H}_2 = (\Delta\hat{H}_f^o)_{CH_4} + \left[\int_{25}^{600 \overset{\text{Table B.2}}{\downarrow}} C_p \ dT \right] = -74.85 + 29.46 = \underline{\underline{-45.39 \text{ kJ/mol}}}$

$H_2(g,600°C): \hat{H}_3 = \hat{H}_{H_2}(600°C) \overset{\text{Table B.8}}{\downarrow} = \underline{\underline{16.81 \text{ kJ/mol}}}$

$CO(g,600°C): \hat{H}_4 = (\Delta\hat{H}_f^o)_{CO} + \hat{H}_{CO}(600°C) = \ -110.52 + 17.57 \ \text{kJ/mol} \overset{\text{Table B.1} \atop \text{Table B.8}}{\downarrow} = \underline{\underline{-92.95 \text{ kJ/mol}}}$

c. For the reaction of parts (a) and (b), the enthalpy change and extent of reaction are :

$$\Delta H = \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in} = [-1.5515 - (-1.5175)] \text{ kJ} = -0.0340 \text{ kJ}$$

$$\xi = \frac{(n_{CH_4})_{out} - (n_{CH_4})_{in}}{\nu_{CH_4}} = \frac{0.75 \times 0.01286}{1} \text{mol} = 0.009645 \text{ mol}$$

$$\Delta H = \xi \, \Delta \hat{H}_r \left(600°C\right) \Rightarrow \Delta \hat{H}_r \left(600°C\right) = \frac{-0.0340 \text{ kJ}}{0.009645} = \underline{\underline{-3.53 \text{ kJ/mol}}}$$
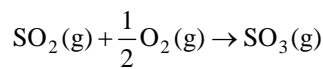
$$\Delta \hat{U}_r \left(600° C\right) = \Delta \hat{H}_r \left(600° C\right) - RT \Big[\underset{\substack{\text{gaseous} \\ \text{products}}}{\sum \nu_i} - \underset{\substack{\text{gaseous} \\ \text{reactants}}}{\sum \nu_i} \Big]$$
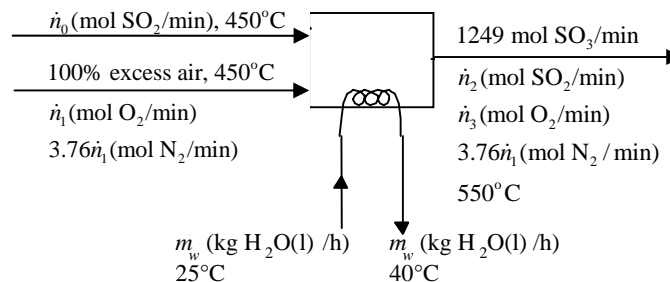
d.

$$= -3.53 \text{ kJ/mol} - \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right| \frac{873 \text{ K}}{} \left| \frac{(1+1+1-1)}{} \right| = \underline{\underline{-18.0 \text{ kJ/mol}}}$$

$$Q = \xi \, \Delta \hat{U}_r \left(600°C\right) = (0.009645 \text{ mol})(-18.0 \text{ kJ/mol}) = \underline{\underline{-0.174 \text{ kJ}}} \text{ (transferred from reactor)}$$

9.16 a. $SO_2(g) + \dfrac{1}{2} O_2(g) \rightarrow SO_3(g)$

Basis: $\dfrac{100 \text{ kg SO}_3}{\text{min}} \left| \dfrac{10^3 \text{ mol SO}_3}{80.07 \text{ kg SO}_3} \right| = 1249 \text{ mol SO}_3/\text{min}$

Assume low enough pressure for $\hat{H}$ to be independent of P.

$\dfrac{SO_3 \text{ balance :}}{\text{(Generation=output)}}$ $\dfrac{\dot{n}_0 \text{ (mol SO}_2 \text{ fed)}}{\text{min}} \left| \dfrac{0.65 \text{ mol SO}_2 \text{ react}}{1 \text{ mol SO}_2 \text{ fed}} \right| \dfrac{1 \text{ mol SO}_3 \text{ produced}}{1 \text{ mol SO}_2 \text{ react}} = 1249 \dfrac{\text{mol SO}_3}{\text{min}}$

$\Rightarrow \dot{n}_0 = \underline{\underline{1922 \text{ mol SO}_2 / \text{min fed}}}$

<u>100% excess air:</u> $\dot{n}_1 = \dfrac{1922 \text{ mol SO}_2}{\text{min}} \left| \dfrac{0.5 \text{ mol O}_2 \text{ reqd}}{1 \text{ mol SO}_2} \right| \dfrac{(1+1) \text{ mol O}_2 \text{ fed}}{1 \text{ mol O}_2 \text{ reqd}} = \underline{\underline{1922 \text{ mol O}_2/\text{min fed}}}$

<u>N$_2$ balance</u> : $3.76(1922) = \underline{\underline{7227 \text{ mol} / \text{min (in \& out)}}}$

<u>65% conversion :</u> $\dot{n}_2 = 1922(1-0.65) \text{ mol/s} = \underline{\underline{673 \text{ mol SO}_2/\text{min out}}}$

<u>O balance:</u> $(2)(1922) + (2)(1922) = (3)(1249) + (2)(673) + 2\dot{n}_3 \Rightarrow \dot{n}_3 = 1298 \text{ mol} / \text{min out}$

b.

$$\text{Extent of reaction}: \quad \dot{\xi} = \frac{\left|(\dot{n}_{SO_2})_{out} - (\dot{n}_{SO_2})_{in}\right|}{\left|\nu_{SO_2}\right|} = \frac{|673 - 1922|}{|1|} = \underline{\underline{1249 \text{ mol } / \text{min}}}$$

$$\Delta\hat{H}_r^o = (\Delta\hat{H}_f^o)_{SO_3(g)} - (\Delta\hat{H}_f^o)_{SO_2(g)} \overset{\overset{\text{Table B.1}}{\downarrow}}{=} -395.18 - (-296.9) = \underline{\underline{-99.28 \text{ kJ} / \text{mol}}}$$

$\underline{\text{References}}: \ SO_2(g), \ O_2(g), \ N_2(g), \ SO_3(g) \ \text{at} \ 25°C$

Substance	$\dot{n}_{in}$ (mol / min)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / min)	$\hat{H}_{out}$ (kJ / mol)
SO_2	1922	$\hat{H}_1$	673	$\hat{H}_4$
O_2	1922	$\hat{H}_2$	1298	$\hat{H}_5$
N_2	7227	$\hat{H}_3$	7227	$\hat{H}_6$
SO_3	–	–	1249	$\hat{H}_7$

$$SO_2(g, 450°C): \ \hat{H}_1 = \int_{25}^{450} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p} \ dT = \underline{\underline{19.62 \text{ kJ} / \text{mol}}}$$

$$O_2(g, 450°C) = \hat{H}_2 = \hat{H}_{O_2}(450°C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{13.36 \text{ kJ} / \text{mol}}}$$

$$N_2(g, 450°C) = \hat{H}_3 = \hat{H}_{N_2}(450°C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{12.69 \text{ kJ} / \text{mol}}}$$

$\underline{\text{Out}}:$

$$SO_2(g, 550°C): \ \hat{H}_4 = \int_{25}^{550} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p} \ dT = \underline{\underline{24.79 \text{ kJ/mol}}}$$

$$O_2(g, 550°C) = \hat{H}_5 = \hat{H}_{O_2}(550°C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{16.71 \text{ kJ} / \text{mol}}}$$

$$N_2(g, 550°C) = \hat{H}_6 = \hat{H}_{N_2}(550°C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{15.81 \text{ kJ} / \text{mol}}}$$

$$SO_3(g, 550°C): \ \hat{H}_7 = \int_{25}^{550} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p} \ dT = \underline{\underline{35.34 \text{ kJ} / \text{mol}}}$$

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r^o + \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i$$

$$= (1249)(-98.28) + (673)(24.796) + (179.8)(16.711) + (7227)(15.808) + (1249)(35.336) - (19$$

$$- 1922(13.362) - (7227)(12.691)$$

$$= \frac{-8.111\times10^4 \text{ kJ}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-1350 \text{ kW}}}$$

c.

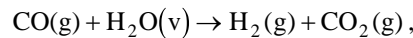Assume system is adiabatic, so that $\dot{Q}_{\text{lost from reactor}} = \dot{Q}_{\text{gained by cooling water}}$

9.16 (cont'd)

$$\dot{Q} = \Delta \dot{H} = \dot{m}_w \left[\hat{H}_w \underset{\underset{\text{Table B.5}}{\uparrow}}{\left(1, \ 40^\circ C\right)} - \hat{H}_w \underset{\underset{\text{Table B.5}}{\uparrow}}{\left(1, \ 25^\circ C\right)} \right]$$

d. $\Rightarrow 8.111 \times 10^4 \dfrac{\text{kJ}}{\text{min}} = \dot{m}_w \left(\dfrac{\text{kg}}{\text{min}} \right) [167.5 - 104.8] \dfrac{\text{kJ}}{\text{kg}} \Rightarrow \underline{\underline{\dot{m}_w = 1290 \ \text{kg/min cooling water}}}$
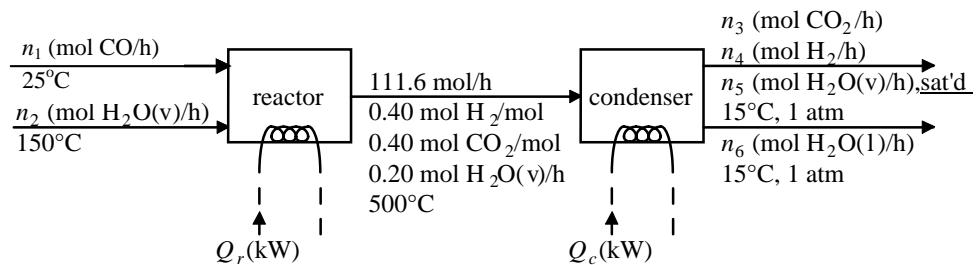
If elemental species were taken as references, the heats of formation of each molecular species would have to be taken into account in the enthalpy calculations and the heat of reaction term would not have been included in the calculation of $\Delta \dot{H}$.

9.17 $CO(g) + H_2O(v) \rightarrow H_2(g) + CO_2(g)$,

$$\Delta \hat{H}_r^\circ = \left(\Delta \hat{H}_f^\circ \right)_{CO_2(g)} - \left(\Delta \hat{H}_f^\circ \right)_{CO(g)} - \left(\Delta \hat{H}_f^\circ \right)_{H_2O(v)} \overset{\underset{\text{Table B.1}}{\downarrow}}{=} -41.15 \dfrac{\text{kJ}}{\text{mol}}$$

a.   Basis : $\left[2.5 \ \text{m}^3(\text{STP}) \ \text{product gas/h} \right] \left[1000 \ \text{mol} / 22.4 \ \text{m}^3 (\text{STP}) \right] = 111.6 \ \text{mol/h}$

C balance on reactor : $\dot{n}_1 = (0.40)(111.6 \ \text{mol/h}) = 44.64 \ \text{mol CO/h}$

H balance on reactor : $2\dot{n}_2 = 111.6 \left[(2)(0.40) + (2)(0.20) \right] \text{mol/h} \Rightarrow \dot{n}_2 = 66.96 \ \text{mol } H_2O(v)/h$

Steam theoretically required $= \dfrac{44.64 \ \text{mol CO}}{\text{h}} \left| \dfrac{1 \ \text{mol } H_2O}{1 \ \text{mol CO}} \right. = 44.64 \ \text{mol } H_2O$

% excess steam $= \dfrac{(66.96 - 44.64) \ \text{mol/h}}{44.64 \ \text{mol/h}} \times 100\% = \underline{\underline{50\% \ \text{excess steam}}}$

CO_2 balance on condenser : $\dot{n}_3 = (0.40)(111.6 \ \text{mol/h}) = 44.64 \ \text{mol } CO_2/h$

H_2 balance on condenser: $\dot{n}_4 = (0.40)(111.6 \ \text{mol/h}) = 44.64 \ \text{mol } H_2/h$

Saturation of condenser outlet gas:

$$y_{H_2O} = \dfrac{p_w^*(15^\circ C)}{p} \Rightarrow \dfrac{\dot{n}_5 (\text{mol } H_2O/h)}{(44.64 + 44.64 + \dot{n}_5)(\text{mol/h})} = \dfrac{12.788 \ \text{mm Hg}}{760 \ \text{mm Hg}} \Rightarrow \dot{n}_5 = 1.53 \ \text{mol } H_2O(v)/h$$

H_2O balance on condenser: $(111.6)(0.20)\text{mol } H_2O/h = 1.53 + \dot{n}_6$

$$\Rightarrow \dot{n}_6 = 20.8 \ \text{mol } H_2O/h \ \text{condensed} = \underline{\underline{0.374 \ \text{kg / h}}}$$

9.17 (cont'd)

b. Energy balance on condenser

References : $H_2(g)$, $CO_2(g)$ at $25°C$, H_2O at reference point of steam tables

Substance	$\dot{n}_{in}$ mol / h	$\hat{H}_{in}$ kJ / mol	$\dot{n}_{out}$ mol / h	$\hat{H}_{out}$ kJ / mol
$CO_2(g)$	44.64	$\hat{H}_1$	44.64	$\hat{H}_4$
$H_2(g)$	44.64	$\hat{H}_2$	44.64	$\hat{H}_5$
$H_2O(v)$	22.32	$\hat{H}_3$	1.53	$\hat{H}_6$
$H_2O(l)$	–	–	20.80	$\hat{H}_7$

Enthalpies for CO_2 and H_2 from Table B.8

$$CO_2(g,500°C) : \hat{H}_1 = \hat{H}_{CO_2}(500°C) = 21.34 \text{ kJ / mol}$$

$$H_2(g,500°C) : \hat{H}_2 = \hat{H}_{H_2}(500°C) = 13.83 \text{ kJ / mol}$$

$$H_2O(v,500°C) : \hat{H}_3 = 3488 \frac{kJ}{kg} \times \left(\frac{18 \text{ kg}}{10^3 \text{ mol}}\right) = 62.86 \text{ kJ/mol}$$

$$CO_2(g,15°C) : \hat{H}_4 = \hat{H}_{CO_2}(15°C) = -0.552 \text{ kJ/mol}$$

$$H_2(g,15°C) : \hat{H}_5 = \hat{H}_{H_2}(15°C) = -0.432 \text{ kJ / mol}$$

$$H_2O(v,15°C) : \hat{H}_6 = 2529 \frac{kJ}{kg} \times \left(\frac{18.0 \text{ kg}}{10^3 \text{ mol}}\right) = 45.52 \text{ kJ/mol}$$

$$H_2O(l,15°C) : \hat{H}_7 = 62.9 \frac{kJ}{kg} \times \left(\frac{18.0 \text{ kg}}{10^3 \text{ mol}}\right) = 1.13 \text{ kJ/mol}$$

$$\dot{Q} = \Delta\dot{H} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = \frac{(49.22 - 2971.8) \text{ kJ}}{h} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-0.812 \text{ kW}}}$$

(heat transferred from condenser)

c. Energy balance on reactor :

References : $H_2(g)$, $C(s)$, $O_2(g)$ at $25°C$

Substance	$\dot{n}_{in}$ (mol / h)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / h)	$\hat{H}_{out}$ (kJ / mol)
$CO(g)$	44.64	$\hat{H}_1$	–	–
$H_2O(v)$	66.96	$\hat{H}_2$	22.32	$\hat{H}_3$
$H_2(g)$	–	–	44.64	$\hat{H}_4$
$CO_2(g)$	–	–	44.64	$\hat{H}_5$

$$CO(g,25°C) : \hat{H}_1 = (\Delta\hat{H}_f°)_{CO} \overset{\text{Table B.1}}{=} \underline{\underline{-110.52 \text{ kJ / mol}}}$$

$$H_2O(v,150°C) : \hat{H}_2 = (\Delta\hat{H}_f°)_{H_2O(v)} + \hat{H}_{H_2O}(150°C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-237.56 \text{ kJ/mol}}}$$

9.17 (cont'd)

$$H_2O(v,500°C) : \hat{H}_3 = (\Delta\hat{H}_f°)_{H_2O(v)} + \hat{H}_{H_2O}(500°C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-224.82 \text{ kJ/mol}}}$$

$$H_2(g,500°C) : \hat{H}_4 = \hat{H}_{H_2}(500°C) \overset{\text{Table B.8}}{=} \underline{\underline{13.83 \text{ kJ / mol}}}$$

$$CO_2(g,500°C) : \hat{H}_5 = (\Delta\hat{H}_f°)_{CO_2} + \hat{H}_{CO_2}(500°C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-372.16 \text{ kJ / mol}}}$$

$$Q = \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \frac{[-21013.83 - (-20839.96)] \text{ kJ}}{h} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-0.0483 \text{ kW}}}$$

(heat transferred from reactor)

d.

Benefits

Preheating CO $\Rightarrow$ more heat transferred from reactor (possibly generate additional steam for plant)
Cooling CO $\Rightarrow$ lower cooling cost in condenser.

9.18 b.

References : FeO(s), CO(g), Fe(s), CO_2(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)
FeO	1.00	0	n_1	$\hat{H}_1$
CO	n_0	$\hat{H}_0$	n_2	$\hat{H}_2$
Fe	–	–	n_3	$\hat{H}_3$
CO_2	–	–	n_4	$\hat{H}_4$

$$Q = \xi \Delta \hat{H}_r^{\circ} + \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in}$$

$$\Rightarrow Q = \xi \Delta \hat{H}_r^{\circ} + n_1 \hat{H}_1 + n_2 \hat{H}_2 + n_3 \hat{H}_3 + n_4 \hat{H}_4 - n_0 \hat{H}_0$$

<u>Fractional Conversion</u> : $X = \dfrac{(1.00 - n_1)}{1.00} \Rightarrow \underline{\underline{n_1 = 1 - X}}$

<u>CO consumed</u> : $\dfrac{1 \text{ mol CO}}{1 \text{ mol FeO consumed}} \left| \dfrac{(1-n_1) \text{ mol FeO consumed}}{} \right. = (1-n_1) \text{ mol CO}$

$$\Rightarrow n_2 = n_0 - (1-n_1) = \underline{\underline{n_0 - X}}$$

<u>Fe produced</u> : $n_3 = \dfrac{1 \text{ mol Fe}}{1 \text{ mol FeO consumed}} \left| \dfrac{(1-n_1) \text{ mol FeO consumed}}{} \right. = (1-n_1) \text{ mol Fe} = \underline{\underline{X}}$

<u>CO_2 produced</u> : $n_4 = \dfrac{1 \text{ mol } CO_2}{1 \text{ mol FeO consumed}} \left| \dfrac{(1-n_1) \text{ mol FeO consumed}}{} \right. = (1-n_1) \text{ mol } CO_2 = \underline{\underline{X}}$

<u>Extent of reaction</u> : $\xi = \dfrac{\left|(n_{CO})_{out} - (n_{CO})_{in}\right|}{\left|v_{CO}\right|} = \dfrac{\left|n_2 - n_0\right|}{1} = \underline{\underline{X}}$

$$\hat{H}_i = \int_{25}^{T} C_{pi} dT \qquad \text{for } i = 0,1,2,3,4$$

$$\hat{H}_0 = 0.02761 \, (T_0 - 298) + 2.51 \times 10^{-6} (T_0^2 - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_0 = (-8.451 + 0.02761 \, T_0 + 2.51 \times 10^{-6} \, T_0^2) \text{ kJ / mol}}}$$

$$\hat{H}_1 = 0.0528 \, (T - 298) + 3.1215 \times 10^{-6} (T^2 - 298^2) + 3.188 \times 10^2 (1/T - 1/298)$$

$$\Rightarrow \underline{\underline{\hat{H}_1 = (-17.0814 + 0.0528 \, T + 3.1215 \times 10^{-6} T^2 + 3.188 \times 10^2 / T) \text{ kJ / mol}}}$$

$$\hat{H}_2 = (0.02761 \, (T - 298) + 2.51 \times 10^{-6} (T^2 - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_2 = -8.451 + 0.02761 \, T + 2.51 \times 10^{-6} \, T^2) \text{ kJ / mol}}}$$

$$\hat{H}_3 = 0.01728 \, (T - 298) + 1.335 \times 10^{-5} (T^2 - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_3 = (-6.335 + 0.01728 \, T + 1.335 \times 10^{-5} \, T^2) \text{ kJ / mol}}}$$

$$\hat{H}_4 = 0.04326(T - 298) + 0.573 \times 10^{-5} (T^2 - 298^2) + 8.18 \times 10^2 (1/T - 1/298)$$

$$\Rightarrow \underline{\underline{\hat{H}_4 = (-16.145 + 0.04326 \, T + 0.573 \times 10^{-5} T^2 + 8.18 \times 10^2 / T) \text{ kJ / mol}}}$$

9.18 (cont'd)

c. $n_0 = 2.0$ mol CO, $T_0 = 350$ K, $T = 550$ K, and $X = 0.700$ mol FeO reacted/mol FeO fed

$$\Rightarrow n_1 = 1 - 0.7 = 0.3, \ n_2 = 2 - 0.7 = 1.3, \ n_3 = 0.7, \ n_4 = 0.7, \ \xi = 0.7$$

Summary: $\hat{H}_0 = 1.520$ kJ/mol, $\hat{H}_1 = 13.48$ kJ/mol, $\hat{H}_2 = 7.494$ kJ/mol,

$\hat{H}_3 = 7.207$ kJ/mol, $\hat{H}_4 = 10.87$ kJ/mol

$\Delta \hat{H}_r^\circ = -16.48$ kJ/mol

$Q = (0.7)(-16.48) + (0.3)(13.48) + (1.3)(7.494) + (0.7)(7.207) + (0.7)(10.87) - (2)(1.520)$

$\Rightarrow Q = 11.86$ kJ

d.

no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	400	1	298	1	0	0	1	1	2.995	0	0	0	0	-19.48
1	400	1	400	1	0	0	1	1	2.995	5.335	2.995	2.713	4.121	-12.64
1	400	1	500	1	0	0	1	1	2.995	10.737	5.982	5.643	8.553	-5.279
1	400	1	600	1	0	0	1	1	2.995	16.254	9.019	8.839	13.237	2.601
1	400	1	700	1	0	0	1	1	2.995	21.864	12.11	12.303	18.113	10.941
1	400	1	800	1	0	0	1	1	2.995	27.555	15.24	16.033	23.152	19.71
1	400	1	900	1	0	0	1	1	2.995	33.321	18.43	20.031	28.339	28.895
1	400	1	1000	1	0	0	1	1	2.995	39.159	21.67	24.295	33.663	38.483

no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	298	1	700	1	0	0	1	1	0	21.864	12.11	12.303	18.113	13.936
1	400	1	700	1	0	0	1	1	2.995	21.864	12.11	12.303	18.113	10.941
1	500	1	700	1	0	0	1	1	5.982	21.864	12.11	12.303	18.113	7.954
1	600	1	700	1	0	0	1	1	9.019	21.864	12.11	12.303	18.113	4.917
1	700	1	700	1	0	0	1	1	12.11	21.864	12.11	12.303	18.113	1.83
1	800	1	700	1	0	0	1	1	15.24	21.864	12.11	12.303	18.113	-1.308
1	900	1	700	1	0	0	1	1	18.43	21.864	12.11	12.303	18.113	-4.495
1	1000	1	700	1	0	0	1	1	21.67	21.864	12.11	12.303	18.113	-7.733

no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	400	0	500	0	1	1	0	0	2.995	10.737	5.55	5.643	8.533	13.72
1	400	0.1	500	0.1	0.9	0.9	0.1	0.1	2.995	10.737	5.55	5.643	8.533	11.82
1	400	0.2	500	0.2	0.8	0.8	0.2	0.2	2.995	10.737	5.55	5.643	8.533	9.92
1	400	0.3	500	0.3	0.7	0.7	0.3	0.3	2.995	10.737	5.55	5.643	8.533	8.02
1	400	0.4	500	0.4	0.6	0.6	0.4	0.4	2.995	10.737	5.55	5.643	8.533	6.12
1	400	0.5	500	0.5	0.5	0.5	0.5	0.5	2.995	10.737	5.55	5.643	8.533	4.22
1	400	0.6	500	0.6	0.4	0.4	0.6	0.6	2.995	10.737	5.55	5.643	8.533	2.32
1	400	0.7	500	0.7	0.3	0.3	0.7	0.7	2.995	10.737	5.55	5.643	8.533	0.42
1	400	0.8	500	0.8	0.2	0.2	0.8	0.8	2.995	10.737	5.55	5.643	8.533	-1.48
1	400	0.9	500	0.9	0.1	0.1	0.9	0.9	2.995	10.737	5.55	5.643	8.533	-3.38
1	400	1	500	1	0	0	1	1	2.995	10.737	5.55	5.643	8.533	-5.28

no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
0.5	400	0.5	400	0.5	0.5	0.0	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
0.6	400	0.5	400	0.5	0.5	0.1	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
0.8	400	0.5	400	0.5	0.5	0.3	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.0	400	0.5	400	0.5	0.5	0.5	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653

1.2	400	0.5	400	0.5	0.5	0.7	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.4	400	0.5	400	0.5	0.5	0.9	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.6	400	0.5	400	0.5	0.5	1.1	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.8	400	0.5	400	0.5	0.5	1.3	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
2.0	400	0.5	400	0.5	0.5	1.5	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
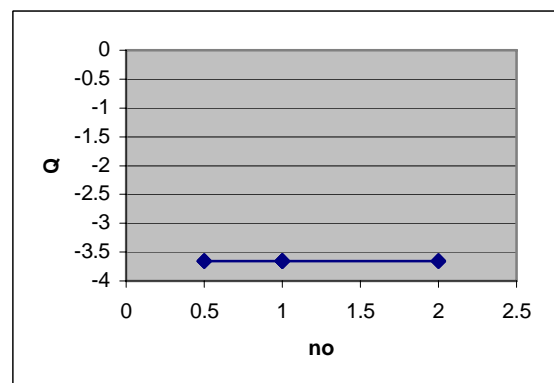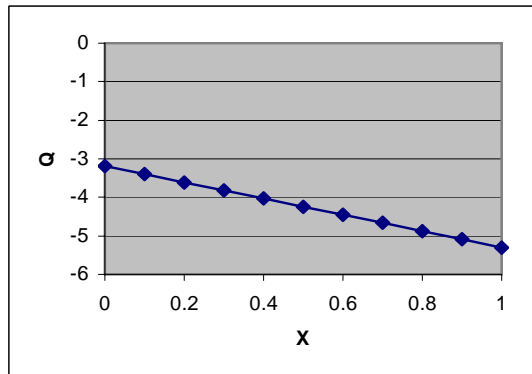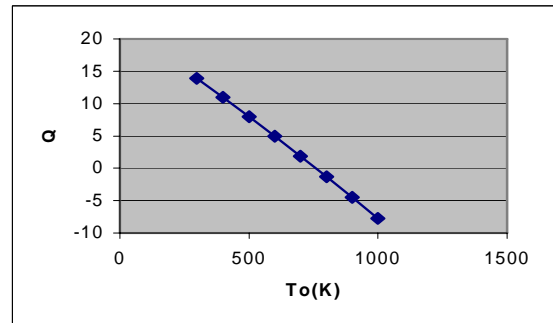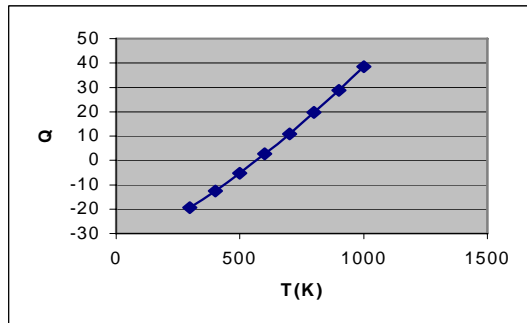
9.19   a.   Fermentor capacity : 550,000 gal

Solution volume : $(0.9 \times 550,000) = 495,000$ gal

Final reaction mixture : $\begin{cases} 0.071 \ lb_m \ C_2H_5OH \ / \ lb_m \ \text{solution} \\ 0.069 \ lb_m \ (\text{yeast, other species}) \ / \ lb_m \ \text{solution} \\ 0.86 \ lb \ H_2O \ / \ lb_m \ \text{solution} \end{cases}$

Mass of tank contents : $\dfrac{495,000 \ \text{gal}}{} \ \bigg| \ \dfrac{1 \ ft^3}{7.4805 \ \text{gal}} \ \bigg| \ \dfrac{65.52 \ lb_m}{1 \ ft^3} = 4335593 \ lb_m$

Mass of ethanol produced : $\dfrac{4.336 \times 10^6 \ lb_m \ \text{solution}}{} \ \bigg| \ \dfrac{0.071 \ lb_m \ C_2H_5OH}{lb_m \ \text{solution}} = \underline{\underline{3.078 \times 10^5 \ lb_m \ C_2H_5}}$

$\Rightarrow \dfrac{3.078 \times 10^5 \ lb_m \ C_2H_5OH}{} \ \bigg| \ \dfrac{1 \ lb\text{-mole} \ C_2H_5OH}{46.1 \ lb_m \ C_2H_5OH} = 6677 \ lb\text{-mole} \ C_2H_5OH$

$\Rightarrow \dfrac{307827 \ lb_m \ C_2H_5OH}{} \ \bigg| \ \dfrac{1 \ ft^3 \ C_2H_5OH}{49.67 \ lb_m \ C_2H_5OH} \ \bigg| \ \dfrac{7.4805 \ \text{gal}}{1 \ ft^3} = 46,360 \ \text{gal} \ C_2H_5OH$

9.19 (cont'd)

Makeup water required : $495,000 \text{ gal} - \dfrac{46,360 \text{ gal } C_2H_5OH}{} \left| \dfrac{25 \text{ gal mash}}{2.6 \text{ gal } C_2H_5OH} \right. = \underline{\underline{4.9 \times 10^4 \text{ gal}}}$

b. Acres reqd. : $\dfrac{46,360 \text{ gal } C_2H_5OH}{1 \text{ batch}} \left| \dfrac{1 \text{ bu}}{2.6 \text{ gal } C_2H_5OH} \right| \dfrac{1 \text{ acre}}{101 \text{ bu}} \left| \dfrac{1 \text{ batch}}{8 \text{ h}} \right| \dfrac{24 \text{ h}}{1 \text{ day}} \left| \dfrac{330 \text{ days}}{1 \text{ year}} \right. = \underline{\underline{1.75 \times 10^5 \dfrac{\text{acres}}{\text{year}}}}$
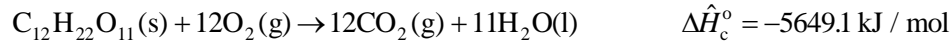
$C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l)$ $\qquad \Delta \hat{H}_c^o = -5649.1 \text{ kJ / mol}$

$\Delta \hat{H}_c^o = 12 \, \Delta \hat{H}_f^o (CO_2) + 11 \Delta \hat{H}_f^o (H_2O) - \Delta \hat{H}_f^o (C_{12}H_{22}O_{11})$

$\qquad \Rightarrow \Delta \hat{H}_f^o (C_{12}H_{22}O_{11}) = -2217.14 \text{ kJ / mol}$

$C_{12}H_{22}O_{11}(s) + H_2O(l) \rightarrow 4C_2H_5OH(l) + 4CO_2(g)$

$\Delta \hat{H}_r^o = 4 \, \Delta \hat{H}_f^o (C_2H_5OH) + 4 \, \Delta \hat{H}_f^o (CO_2) - \Delta \hat{H}_f^o (C_{12}H_{22}O_{11}) - \Delta \hat{H}_f^o (H_2O) = -184.5 \text{kJ / mol}$
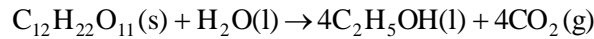
c. $\qquad \Rightarrow \Delta \hat{H}_r^o = \dfrac{-181.5 \text{ kJ}}{1 \text{ mol}} \left| \dfrac{453.6 \text{ mol}}{1 \text{ lb - mole}} \right| \dfrac{0.9486 \text{ Btu}}{1 \text{ kJ}} = \underline{\underline{-7.811 \times 10^4 \text{ Btu / lb - mole}}}$

Moles of maltose :

$\dfrac{4.336 \times 10^6 \text{ lb}_m \text{ solution}}{} \left| \dfrac{0.071 \text{ lb } C_2H_5OH}{1 \text{ lb}_m \text{ solution}} \right| \dfrac{1 \text{ lb - mole } C_2H_5OH}{46.1 \text{ lb } C_2H_5OH} \left| \dfrac{1 \text{ lb - mole } C_{12}H_{22}O_{11}}{4 \text{ lb - mole } C_2H_5OH} \right.$

$\qquad = 1669 \text{ lb - moles } C_{12}H_{22}O_{11} \; \Rightarrow \; \xi = n_{C_{10}H_{22}O_{11}} = 1669 \text{ lb - moles}$

$Q = \xi \Delta \hat{H}_r + mC_p(95°\text{F} - 85°\text{F})$

$\qquad = (1669 \text{ lb - moles})(-7.811 \times 10^4 \dfrac{\text{Btu}}{\text{lb - mole}}) + (4.336 \times 10^6 \text{ lb}_m)(0.95 \dfrac{\text{Btu}}{\text{lb -}°\text{F}})(10°\text{F})$

d. $\qquad = \underline{\underline{-8.9 \times 10^7 \text{ Btu}}}$ (heat transferred from reactor)

Brazil has a shortage of natural reserves of petroleum, unlike Venezuela.

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

$2NH_3 + \dfrac{3}{2}O_2 \rightarrow N_2 + 3H_2O$

References: $N_2(g), H_2(g), O_2(g),$ at 25°C

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
	(mol/min)	(kJ/mol)	(mol/min)	(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	$\hat{H}_6$

$\hat{H}_i = \Delta \hat{H}_{fi}^o + \displaystyle\int_{25}^{T} C_{pi} dT$

Table B.1
$\downarrow$

$NH_3(g, 25°C): \; \hat{H}_1 = (\Delta \hat{H}_f^o)_{NH_3} = \underline{\underline{-46.19 \text{ kJ/mol}}}$

9.20 (cont'd)

Table B.8
$$\downarrow$$
Air(g, 150°C): $\hat{H}_2$ = 3.67 kJ/mol

Table B.1, Table B.2
$$\downarrow$$
NO(g, 700°C): $\hat{H}_3 = 90.37 + \int_{25}^{700} C_p dT$ = 111.97 kJ/mol

Table B.1,
Table B.8
$$\downarrow$$
H_2O(g, 700°C): $\hat{H}_4$ = −216.91 kJ/mol

Table B.8
$$\downarrow$$
N_2(g, 700°C): $\hat{H}_5$ = 20.59 kJ/mol

Table B.8
$$\downarrow$$
O_2(g, 700°C): $\hat{H}_6$ = 21.86 kJ/mol

b. $\dot{Q} = \Delta \dot{H} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = -4890 \text{ kJ/min} \times (1 \text{ min} / 60s) = \underline{\underline{-81.5 \text{ kW}}}$

(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.** <u>Basis</u>: 1 mol feed

1 mol at 310°C		Products at 310°C
0.537 C_2H_4 (v)		n_1 (mol C_2H_4 (v))
0.367 H_2O (v)		n_2 (mol H_2O(v))
0.096 N_2(g)		0.096 mol N_2 (g)
		n_3 (mol C_2H_5OH (v))
		n_4 (mol $(C_2H_5)_2O$) (v))

$C_2H_4(v) + H_2O(v) \Leftrightarrow C_2H_5OH(v)$

$2C_2H_5OH(v) \Leftrightarrow (C_2H_5)_2O(v) + H_2O(v)$
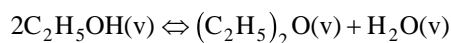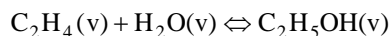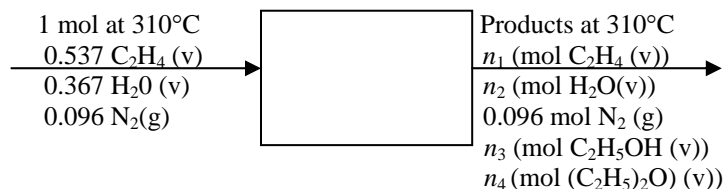
<u>5% ethylene conversion:</u> $(0.537)(0.05) = 0.02685 \text{ mol } C_2H_4$ consumed

$$\Rightarrow n_1 = (0.95)(0.537) = 0.510 \text{ mol } C_2H_4$$

<u>90% ethanol yield:</u>

$$n_3 = \frac{0.02685 \text{ mol } C_2H_4 \text{ consumed}}{} \left| \frac{0.9 \text{ mol } C_2H_5OH}{1 \text{ mol } C_2H_4} \right. = 0.02417 \text{ mol } C_2H_5OH$$

<u>C balance :</u> $(2)(0.537) = (2)(0.510) + (2)(0.02417) + 4n_4 \Rightarrow n_4 = 1.415 \times 10^{-3} \text{ mol } (C_2H_5)_2O$

<u>O balance :</u> $0.367 = n_2 + 0.02417 + 1.415 \times 10^{-3} \Rightarrow n_2 = 0.3414 \text{ mol } H_2O$

9.21 (cont'd)

References: $C(s)$, $H_2(g)$, $O_2(g)$ at 25°C, $N_2(g)$ at 310°C

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
C_2H_4	0.537	$\hat{H}_1$	0.510	$\hat{H}_1$
H_2O	0.367	$\hat{H}_2$	0.3414	$\hat{H}_2$
N_2	0.096	0	0.096	0
C_2H_5OH	–	–	0.02417	$\hat{H}_3$
$(C_2H_5)_2O$	–	–	1.415×10^{-3}	$\hat{H}_4$

$\underline{C_2H_4\,(g,\ 310°C)}$: $\hat{H}_1 = (\Delta\hat{H}_f^o)_{C_2H_4} + \int_{25}^{310} C_p dT \underset{\substack{\text{Table B.1 for }\Delta\hat{H}_f^o \\ \text{Table B.2 for } C_p}}{\Rightarrow} (52.28+16.41) = 68.69$ kJ/mol

$\underline{H_2O(g,\ 310°C)}$: $\hat{H}_2 = (\Delta\hat{H}_f^o)_{H_2O(v)} + \hat{H}_{H_2O(v)}(310°C) \underset{\substack{\text{Table B.1} \\ \text{Table B.8}}}{\Rightarrow} (-241.83+9.93) = -231.90$ kJ/mol

b.

$\underline{C_2H_5OH(g,\ 310°C)}$: $\hat{H}_3 = (\Delta\hat{H}_f^o)_{C_2H_5OH(g)} + \int_{25}^{310} C_p dT \underset{\substack{\text{Table B.1} \\ \text{Table B.2}}}{\Rightarrow} (-235.31+24.16) = -211.15$ kJ/mol

$\underline{(C_2H_5)_2O(g,\ 310°C)}$: $\hat{H}_4 = \left(\Delta\hat{H}_f^o\right)_{(C_2H_5)O(l)} + \Delta\hat{H}_v(25°C) + \int_{25}^{310} C_p dT = (-272.8 + 26.05 + 42.52)$

$= -204.2$ kJ/mol

Energy balance: $Q = \Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = -1.3$ kJ $\Rightarrow$ $\underline{\underline{1.3\ \text{kJ transferred from reactor/mol feed}}}$

To suppress the undesired side reaction. Separation of unconsumed reactants from products and recycle of ethylene.

9.22

$C_6H_5CH_3 + O_2 \rightarrow C_6H_5CHO + H_2O$

$C_6H_5CH_3 + 9O_2 \rightarrow 7CO_2 + 4H_2O$
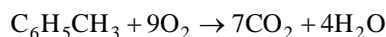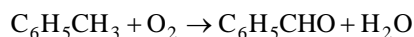
Basis: 100 lb-mole of $C_6H_5CH_3$ fed to reactor.
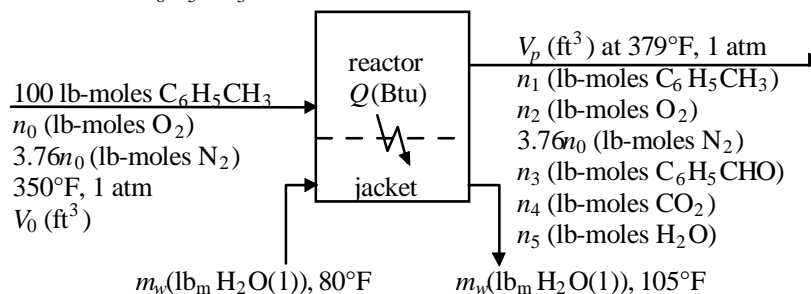
Strategy:

All material and energy balances will be performed for the assumed basis of 100 lb-mole $C_6H_5CH_3$. The calculated quantities will then be scaled to the known flow rate of water in the product gas $(29.3\ \text{lb}_m/4\ \text{h})$.

9.22 (cont'd)

Plan of attack: % excess air $\Rightarrow n_0$ Ideal gas equation of state $\Rightarrow V_0$

13% C_6H_5CHO formation $\Rightarrow n_3$ Ideal gas equation of state $\Rightarrow V_p$

0.5% CO_2 formation $\Rightarrow n_4$ E. B. on reactor $\Rightarrow Q$

C balance $\Rightarrow n_1$ E. B. on jacket $\Rightarrow m_w$

H balance $\Rightarrow n_5$ Scale V_0, V_p, Q, m_w by $(\dot{n}_5)$actual $/ (n_5)$basis

O balance $\Rightarrow n_2$

<u>100% excess air:</u>

$$n_0 = \frac{100 \text{ lb-moles } C_6H_5CH_3}{} \left| \frac{1 \text{ mol } O_2 \text{ reqd}}{1 \text{ mole } C_6H_5CH_3} \right| \frac{(1+1)\text{mole } O_2 \text{ fed}}{1 \text{ mol } O_2 \text{ reqd}} = 200 \text{ lb-moles } O_2$$

<u>N_2 feed $(\&\text{ output}) = 3.76(200)$lb-moles $N_2 = 752$ lb-moles N_2</u>

$$\underline{13\% \rightarrow C_6H_5CHO \Rightarrow n_3} = \frac{100 \text{ lb-moles } C_6H_5CH_3}{} \left| \frac{0.13 \text{ mole } C_6H_5CH_3 \text{ react}}{1 \text{ mole } C_6H_5CH_3 \text{ fed}} \right| \frac{1 \text{ mole } C_6H_5CHO \text{ formed}}{1 \text{ mole } C_6H_5CH_3 \text{ react}}$$

$$= 13 \text{ lb-moles } C_6H_5CHO$$

$$\underline{0.5\% \rightarrow CO_2 \Rightarrow n_4} = \frac{(100)(0.005)\text{lb-moles } C_6H_5CH_3 \text{ react}}{} \left| \frac{7 \text{ moles } CO_2}{1 \text{ mole } C_6H_5CH_3} \right| = 3.5 \text{ lb-moles } CO_2$$

<u>C balance:</u> $\overset{\overset{\text{mol C/mole } C_7H_8}{\downarrow}}{(100)(7)}$ lb-moles $C = 7n_1 + (13)(7) + (3.5)(1) \Rightarrow n_1 = 86.5$ lb-moles $C_6H_5CH_3$

<u>H balance:</u> $(100)(8)$lb-moles $H = (86.5)(8) + (13)(6) + 2n_5 \Rightarrow n_5 = 15.0$ lb-moles $H_2O(v)$

<u>O balance:</u> $(200)(2)$lb-moles $O = 2n_2 + (13)(1) + (3.5)(2) + (15)(1) \Rightarrow n_2 = 182.5$ lb-moles O_2

<u>Ideal gas law – inlet:</u>

$$V_0 = \frac{(100 + 200 + 752)\text{lb-moles}}{} \left| \frac{359 \text{ ft}^3 \text{(STP)}}{1 \text{ lb-moles}} \right| \frac{(350 + 460)^\circ R}{492^\circ R} = 6.218 \times 10^5 \text{ ft}^3$$

<u>Ideal gas law – outlet:</u>

$$V_p = \frac{\left(\overset{C_7H_8}{86.5} + \overset{O_2}{182.5} + \overset{C_7H_8O}{13} + \overset{CO_2}{3.5} + \overset{H_2O}{15} + \overset{N_2}{752}\right)\text{lb-moles}}{} \left| \frac{359 \text{ ft}^3}{1 \text{ lb-mole}} \right| \frac{(379 + 460)^\circ R}{492^\circ R} = 6.443 \times 10^5 \text{ ft}^3$$

9.22 (cont'd)

Energy balance on reactor (excluding cooling jacket)

References : $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at $25°C(77°F)$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	(lb - moles)	(Btu/lb - mole)	(lb - moles)	(Btu/lb - mole)
$C_6H_5CH_3$	100	$\hat{H}_1$	86.5	$\hat{H}_4$
O_2	200	$\hat{H}_2$	182.5	$\hat{H}_5$
N_2	752	$\hat{H}_3$	752	$\hat{H}_6$
C_6H_5CHO	–	–	13	$\hat{H}_7$
CO_2	–	–	3.5	$\hat{H}_8$
H_2O	–	–	15	$\hat{H}_9$

Enthalpies:

$$C_6H_5CH_3(g,T):\ \hat{H}(T)=\left[\overset{\overset{\text{Table B.1}}{\downarrow}}{\Delta\hat{H}_f^o}\ (kJ/mol)\times\frac{430.28\ \text{Btu/lb - mole}}{1\ kJ/mol}+31\frac{\text{Btu}}{\text{lb - mole}\cdot°F}(T-77)°F\right]$$

$C_6H_5CH_3(g,350°F):\hat{H}_1 = 2.998\times10^4\ \text{Btu/lb - mole}$

$C_6H_5CH_3(g,379°F):\hat{H}_4 = 3.088\times10^4\ \text{Btu/lb - mole}$

$C_6H_5CHO(g,T):\ \hat{H}(T)=\left[-17200+31(T-77)°F\right]\ \text{Btu/lb - mole}$

$\Rightarrow \hat{H}_7 = -7.83\times10^3\ \text{Btu/lb - mole}$

$O_2(g,350°F):\ \hat{H}_2 = \hat{H}_{O_2}(350°F)\overset{\overset{\text{Table B.9}}{\downarrow}}{=}\ 1.972\times10^3\ \text{Btu / lb – mole}$

$N_2(g,350°F):\ \hat{H}_3 = \hat{H}_{N_2}(350°F)\overset{\overset{\text{Table B.9}}{\downarrow}}{=}\ 1.911\times10^3\ \text{Btu / lb – mole}$

$O_2(g,379°F):\ \hat{H}_5 = \hat{H}_{O_2}(379°F)\overset{\overset{\text{Table B.9}}{\downarrow}}{=}\ 2.186\times10^3\ \text{Btu / lb – mole}$

$N_2(g,379°F):\ \hat{H}_6 = \hat{H}_{N_2}(379°F)\overset{\overset{\text{Table B.9}}{\downarrow}}{=}\ 2.116\times10^3\ \text{Btu / lb – mole}$

$CO_2(g,379°F):\ \hat{H}_8 = (\Delta\hat{H}_f^°)_{CO_2(g)}+\hat{H}_{CO_2}(379°F)\overset{\overset{\text{Table B.1 and B.9}}{\downarrow}}{=}\ -1.664\times10^5\ \text{Btu / lb – mole}$

$H_2O(g,379°F):\ \hat{H}_9 = (\Delta\hat{H}_f^°)_{H_2O(g)}+\hat{H}_{H_2O}(379°F)\overset{\overset{\text{Table B.1 and B.9}}{\downarrow}}{=}\ -1.016\times10^5\ \text{Btu / lb – mole}$

Energy Balance :

$$Q = \Delta H = \sum_{out}n_i\hat{H}_i - \sum_{in}n_i\hat{H}_i = -2.376\times10^6\ \text{Btu}$$

Energy balance on cooling jacket:

$$Q = \Delta H = m_w\int_{80}^{105}(C_p)_{H_2O(l)}dT$$

$\Downarrow$ $Q = +2.376\times10^4\ \text{Btu}$, $C_p = 1.0\ \text{Btu}/(\text{lb}_m\cdot°F)$

$$2.376\times10^6\,\text{Btu} = m_w(\text{lb}_m)\times1.0\frac{\text{Btu}}{\text{lb}_m\cdot°F}\times(105-80)°F \Rightarrow m_w = 9.504\times10^4\ \text{lb}_m\ H_2O(l)$$

9.22(cont'd)
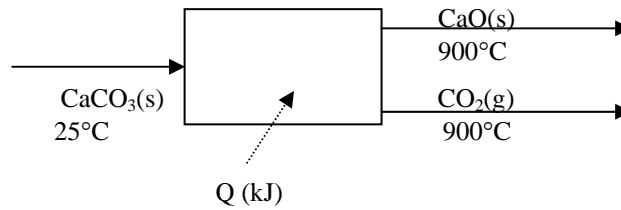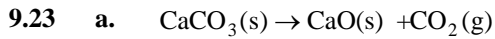
Scale factor: $\dfrac{(\dot{n}_5)_{\text{actual}}}{(n_5)_{\text{basis}}} = \dfrac{29.3\ \text{lb}_\text{m}\ \text{H}_2\text{O}}{4\ \text{h}}\ \bigg|\ \dfrac{1\text{b-mole}\ \text{H}_2\text{O}}{18.016\ \text{lb}_\text{m}\ \text{H}_2\text{O}}\ \bigg|\ \dfrac{1}{15.0\ \text{lb-moles}\ \text{H}_2\text{O}} = 0.02711\ \text{h}^{-1}$

a. $V_0 = \left(6.218 \times 10^5\ \text{ft}^3\right)\left(0.02711\ \text{h}^{-1}\right) = \underline{\underline{1.69 \times 10^4\ \text{ft}^3/\text{h}\ \ (\text{feed})}}$

$V_p = \left(6.443 \times 10^5\ \text{ft}^3\right)\left(0.02711\ \text{h}^{-1}\right) = \underline{\underline{1.75 \times 10^4\ \text{ft}^3/\text{h}\ \ (\text{product})}}$

b. $Q = \left(-2.376 \times 10^6\ \text{Btu}\right)\left(0.02711\ \text{h}^{-1}\right) = \underline{\underline{-6.44 \times 10^4\ \text{Btu/h}}}$

$\dot{m}_w = \left(9.504 \times 10^4\ \text{Btu}\right)\left(0.02711\ \text{h}^{-1}\right) = \dfrac{2577\ \text{lb}_\text{m}}{\text{h}}\ \bigg|\ \dfrac{1\ \text{ft}^3}{62.4\ \text{lb}_\text{m}}\ \bigg|\ \dfrac{7.4805\ \text{gal}}{1\ \text{ft}^3}\ \bigg|\ \dfrac{1\ \text{h}}{60\ \text{min}} = \underline{\underline{5.15\ \text{gal}\ \text{H}_2\text{O}/\text{min}}}$

9.23   a. $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$

Q (kJ)

$\underline{\text{Basis}} : 1000\ \text{kg}\ CaCO_3 = \dfrac{1000\ \text{kg}}{}\ \bigg|\ \dfrac{1\ \text{mol}}{0.100\ \text{kg}} = 10.0\ \text{kmol}\ CaCO_3 \Rightarrow$

10.0 kmol CaO(s) produced
10.0 kmol CO_2(g) produced
10.0 kmol $CaCO_3$(s) fed

References: Ca(s), C(s), O$_2$(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ/mol)
$CaCO_3$	10^4	$\hat{H}_1$	–	–
CaO	–	–	10^4	$\hat{H}_2$
CO_2	–	–	10^4	$\hat{H}_3$

$CaCO_3(s,\ 25^\circ C) : \hat{H}_1 = (\Delta\hat{H}_f^\circ)_{CaCO_3(s)} \overset{\underset{\text{Table B.1}}{}}{=} -1206.9\ \text{kJ/mol}$

$CaO(s,\ 900^\circ C) : \hat{H}_2 = (\Delta\hat{H}_f^\circ)_{CaO(s)} + \displaystyle\int_{298}^{1173} C_p dT \overset{\underset{\substack{\text{Table B.1,}\\\text{Table B.2}}}{}}{=} (-635.6 + 48.54)\ \text{kJ/mol} = -587.06\ \text{kJ/mol}$

$CO_2(g,\ 900^\circ C) : \hat{H}_3 = (\Delta\hat{H}_f^\circ)_{CO_2(g)} + \hat{H}_{CO_2}(900^\circ C) \overset{\underset{\substack{\text{Table B.1,}\\\text{Table B.8}}}{}}{=} (-393.5 + 42.94)\ \text{kJ/mol} = -350.56\ \text{kJ/mol}$

$\underline{\text{Energy balance}} :\ Q = \Delta H = \left(\displaystyle\sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i\right) = \underline{\underline{2.7 \times 10^6\ \text{kJ}}}$

b.   Basis : 1000 kg $CaCO_3$ fed $\Rightarrow$ 10.0 kmol $CaCO_3$

$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$

$2CO + O_2 \rightarrow 2CO_2$

10 kmol $CaCO_3$
25 °C
200 kmol at 900°C

0.75 N_2
0.020 O_2
0.090 CO
0.14 CO_2

n_1 [kmol CaO(s)]

Product gas at 900°C
n_2 (kmol CO_2)
n_3 (kmol N_2)
n_4 (kmol CO)
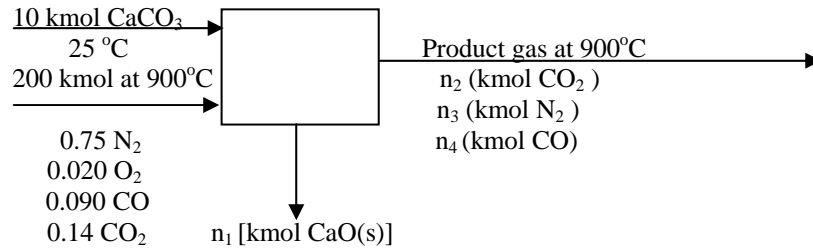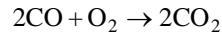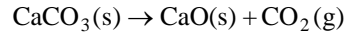
10 kmol $CaCO_3$ react $\Rightarrow n_1 = 10.0$ kmol CaO

$$n_2 = (0.14)(200) + \frac{10.0 \text{ kmol } CaCO_3 \text{ react}}{} \left| \frac{1 \text{ kmol } CO_2}{1 \text{ kmol } O_2} \right. + \frac{4 \text{ kmol } O_2 \text{ react}}{} \left| \frac{2 \text{ kmol } CO_2}{1 \text{ kmol } O_2} \right. = 46 \text{ kmol } CO_2$$

$n_3 = (0.75)(200) = 150$ kmol N_2

C balance: $(10.0)(1) + (200)(0.09)(1) + (200)(0.14)(1) = 46(1) + n_4(1) \Rightarrow n_4 = 10.0$ kmol CO

References : Ca(s), C(s), O_2(g), N_2(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
$CaCO_3$	10.0	$\hat{H}_1$	–	–
CaO	–	–	10	−587.06
CO_2	28	−350.56	46	−350.56
CO	18	$\hat{H}_2$	10	$\hat{H}_2$
O_2	4.0	$\hat{H}_3$	–	–
N_2	150	$\hat{H}_4$	150	$\hat{H}_4$

$CaCO_3$(s, 25°C) : $\hat{H}_1 = (\Delta \hat{H}_f^\circ)_{CaCO_3(s)} \overset{\text{Table B.1}}{=} -1206.9$ kJ/mol

CO(g, 900°C) : $\hat{H}_1 = (\Delta \hat{H}_f^\circ)_{CO(g)} + \hat{H}_{CO}(900°C) \overset{\text{Table B.1, Table B.8}}{=} (-110.52 + 27.49)$ kJ/mol $= -83.03$ kJ/mol

O_2(g, 900°C) : $\hat{H}_2 = \hat{H}_{O_2}(900°C) \overset{\text{Table B.8}}{=} 28.89$ kJ/mol

N_2(g, 900°C) : $\hat{H}_3 = \hat{H}_{N_2}(900°C) \overset{\text{Table B.8}}{=} 27.19$ kJ/mol

$$Q = \Delta H = \left(\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i \right) = 0.44 \times 10^6 \text{ kJ}$$

% reduction in heat requirement $= \left| \frac{2.7 \times 10^6 - 0.44 \times 10^6}{2.7 \times 10^6} \right| \times 100 = 83.8\%$

c.   The hot combustion gases raise the temperature of the limestone, so that less heat from the outside is needed to do so. Additional thermal energy is provided by the combustion of CO.

9.24 **a.** $A + B \rightarrow C$ $\qquad$ (1)

$\qquad$ $2C \rightarrow D + B$ $\qquad$ (2)

Basis: 1 mol
x_{AO} (mol A / mol)
x_{BO} (mol B / mol)
x_{IO} (mol I / mol)

n_A (mol A)
n_B (mol B)
n_C (mol C)
n_D (mol D)
n_I (mol I)
$T(°C)$
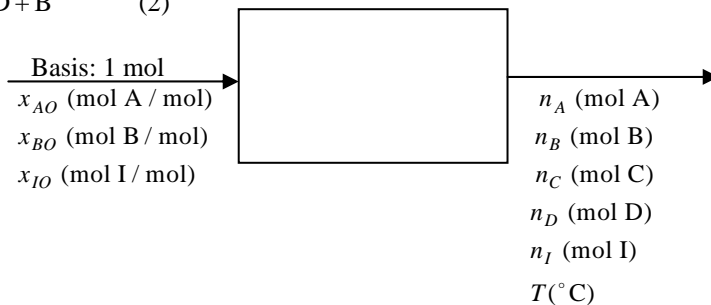
Fractional conversion: $\quad f_A = \dfrac{\text{mol A consumed}}{\text{mol A feed}} = \dfrac{x_{AO} - n_A}{x_{AO}} \Rightarrow \underline{\underline{n_A = x_{AO}(1 - f_A)}}$

C generated: $\quad n_0 = \dfrac{x_{A0}\,(\text{mol A fed})}{} \left| \dfrac{f_A\,(\text{mol A consumed})}{\text{mol A fed}} \right| \dfrac{Y_C\,(\text{mol C generated})}{\text{mol A consumed}}$

$\qquad \Rightarrow \underline{\underline{n_C = x_{AO} f_A Y_C}}$

D generated: $n_D = 0.5 \times \text{mol C consumed} = (1/2) \times (\text{mol A consumed} - \text{mol C out})$

$\qquad \Rightarrow \underline{\underline{n_D = (1/2)(x_{AO} f_A - n_C)}}$

Balance on B: mol B out = mol B in − mol B consumed in (1) + mol B generated in (2)

$\qquad\qquad\qquad\qquad$ = mol B in − mol A consumed in (1) + mol D generated in (2)

$\qquad\qquad \Rightarrow \underline{\underline{n_B = x_{BO} - x_{AO} f_A + n_D}}$

Balance on I: mol I out = mol I in $\Rightarrow \underline{\underline{n_I = x_{IO}}}$

b.

Species	Formula	DHf	a	b	c	d
A	C2H4(v)	52.28	0.04075	1.15E-04	-6.89E-08	1.77E-11
B	H2O(v)	-241.83	0.03346	6.88E-06	7.60E-09	-3.59E-12
C	C2H5OH(v)	-235.31	0.06134	1.57E-04	-8.75E-08	1.98E-11
D	C4H10)O(v	-246.75	0.08945	4.03E-04	-2.24E-07	0
I	N2(g)	0	0.02900	2.20E-05	5.72E-09	-2.87E-12

Tf	Tp	xA0	xB0	xI0	fA	YC
310	310	0.537	0.367	0.096	0.05	0.90

Species	n(in) (mol)	H(in) (kJ/mol)	n(out) (mol)	H(out) (kJ/mol)
A	0.537	68.7	0.510	68.7
B	0.367	-231.9	0.341	-231.9
C	0	-211.2	0.024	-211.2
D	0	-204.2	0.001	-204.2
I	0.096	9.4	0.096	9.4

Q(kJ) =   **-1.31**

c. For $T_f = 125°C$, $Q = \underline{7.90 \text{ kJ}}$. Raising T_p, lowering f_A, and raising Y_C all increase Q.

9.25   **a.** $CH_4(g) + O_2(g) \rightarrow HCHO(g) + H_2O(g)$
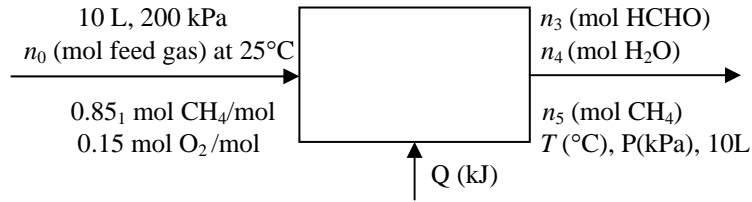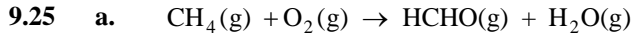
$$\text{\underline{Basis}} : n_0 = \frac{200 \text{ kPa}}{} \left| \frac{1000 \text{ Pa}}{1 \text{ kPa}} \right| \frac{10 \text{ L}}{} \left| \frac{10^{-3} \text{ m}^3}{1 \text{ L}} \right| \frac{1 \text{ mol K}}{8.314 \text{ m}^3 \text{ Pa}} \left| \frac{}{298 \text{ K}} \right.$$

$$= 0.8072 \text{ mol feed gas mixture}$$

$\underline{0.8072 \text{ mol feed gas mixture}} \Rightarrow (0.85)(0.8072) = 0.6861 \text{ mol } CH_4,$

$$\Rightarrow (0.15)(0.8072) = 0.1211 \text{ mol } O_2$$

$\underline{CH_4 \text{ consumed}} : \dfrac{1 \text{ mol } CH_4}{1 \text{ mol } O_2 \text{ fed}} \left| \dfrac{0.1211 \text{ mol } O_2 \text{ fed}}{} \right. = 0.1211 \text{ mol } CH_4$

$$\Rightarrow n_5 = (0.6861 - 0.1211) \text{ mol } CH_4 = 0.5650 \text{ mol } CH_4$$

$\underline{HCHO \text{ produced}} : n_3 = \dfrac{1 \text{ mol } HCHO}{1 \text{ mol } CH_4 \text{ consumed}} \left| \dfrac{0.1211 \text{ mol } CH_4 \text{ consumed}}{} \right. = 0.1211 \text{ mol } HCHO$

$\underline{H_2O \text{ produced}} : n_4 = \dfrac{1 \text{ mol } H_2O}{1 \text{ mol } CH_4 \text{ consumed}} \left| \dfrac{0.1211 \text{ mol } CH_4 \text{ consumed}}{} \right. = 0.1211 \text{ mol } H_2O$

$\underline{\text{Extent of reaction}} : \xi = \dfrac{\left| (n_{O_2})_{out} - (n_{O_2})_{in} \right|}{\left| \nu_{O_2} \right|} = \dfrac{\left| 0 - 0.1211 \right|}{\left| 1 \right|} = 0.1211 \text{ mol}$

<u>References</u> : $CH_4(g), \ O_2(g), \ HCHO(g), \ H_2O(g), \text{ at } 25^o C$

Substance	n_{in} mol	$\hat{U}_{in}$ kJ/mol	n_{out} mol	$\hat{U}_{out}$ kJ/mol
CH_4	0.6861	0	0.5650	$\hat{U}_1$
O_2	0.1211	0	–	–
HCHO	–	–	0.1211	$\hat{U}_2$
H_2O	–	–	0.1211	$\hat{U}_3$

$$\hat{U}_i = \int_{25}^{T} (C_v)_i \, dT = \int_{25}^{T} (C_p - R)_i \, dT \quad i = 1,2,3$$

Using $(C_p)_i$ from Table B.2 and $R = 8.314 \times 10^{-3} \text{ kJ / mol} \cdot \text{K}$:

$\hat{U}_1 = (0.02599 \, T + 2.7345 \times 10^{-5} \, T^2 + 0.1220 \times 10^{-8} \, T^3 - 2.75 \times 10^{-12} \, T^4 - 0.6670) \text{ kJ / mol}$

$\hat{U}_2 = (0.02597 \, T + 2.1340 \times 10^{-5} \, T^2 - 2.1735 \times 10^{-12} \, T^4 - 0.6623) \text{ kJ / mol}$

$\hat{U}_3 = (0.02515 \, T + 0.3440 \times 10^{-5} \, T^2 + 0.2535 \times 10^{-8} \, T^3 - 0.8983 \times 10^{-12} \, T^4 - 0.6309) \text{ kJ / mol}$

9.25 (cont'd)

$$Q = \frac{100\ \text{J}}{\text{s}} \left| \frac{85\ \text{s}}{} \right| \frac{1\ \text{kJ}}{1000\ \text{J}} = 8.5\ \text{kJ}$$

Table B.1

$$\Delta\hat{H}_r^o = (\Delta\hat{H}_f^o)_{\text{HCHO}} + (\Delta\hat{H}_f^o)_{\text{H}_2\text{O}} - (\Delta\hat{H}_f^o)_{\text{CH}_4} \quad \overset{\downarrow}{=} \quad \big((-115.90) + (-241.83) - (-74.85)\big)\ \text{kJ}\ /\ \text{mol}$$

$$= -282.88\ \text{kJ}\ /\ \text{mol}$$

$$\Delta\hat{U}_r^o = \Delta\hat{H}_r^o - RT\Big(\sum_{\substack{\text{gaseous} \\ \text{products}}} \nu_i - \sum_{\substack{\text{gaseous} \\ \text{reactants}}} \nu_i\Big)$$

$$= -282.88\ \text{kJ}\ /\ \text{mol} - \frac{8.314\ \text{J}}{\text{mol K}} \left| \frac{298\ \text{K}}{} \right| \frac{(1+1-1-1)}{} \left| \frac{1\ \text{kJ}}{10^3\ \text{J}} \right. = -282.88\ \text{kJ}\ /\ \text{mol}$$

Energy Balance :

$$Q = \xi\Delta\hat{U}_r^o + \sum (n_i)_{\text{out}}(\hat{U}_i)_{\text{out}} - \sum (n_i)_{\text{in}}(\hat{U}_i)_{\text{in}}$$

$$= (0.1211)(-282.88\ \text{kJ}\ /\ \text{mol}) + 0.5650\ \hat{U}_1 + 0.1211\ \hat{U}_2 + 0.1211\ \hat{U}_3$$

Substitute for $\hat{U}_1$ through $\hat{U}_3$ and Q

$$0 = 0.02088\ T + 1.845 \times 10^{-5}\ T^2 + 0.09963 \times 10^{-8}\ T^3 - 1.926 \times 10^{-12}\ T^4 - 43.29\ \text{kJ}\ /\ \text{mol}$$

Solve for T using E - Z Solve $\Rightarrow T = 1091^\circ\text{C} = 1364\ \text{K}$

$$\Rightarrow P = nRT\ /\ V = \frac{0.8072\ \text{mol}}{} \left| \frac{8.314\ \text{m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}} \right| \frac{1364\ \text{K}}{10\ \text{L}} \left| \frac{1\ \text{L}}{10^{-3}\text{m}^3} \right. = 915 \times 10^3\ \text{Pa} = \underline{\underline{915\ \text{kPa}}}$$

b. Add heat to raise the reactants to a temperature at which the reaction rate is significant.

c. Side reaction : $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. T would have been higher (more negative heat of reaction for combustion of methane), volume and total moles would be the same, therefore $P = nRT\ /\ V$ would be greater.

9.26 **a.**

Basis: 2 mol C_2H_4 fed to reactor

$$C_2H_4(g) + \frac{1}{2}O_2(g) \rightarrow C_2H_4O(g)$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$
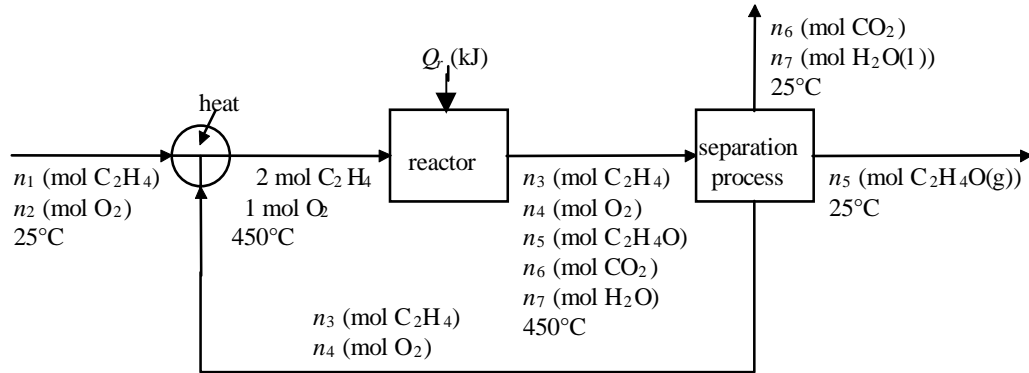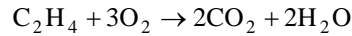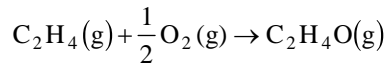
25% conversion $\Rightarrow$ 0.500 mol C_2H_4 consumed $\Rightarrow n_3 = \underline{\underline{1.50 \ \text{mol} \ C_2H_4}}$

70% yield $\Rightarrow n_5 = \dfrac{0.500 \ \text{mol} \ C_2H_4 \ \text{consumed}}{} \left| \dfrac{0.700 \ \text{mol} \ C_2H_4O}{1 \ \text{mol} \ C_2H_4} = \underline{\underline{0.350 \ \text{mol} \ C_2H_4O}}$

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: $n_7 = \dfrac{0.300 \ \text{mol} \ CO_2}{} \left| \dfrac{1 \ \text{mol} \ H_2O}{1 \ \text{mol} \ CO_2} = \underline{\underline{0.300 \ \text{mol} \ H_2O}}$

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 $25° C$

$$\hat{H}_i(T) = \Delta \hat{H}_{fi}^{\circ} + \int_{25}^{T} C_p dT \quad \text{for} \ C_2H_4$$

$$= \Delta \hat{H}_f^0 + \int_{298}^{T+273} C_p dT \quad \text{for} \ C_2H_4O$$

$$= \Delta \hat{H}_{fi}^{\circ} + \hat{H}_i \text{(table B.8)} \quad \text{for} \ O_2, \ CO_2, \ H_2O(g)$$

$$= \Delta \hat{H}_f^{\circ} \quad \text{for} \ H_2O(l)$$

9.26 (cont'd)

	Overall Process					Reactor			

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)	substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)
C_2H_4	0.500	52.28	–	–	C_2H_4	2	79.26	1.50	79.26
O_2	0.625	0	–	–	O_2	1	13.37	0.375	13.37
C_2H_4O	–	–	0.350	–51.00	C_2H_4O	–	–	0.350	–19.99
CO_2	–	–	0.300	–393.5	CO_2	–	–	0.300	–374.66
$H_2O(l)$	–	–	0.300	–285.84	$H_2O(g)$	–	–	0.300	–226.72

Energy balance on process: $Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{-248 \text{ kJ}}}$

Energy balance on reactor: $Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{-236 \text{ kJ}}}$

c. Scale to 1500 kg C_2H_4O/day :

$\underline{C_2H_4O \text{ production for initial basis}} = (0.350 \text{ mol})(\frac{44.05 \text{ kg}}{10^3 \text{ mol}}) = 0.01542 \text{ kg } C_2H_4O$

$\Rightarrow$ Scale factor $= \dfrac{1500 \text{ kg/day}}{0.01542 \text{ kg}} = 9.73 \times 10^4 \text{ day}^{-1}$

$\left.\begin{array}{l}\text{In initial basis, fresh feed contains} \\ \quad 0.500 \text{ mol } C_2H_4 \\ \quad 0.625 \text{ mol } O_2 \end{array}\right\}$ $\begin{array}{l}\overline{M} = (0.500)(28.05 \text{ g } C_2H_4/\text{mol}) + (0.625)(32.0 \text{ g } O_2/\text{mol}) \\ \quad = 34.025 \times 10^{-3} \text{ kg}\end{array}$

$\underline{\text{Fresh feed rate}} = (34.025 \times 10^{-3} \text{ kg})(9.73 \times 10^4 \text{ day}^{-1}) = \underline{\underline{3310 \text{ kg/day } (44.4\% \ C_2H_4, \ 55.6\% \ O_2)}}$

$Q_{process} = \dfrac{(-248 \text{ kJ})(9.73 \times 10^4 \text{ day}^{-1})}{} \left| \dfrac{1 \text{ day}}{24 \text{ hr}} \right| \dfrac{1 \text{ hr}}{3600 \text{ s}} \left| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} \right. = \underline{\underline{-279 \text{ kW}}}$
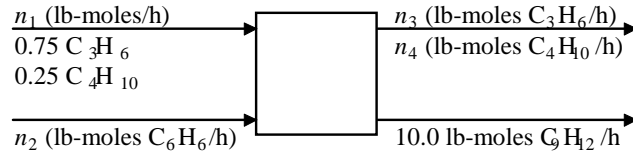
$Q_{reactor} = \dfrac{(-236 \text{ kJ})(9.73 \times 10^4 \text{ day}^{-1})}{} \left| \dfrac{1 \text{ day}}{24 \text{ hr}} \right| \dfrac{1 \text{ hr}}{3600 \text{ s}} \left| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} \right. = \underline{\underline{-265 \text{ kW}}}$

9.27 **a.**

Basis: $\dfrac{1200 \text{ lb}_m \text{ C}_9\text{H}_{12}}{\text{h}} \left| \dfrac{1 \text{ lb - mole}}{120 \text{ lb}_m} \right. = 10.0 \text{ lb - moles cumene produced/h}$

Overall process :

$$\text{C}_3\text{H}_6(l) + \text{C}_6\text{H}_6(l) \rightarrow \text{C}_9\text{H}_{12}(l), \qquad \Delta\hat{H}_r(77°F) = -39520 \text{ Btu/lb - mole}$$

Benzene balance: $\dot{n}_2 = \dfrac{10.0 \text{ lb - moles C}_9\text{H}_{12} \text{ produced}}{\text{h}} \left| \dfrac{1 \text{ mole C}_6\text{H}_6 \text{ consumed}}{1 \text{ mole C}_9\text{H}_{12}\text{produced}} \right.$
(input=consumption)

$\qquad = \dfrac{10.0 \text{ lb - moles C}_6\text{H}_6}{\text{h}} \left| \dfrac{78.1 \text{ lb}_m \text{ C}_6\text{H}_6}{1 \text{ lb - mole}} \right. = \underline{\underline{781 \text{ lb}_m \text{ C}_6\text{H}_6/\text{h}}}$

Propylene balance: $0.75\dot{n}_1 = \dot{n}_3 + \dfrac{10.0 \text{ lb - moles C}_9\text{H}_{12}}{\text{h}} \left| \dfrac{1 \text{ mole C}_3\text{H}_6}{1 \text{ mole C}_9\text{H}_{12}} \right.$
(input=output+consumption)

$\left. \begin{array}{l} \Rightarrow 0.75\dot{n}_1 = \dot{n}_3 + 10 \\ 20\% \text{ C}_3\text{H}_6 \text{ unreacted} \Rightarrow \dot{n}_3 = 0.20(0.75\dot{n}_1) \end{array} \right\} \Rightarrow \begin{array}{l} \dot{n}_1 = 16.67 \text{ lb - moles/h} \\ \dot{n}_3 = 2.50 \text{ lb - moles C}_3\text{H}_6/\text{h} \end{array}$

Mass flow rate of $\text{C}_3\text{H}_6 / \text{C}_4\text{H}_{10}$ feed $= \dfrac{(0.75)(16.67)\text{lb - moles C}_3\text{H}_6}{\text{h}} \left| \dfrac{42.08 \text{ lb}_m \text{ C}_3\text{H}_6}{1 \text{ lb - mole}} \right.$

$\qquad + \dfrac{(0.25)(16.67)\text{lb - moles C}_4\text{H}_{10}}{\text{h}} \left| \dfrac{58.12 \text{ lb}_m \text{ C}_4\text{H}_{10}}{1 \text{ lb - mole}} \right. = \underline{\underline{768 \text{ lb}_m/\text{h}}}$

Reactor :

Benzene feed rate $= \dfrac{10.0 \text{ lb - moles fresh feed}}{\text{h}} \left| \dfrac{(3+1)\text{moles fed to reactor}}{1 \text{ mole fresh feed}} \right. = 40 \text{ lb - moles C}_6\text{H}_6/\text{h}$
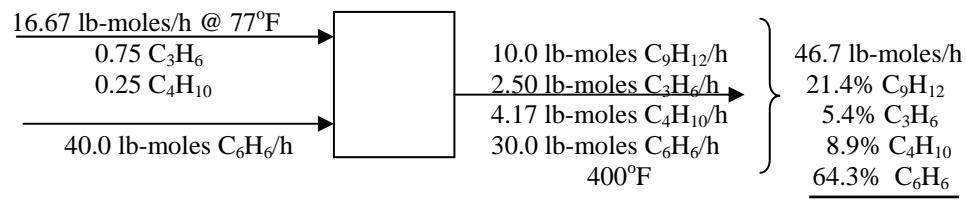
Overhead from T1 $\Rightarrow \left. \begin{array}{l} 2.50 \text{ lb - moles C}_3\text{H}_6/\text{h} \\ 4.17 \text{ lb - moles C}_4\text{H}_{10}/\text{h} \end{array} \right\} \Rightarrow \begin{array}{l} \underline{\underline{6.67 \text{ lb - moles/h}}} \\ \underline{\underline{37.5\% \text{ C}_3\text{H}_6}} \\ \underline{\underline{62.5\% \text{ C}_4\text{H}_{10}}} \end{array}$

b.

Heat exchanger :
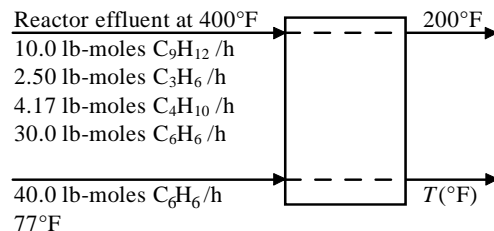
9.27 (cont'd)

Energy balance: $\Delta H = 0 \Rightarrow \sum n_i \left(\hat{H}_{i,\,\text{out}} - \hat{H}_{i,\,\text{in}} \right) = \sum n_i C_{pi} \left(T_{\text{out}} - T_{\text{in}} \right)_i = 0$

(Assume adiabatic)

$$\left[\frac{10\ \text{lb-moles}\ C_9H_{12}}{h} \middle| \frac{120\ \text{lb}_m}{1\ \text{lb-mole}} \middle| \frac{0.40\ \text{Btu}}{1\text{b}_m \cdot ^\circ F} \right] \left(200^\circ F - 400^\circ F \right) + \overset{\underset{\displaystyle C_3H_6}{\downarrow}}{(2.50)}(42.08)(0.57)\left(200^\circ F - 400 \right.$$

$$+ \overset{\underset{\displaystyle C_4H_{10}}{\downarrow}}{(4.17)}(58.12)(0.55)\left(200^\circ F - 400^\circ F \right) + (30.0)(78.11)(0.45)\left(200^\circ F - 400^\circ F \right)$$

$$\underset{\substack{C_6H_6\ \text{in} \\ \text{effluent}}}{\uparrow}$$

$$+ (40.0)\,(78.11)(0.45)\left(T - 77^\circ F \right) = 0 \Rightarrow \underline{\underline{T = 323^\circ F}}$$

$$\underset{\substack{C_6H_6\ \text{fed} \\ \text{to reactor}}}{\uparrow}$$

(Refer to flow chart of Part b: $T = 323^\circ F$)

References : $C_3H_6(l)$, $C_4H_{10}(l)$, $C_6H_6(l)$, $C_9H_{12}(l)$ at $77^\circ F$

$\hat{H}_i\,(\text{Btu/lb-mole}) = C_{pi}\,(\text{Btu/lb}_m\cdot^\circ F)\,M_i\,(\text{lb}_m/\text{lb-mole})(T - 77)(^\circ F)$

Substance	$\dot{n}_{\text{in}}$ (lb-mole / h)	$\hat{H}_{\text{in}}$ (Btu / lb-mole)	$\dot{n}_{\text{out}}$ (lb-mole / h)	$\hat{H}_{\text{out}}$ (Btu / lb-mole)
C_3H_6	12.0	0	2.50	7750
C_4H_{10}	4.17	0	4.17	10330
C_6H_6	40.0	8650	30.0	11350
C_9H_{12}	–	–	10.0	15530

Energy balance on reactor :

$$Q = \Delta H = \frac{\dot{n}_{C_9H_{12}}\,\Delta \hat{H}_r^o}{\nu_{C_9H_{12}}} + \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i$$

$$= \frac{(10.0)(-39520)}{(1)} + (2.50)(7750) + (4.17)(10330) + (30.0)(11350) + (10.0)(15530)$$

$$-(40.0)(8650) = \underline{\underline{-183000\ \text{Btu/h}}}\ \left(\text{heat removal} \right)$$

9.28

Basis : $\dfrac{100\ \text{kg}\ C_8H_8}{h} \middle| \dfrac{10^3\ g}{1\ \text{kg}} \middle| \dfrac{1\ \text{mol}}{104.15\ g} = 960\ \text{mol/h styrene produced}$

a. $C_8H_{10}(g) \rightarrow C_8H_8(g) + H_2(g)$
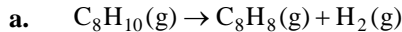
Overall system

Fresh feed
n_1 (mol C_8H_{10}/h)

n_2 (mol H_2 /h)
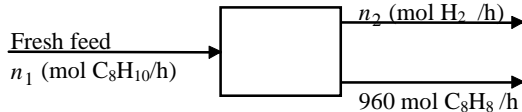
960 mol C_8H_8 /h

Fresh feed rate: $\dot{n}_1 = \dfrac{960\ \text{mol}\ C_8H_8}{h} \middle| \dfrac{1\ \text{mol}\ C_8H_{10}}{1\ \text{mol}\ C_8H_8} = \underline{\underline{960\ \text{mol}\ C_8H_{10}/h}}$ fresh feed
(C$_8$H$_{10}$ balance)

H$_2$ balance : $\dot{n}_2 = \dfrac{960\ \text{mol}\ C_8H_{10}}{h} \middle| \dfrac{1\ \text{mol}\ H_2}{1\ \text{mol}\ C_8H_{10}} = \underline{\underline{960\ \text{mol}\ H_2/h}}$

9.28 (cont'd)

<u>Reactor :</u>

n_3 (mol C_8H_{10} /h)
n_4 (mol H_2O(v)/h)
600°C

$\dot{n}_5$ (mol C_8H_{10} /h)
n_4 (mol H_2O(v)/s)
960 (mol C_8H_8 /s)
960 (mol H_2 /s)
560°C

Q_c (kJ/h)
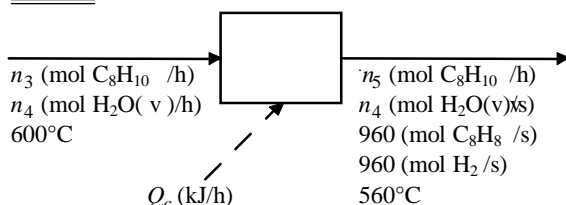
<u>35% 1-pass conversion</u> $\Rightarrow \dfrac{0.35n_3\left(\text{mol } C_8H_{10}\text{ react}\right)}{h}\left|\dfrac{1 \text{ mol } C_8H_8}{1 \text{ mol } C_8H_{10}}\right.=960 \text{ mol } C_8H_8/h$

$\Rightarrow \dot{n}_3 = 2740$ mol C_8H_{10}/h fed to reactor

$\Rightarrow$ <u>Recycle rate</u> $= (2740 - 960) = 1780$ mol C_8H_{10}/h recycled

<u>Reactor feed mixing point</u>

2740 mol C_8H_{10}(v)/h
500°C

n_4 [mol H_2O(v)/h]
700°C

2740 mol C_8H_{10}(v)/h
n_4 [mol H_2O(v)/h]
600°C
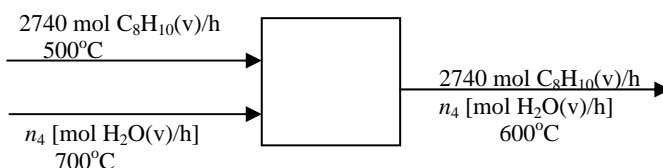
<u>Energy balance:</u> $\Delta H = 2740\Delta\hat{H}_{C_8H_{10}} + \dot{n}_4\Delta\hat{H}_{H_2O} = 0(\text{kJ/h})$
$\text{(Neglect } Q, \Delta E_k)$

$\Delta\hat{H}_{C_8H_{10}} = \left[\int_{500}^{600}\underbrace{(118+0.30T)}_{C_p}dT\right]\dfrac{J}{\text{mol}\cdot°\text{C}}\times\dfrac{1 \text{ kJ}}{10^3 \text{ J}} = 28.3 \text{ kJ/mol}$

$\Delta\hat{H}_{H_2O}\underset{P=1 \text{ bar}}{\overset{\text{Table B.8}}{\Rightarrow}} = -3.9 \text{ kJ/mol}$

$(2740)(28.3)+\dot{n}_4(-3.9) = 0 \Rightarrow \dot{n}_4 = 1.99\times10^4 \text{ mol } H_2O / h$

b.

<u>Ethylbenzene preheater (A) :</u>

$\dfrac{960 \text{ mol fresh feed}}{h}+\dfrac{1780 \text{ mol recycled}}{h}=\dfrac{2740 \text{ mol EB}(l)}{h}$ at 25° C

$\Rightarrow\dfrac{2740 \text{ mol EB}(v)}{h}$ at 500° C

$\Delta\hat{H} = \int_{25}^{136}C_{pi}dT + \Delta\hat{H}_v(136°\text{C})+\int_{136}^{500}C_{pv}dT = (20.2+36.0+77.7)\text{kJ/mol} = 133.9 \text{ kJ/mol}$

$\dot{Q}_A = \Delta\dot{H} = \dfrac{2740 \text{ mol } C_8H_{10}}{h}\left|\dfrac{133.9 \text{ kJ}}{\text{mol } C_8H_{10}}\right. = 3.67\times10^5 \text{ kJ/h (preheater)}$

<u>Steam generator (F) :</u>

19400 mol/h $H_2O(l, 25°\text{C})\rightarrow$ 19400 mol/h $H_2O(v, 700°\text{C}, 1 \text{ atm})$

Table B.5 $\Rightarrow \hat{H}(l, 25°\text{C}) = 104.8 \text{ kJ/kg}$;

Table B.7 $\Rightarrow \hat{H}(v, 700°\text{C}, 1 \text{ atm}\approx1 \text{ bar}) = 3928 \text{ kJ/kg}$

$$\dot{Q}_F = \Delta\dot{H} = \frac{19400 \text{ mol H}_2\text{O}}{h} \left| \frac{18.0 \text{ g}}{1 \text{ mol}} \right| \frac{1 \text{ kg}}{10^3 \text{ g}} \left| \frac{(3928 - 104.8)\text{kJ}}{\text{kg}} \right.$$

$$= \underline{\underline{1.34 \times 10^6}} \text{ kJ/h (steam generator)}$$

Reactor (C) :

References: $C_8H_8(v)$, $C_8H_{10}(v)$, $H_2(g)$, $H_2O(v)$ at $600°\text{C}$

$$\hat{H}_i\left(560°\text{C}\right) = \int_{600}^{560} \left(C_{pv}\right)_i dT \text{ for } C_8H_{10}, C_8H_8$$

$$\approx \hat{H}(\text{T}) \text{ for } H_2, H_2O \text{ (interpolating from Table B.8)}$$

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
	(mol/h)	(kJ/mol)	(mol/h)	(kJ/mol)
C_8H_{10}	2740	0	1780	−11.68
H_2O	19900	0	19900	−1.56
C_8H_8	–	–	960	−10.86
H_2	–	–	960	−1.19

Energy balance :

$$\dot{Q}_c = \Delta\dot{H} = \frac{960 \text{ mol } C_8H_8 \text{ produced}}{h} \left| \frac{124.5 \text{ kJ}}{1 \text{ mol } C_8H_8} \right. + \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i$$

$$= \underline{\underline{5.61 \times 10^4}} \text{ kJ/h (reactor)}$$

c. This is a poorly designed process as shown. The reactor effluents are cooled to $25°\text{C}$, and then all but the hydrogen are reheated after separation. Probably less cooling is needed, and in any case provisions for heat exchange should be included in the design.

9.29 $$CH_3OH \rightarrow HCHO + H_2, \quad H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$
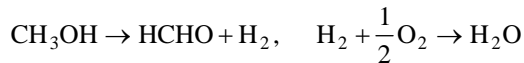
a.
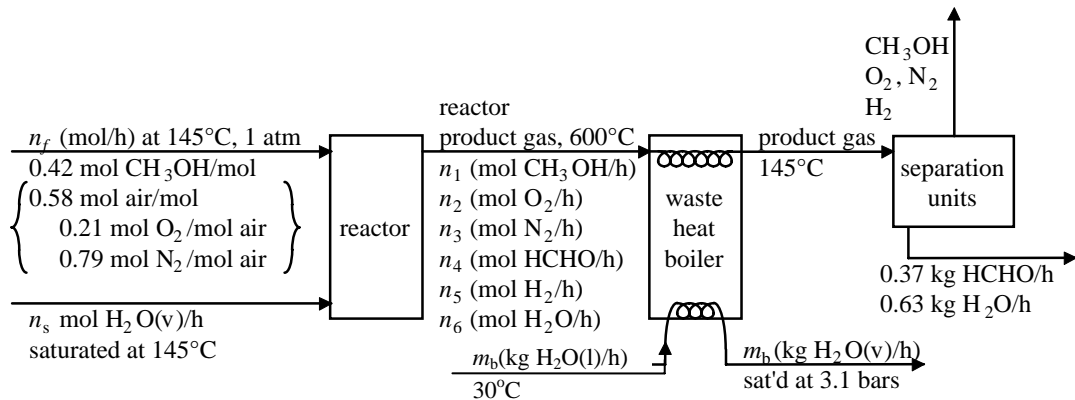
b. In the absence of data to the contrary, we assume that the separation of methanol from formaldehyde is complete.

Methanol vaporizer:

The product stream, which contains 42 mole % $CH_3OH(v)$, is saturated at $T_m\left(°\text{C}\right)$ and 1 atm.

9.29 (cont'd)

$$y_m P = p_m^*(T_m) \Rightarrow (0.42)(760 \text{ mmHg}) = 319.2 \text{ mmHg} = p_m^*(T_m)$$

$$\xrightarrow{\text{Antoine equation}} p_m^* = 319.2 \text{ mmHg} \Rightarrow T_m = \underline{\underline{44.1^\circ\text{C}}}$$

c. Moles HCHO formed :

$$= \frac{36 \times 10^6 \text{ kg solution}}{350 \text{ days}} \left| \frac{0.37 \text{ kg HCHO}}{1 \text{ kg solution}} \right| \frac{1 \text{ kmol}}{30.03 \text{ kg HCHO}} \left| \frac{1 \text{ day}}{24 \text{ h}} \right. = 52.80 \frac{\text{kmol HCHO}}{\text{h}}$$

but if all the HCHO is recovered, then this equals $\dot{n}_4$, or $\dot{n}_4 = 52.80$ kmol HCHO/h

70% conversion :

$$\frac{52.80 \text{ kmol HCHO}}{\text{h}} \left| \frac{1 \text{ kmol CH}_3\text{OH react}}{1 \text{ kmol HCHO formed}} \right| \frac{1 \text{ kmol CH}_3\text{OH fed}}{0.70 \text{ kmol CH}_3\text{OH react}} \left| \frac{1 \text{ kmol feed gas}}{0.42 \text{ kmol CH}_3\text{OH}} \right. = \dot{n}_f$$

$$\Rightarrow \dot{n}_f = 179.59 \text{ kmol/h}$$

Methanol unreacted:

$$\dot{n}_1 = \frac{(0.42)(179.59) \text{kmol CH}_3\text{OH fed}}{\text{h}} \left| \frac{(1-0.70) \text{ kmol CH}_3\text{OH fed}}{1 \text{ kmol CH}_3\text{OH fed}} \right. = 22.63 \frac{\text{kmol CH}_3\text{OH}}{\text{h}}$$

$\underline{N_2 \text{ balance:}}$ $\dot{n}_3 = (179.6 \text{ kmol/h})(0.58)(0.79) = 82.29$ kmol N_2/h

Four reactor stream variables remain unknown — $\dot{n}_s$, $\dot{n}_2$, $\dot{n}_5$, and $\dot{n}_6$ — and four relations are available — H and O balances, the given H_2 content of the product gas (5%), and the energy balance. The solution is tedious but straightforward.

$\underline{\text{H balance:}}$ $(179.6)(0.42)(4) + 2n_s = (22.63)(4) + (52.8)(2) + 2\dot{n}_5 + 2\dot{n}_6$

$$\Rightarrow \dot{n}_s = \dot{n}_5 + \dot{n}_6 - 52.80 \tag{1}$$

$\underline{\text{O balance:}}$ $(179.6)(0.42)(1) + (179.6)(0.58)(0.21)(2) + \dot{n}_s = (22.63)(1) + 2\dot{n}_2 + (52.80)(1) + \dot{n}_6$

$$\Rightarrow \dot{n}_s = 2\dot{n}_2 + \dot{n}_6 - 43.75 \tag{2}$$

$\underline{\text{H}_2 \text{ content:}}$ $\dfrac{\dot{n}_5}{22.63 + \dot{n}_2 + 82.29 + 52.89 + \dot{n}_5 + \dot{n}_6} = 0.05 \Rightarrow 19\dot{n}_5 - \dot{n}_2 - \dot{n}_6 = 157.72 \tag{3}$

References : $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C

$$H = \Delta\hat{H}_f^o + \int_{25}^{T} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p} dT$$

or Table B.8 for O_2, N_2 and H_2

9.29 (cont'd)

substance	$\dot{n}_{in}$ kmol / h	$\hat{H}_{in}$ kJ / kmol	$\dot{n}_{out}$ kmol / h	$\hat{H}_{out}$ kJ / kmol
CH_3OH	75.43	−195220	22.63	−163200
O_2	21.88	3620	n_2	18410
N_2	82.29	3510	82.29	17390
H_2O	n_s	−237740	n_6	−220920
HCHO	–	–	52.80	−88800
H_2	–	–	n_5	16810

Energy Balance :

$$\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0 \implies 18410n_2 + 16810n_5 - 220920n_6 + 237704n_s = -7.406 \times 10^6 \quad (4)$$

We now have four equations in four unknowns. Solve using E-Z Solve.

$$\dot{n}_s = \frac{58.8 \text{ kmol } H_2O(v)}{h} \left| \frac{18.02 \text{ kg}}{1 \text{ kmol}} = \underline{\underline{1060 \text{ kg steam fed/h}}}\right.$$

$\dot{n}_2 = 2.26$ kmol O_2/h , $\dot{n}_5 = 13.58$ kmol H_2/h , $\dot{n}_6 = 98.00$ kmol H_2O/h

Summarizing, the product gas component flow rates are 22.63 kmol CH_3OH/h, 2.26 kmol O_2/h, 82.29 kmol N_2/h, 52.80 kmol HCHO/h, 13.58 kmol H_2/h, and 98.02 kmol H_2O/h

$$\implies \underline{\underline{\frac{272 \text{ kmol/h product gas}}{8\% \ CH_3OH, \ 0.8\% \ O_2, \ 30\% \ N_2, \ 19\% \ HCHO, \ 5\% \ H_2, \ 37\% \ H_2O}}}$$

d.

Energy balance on waste heat boiler. Since we have already calculated specific enthalpies of all components of the product gas at the boiler inlet (at 600°C), and for all but two of them at the boiler outlet (at 145°C), we will use the same reference states for the boiler calculation

Reference States: $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C for reactor gas
$H_2O(l)$ at triple point for boiler water

Substance	$\dot{n}_{in}$ kmol/h	$\hat{H}_{in}$ kJ/kmol	$\dot{n}_{out}$ mol	$\hat{H}_{out}$ kJ/mol
CH_3OH	22.63	−163200	22.63	−195220
O_2	2.26	18410	2.26	3620
N_2	82.29	17390	82.29	3510
H_2O	98.02	−220920	98.02	−237730
HCHO	52.80	−88800	52.80	−111350
H_2	13.58	16810	13.58	3550
H_2O	m_b (kg/h)	125.7 (kJ/kg)	m_b (kg/h)	2726.1 (kJ/kg)

9- 36

9.29 (cont'd)

<u>Energy Balance :</u>

$$\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0$$

$$\Rightarrow m_b (2726.1 - 125.7) - 4.92 \times 10^6 = 0$$

$$\Rightarrow m_b = 1892 \text{ kg steam/h}$$

9.30   a. $C_2H_4 + HCl \rightarrow C_2H_5Cl$

<u>Basis:</u> $\dfrac{1600 \text{ kg } C_2H_5Cl(l)}{h} \left| \dfrac{10^3 \text{ g}}{1 \text{ kg}} \right| \dfrac{1 \text{ mol}}{64.52 \text{ g}} = 24800 \text{ mol/h } C_2H_5Cl$
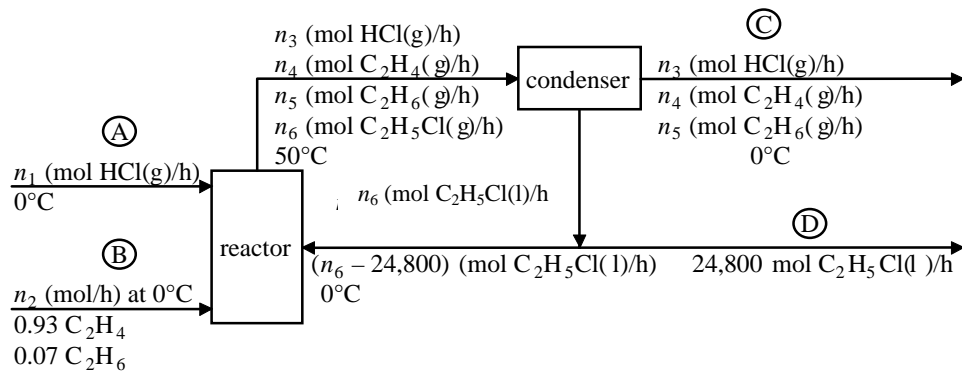
<u>Product composition data:</u>

$$n_3 = 0.015 n_1 \qquad\qquad (1)$$

$$n_4 = 0.015(0.93 n_2) = 0.01395 n_2 \qquad (2)$$

$$n_5 = 0.07 n_2 \qquad\qquad (3)$$

<u>Overall Cl balance :</u>

$$\dfrac{n_1 (\text{mol HCl/h})}{} \left| \dfrac{1 \text{ mol Cl}}{1 \text{ mol HCl}} = (n_3)(1) + (24800)(1) \qquad (4)$$

Solve (4) simultaneously with (1) $\Rightarrow$ $n_1 = 25180 \text{ mol/h} = \underline{\underline{25.18 \text{ kmol HCl fed / h}}}$

$$n_3 = 378 \text{ mol HCl (g)/h}$$

<u>Overall C balance :</u>

$$n_2(0.93)(2) + n_2(0.07)(2) = 2n_4 + 2n_5 + (2)(24800)$$

From Eqs. (2) and (3) $\Rightarrow$ $2n_2 \left[0.93 + 0.07 - 0.0139 - 0.07 \right] = (2)(24800)$

$$n_2 = 27070 \text{ mol fed/h} = \underline{\underline{27.07 \text{ kmol/h of Feed B}}}$$

b. $n_3 = 378 \text{ mol HCl/h}$

$n_4 = 0.01395(27070) = 378 \text{ mol } C_2H_4/h$ $\left.\begin{array}{l} \\ \\ \end{array}\right\}$ $\underline{2.65 \text{ kmol / h of Product C}}$

$n_5 = 0.07(27070) = 1895 \text{ mol } C_2H_6/h$ $\underline{\underline{14.3\% \text{ HCl, } 14.3\% \ C_2H_4 \text{ , } 71.4\% \ C_2H_6}}$

9.30 (cont'd)

c.

Références : $C_2H_4(g),\ C_2H_6(g),\ C_2H_5Cl(g),\ HCl(g)$ at $0°C$

$C_2H_4\big(g,\ 50°C\big)\!:\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow}\ 2.181\ kJ/mol$

$C_2H_6\big(g,\ 50°C\big)\!:\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow}\ 2.512\ kJ/mol$

$HCl\big(g,\ 50°C\big)\!:\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow}\ 1.456\ kJ/mol$

$C_2H_5Cl\big(l,\ 0°C\big)\!:\ \hat{H} = -\Delta \hat{H}_v\big(0°C\big) = -24.7\ kJ/mol$

$C_2H_5Cl\big(g,\ 50°C\big)\!:\ \hat{H} = \int_0^{50} C_{pv} dT = 2.709\ kJ/mol$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	mol	kJ / mol	mol	kJ / mol
HCl	25180	0	378	1.456
C_2H_4	25175	0	378	2.181
C_2H_6	1895	0	1895	2.512
C_2H_5Cl	$n_6 - 24800$	-24.7	n_6	2.709

Energy balance:

$$\Delta H = 0 \Rightarrow \frac{n_A \Delta\hat{H}_r\big(0°C\big)}{v_A} + \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0$$

$$\Rightarrow \frac{(25180 - 378)\,\text{mol HCl react}}{h}\bigg|\frac{-64.5\ kJ}{1\ \text{mol HCl}} + (378)(1.456) + (378)(2.181) + (1895)(2.512)$$

$$+\ 2.709 n_6 - (n_6 - 24800)(-24.7) = 0 \Rightarrow n_6 = 80490\ \text{mol } C_2H_5Cl/h\ \text{ in reactor effluent}$$

$$\underline{C_2H_5Cl\ recycled} = \frac{80490\ \text{mol condensed}}{h} - \frac{24800\ \text{mol product}}{h} = 55690\frac{mol}{h}$$

$$= 55.7\frac{\text{kmol recycled}}{h}$$

d.

C_p is a linear function of temperature.

$\Delta\hat{H}_v$ is independent of temperature.

100% condensation of ethylbenzene in the heat exchanger is assumed.

Heat of mixing and influence of pressure on enthalpy is neglected.
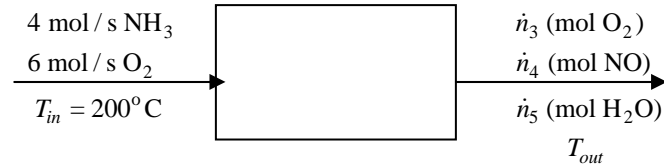
Reactor is adiabatic.

No C_2H_4 or C_2H_6 is absorbed in the ethyl chloride product.

9.31 **a.** $4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$ $\Delta\hat{H}_r^o = -904.7\ kJ/mol$

Basis : 10 mol/s Feed gas

9.31 (cont'd)

$$\begin{array}{ll}
4 \text{ mol}/\text{s NH}_3 & \dot{n}_3 \ (\text{mol O}_2) \\
6 \text{ mol}/\text{s O}_2 & \dot{n}_4 \ (\text{mol NO}) \\
T_{in} = 200^\circ C & \dot{n}_5 \ (\text{mol H}_2\text{O}) \\
& T_{out}
\end{array}$$

<u>O$_2$ consumed :</u> $\dfrac{5 \text{ mol O}_2}{4 \text{ mol NH}_3} \left| \dfrac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}} \right. = 5 \text{ mol}/\text{s} \Rightarrow \dot{n}_3 = (6-1) \text{ mol O}_2 / \text{s} = \underline{\underline{1 \text{ mol O}_2 /}}$

<u>NO produced :</u> $\dot{n}_4 = \dfrac{4 \text{ mol NO produced}}{4 \text{ mol NH}_3} \left| \dfrac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}} \right. = \underline{\underline{4 \text{ mol NO}/\text{s}}}$

<u>H$_2$O produced :</u> $\dot{n}_5 = \dfrac{6 \text{ mol H}_2\text{O produced}}{4 \text{ mol NH}_3} \left| \dfrac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}} \right. = \underline{\underline{6 \text{ mol H}_2\text{O}/\text{s}}}$

<u>Extent of reaction :</u> $\dot{\xi} = \dfrac{\left| (\dot{n}_{\text{NH}_3})_{\text{out}} - (\dot{n}_{\text{NH}_3})_{\text{in}} \right|}{\left| \nu_{\text{NH}_3} \right|} = \dfrac{|0-4|}{|4|} = \underline{\underline{1 \text{ mol}/\text{s}}}$

b. Well-insulated reactor, so no heat loss
No absorption of heat by container wall
Neglect kinetic and potential energy changes;
No shaft work
No side reactions.

c. <u>References :</u> $\text{NH}_3(g), \ \text{O}_2(g), \ \text{NO}(g), \ \text{H}_2\text{O}(g)$ at $25^\circ C$, 1atm

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)
$\text{NH}_3(g)$	4.00	$\hat{H}_1$	–	–
$\text{O}_2(g)$	6.00	$\hat{H}_2$	1.00	$\hat{H}_3$
$\text{NO}(g)$	–	–	4.00	$\hat{H}_4$
$\text{H}_2\text{O}(g)$	–	–	6.00	$\hat{H}_5$

$$\overset{\text{Table B.2}}{\hat{H}_1 = \int_{25}^{200} (C_p)_{\text{NH}_3} dT \ \underset{\downarrow}{=} \ 6.74 \text{ kJ}/\text{mol}}, \quad \hat{H}_2 = \hat{H}_{\text{O}_2}(200^\circ C) \ \overset{\text{Table B.8}}{\underset{\downarrow}{=}} \ 5.31 \text{ kJ}/\text{mol}$$

Using $(C_p)_i$ from Table B.2 :

$\hat{H}_3 = (0.0291 \, T_{\text{out}} + 0.5790\times10^{-5} \, T_{\text{out}}^2 - 0.2025\times10^{-8} \, T_{\text{out}}^3 + 0.3278\times10^{-12} \, T_{\text{out}}^4 - 0.7311) \text{ kJ/mol}$

$\hat{H}_4 = (0.0295 \, T_{\text{out}} + 0.4094\times10^{-5} \, T_{\text{out}}^2 - 0.0975\times10^{-8} \, T_{\text{out}}^3 + 0.0913\times10^{-12} \, T_{\text{out}}^4 - 0.7400) \text{ kJ/mol}$

$\hat{H}_5 = (0.03346 \, T_{\text{out}} + 0.3440\times10^{-5} \, T_{\text{out}}^2 + 0.2535\times10^{-8} \, T_{\text{out}}^3 - 0.8983\times10^{-12} \, T_{\text{out}}^4 - 0.8387) \text{ kJ/mol}$

<u>Energy Balance:</u> $\Delta \dot{H} = 0$

$$\Delta \dot{H} = \dot{\xi} \Delta \hat{H}_r^o + \sum_{i=3}^{5} (n_i)_{\text{out}} (\hat{H}_i)_{\text{out}} - \sum_{i=1}^{2} (n_i)_{\text{in}} (\hat{H}_i)_{\text{in}}$$

9-31 (cont'd)

$$\Rightarrow \Delta \dot{H} = \dot{\xi} \Delta \hat{H}_r^o + (1.00)\hat{H}_3 + (4.00)\hat{H}_4 + (6.00)\hat{H}_5 - (4.00)\hat{H}_1 - (6.00)\hat{H}_2$$

$$\Downarrow \text{ Substitute for } \dot{\xi}, \ \Delta \hat{H}_r^o, \text{ and } \hat{H}_1 \text{ through } \hat{H}_6$$

$$\Delta \dot{H} = (0.3479\, T_{out} + 4.28 \times 10^{-5}\, T_{out}^2 + 0.9285 \times 10^{-8}\, T_{out}^3 - 4.697 \times 10^{-12}\, T_{out}^4)$$
$$- 972.24 \text{ kJ/mol} = 0$$

E-Z Solve $\Rightarrow \underline{\underline{T_{out} = 2223 \ ^\circ C}}$

d. If only the first term from Table B.2 is used, $\hat{H}_i = \int\limits_{25}^{T} (C_{pi})dT = C_{pi}(T - 25)$

$$\hat{H}_1 = 0.03515(200 - 25) = 6.15 \text{ kJ / mol}, \ \hat{H}_2 = 5.31 \text{ kJ / mol}, \ \hat{H}_3 = 0.0291(T_{out} - 25),$$
$$\hat{H}_4 = 0.0295(T_{out} - 25), \ \hat{H}_5 = 0.03346(T_{out} - 25)$$

E.B. $\Delta \dot{H} = \dot{\xi} \Delta \hat{H}_r^o + (1.00)\hat{H}_3 + (4.00)\hat{H}_4 + (6.00)\hat{H}_5 - (4.00)\hat{H}_1 - (6.00)\hat{H}_2 = 0$

$$\Downarrow \text{ Substitute for } \dot{\xi} (=1 \text{ mol/s}), \ \Delta \hat{H}_r^o (= -904.7 \text{ kJ/mol}) \text{ and } \hat{H}_1 \text{ through } \hat{H}_6$$

$$0 = 0.3479\, T_{out} - 969.86 \Rightarrow \underline{\underline{T_{out} = 2788 \ ^\circ C}} \Rightarrow \% \text{ error} = \frac{2788^\circ C - 2223^\circ C}{2223 \ ^\circ C} \times 100 = \underline{\underline{25\%}}$$

e. If the higher temperature were used as the basis, the reactor design would be <u>safer</u> (but more expensive).

9.32 <u>Basis</u> : 100 lb$_m$ coke fed

$$\Rightarrow 84 \text{ lb}_m \text{ C} \Rightarrow 7.00 \text{ lb - moles C fed} \Rightarrow 7.00 \text{ lb - moles CO}_2 \text{ fed}$$

7.00 lb-moles CO$_2$
400°F

7.00 lb-moles(84 lb$_m$)C/hr
16 lb $_m$ash/hr
77°F

n_1 (lb-moles CO)
n_2 (lb-moles CO$_2$)
1830°F

n_3 lb-moles C(s)/hr
16 lb $_m$ash/hr
1830°F

585,900 Btu
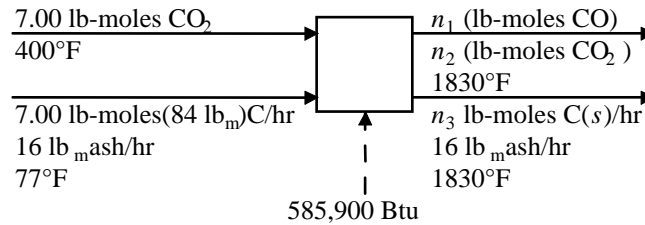
a. $C(s) + CO_2(g) \rightarrow 2CO(g)$,

$$\Delta \hat{H}_r^o \underset{=25^\circ C}{(77^\circ F)} = \left(\Delta \hat{H}_c^o\right)_{CO_2(g)} - 2\left(\Delta \hat{H}_c^o\right)_{CO(g)}$$

$$= \frac{[-393.50 - (2)(-282.99)] \text{ kJ}}{\text{mol}} \left| \frac{0.9486 \text{ Btu}}{1 \text{ kJ}} \right| \frac{453.6 \text{ mols}}{1 \text{ lb - mole}} = 74,210 \text{ Btu/lb - mole}$$

Let $x = $ fractional conversion of C and CO_2 :

$\Downarrow$

$$n_1 = \frac{7.00x(\text{lb - moles C reacted})}{} \left| \frac{2 \text{ lb - moles CO formed}}{1 \text{ lb - mole C reacted}} = 14.0x \text{ lb - moles CO}\right.$$

$$n_2 = 7.00(1 - x) \text{ lb - moles CO}_2$$

$$n_3 = 7.00(1 - x) \text{ lb - moles C(s)}$$

<u>References for enthalpy calculations</u>: $C(s), CO_2(g), CO(g),$ ash at $77^\circ F$

9.32 (cont'd)

$\underline{CO_2(g,400°F)}$: $\hat{H} = \hat{H}_{CO_2}(400°F) \overset{\text{Table B.9}}{\Rightarrow} 3130$ Btu/lb-mole

$\underline{CO_2(g,1830°F)}$: $\hat{H} = \hat{H}_{CO_2}(1830°F) \overset{\text{Table B.9}}{\Rightarrow} 20,880$ Btu/lb-mole

$\underline{CO(g,1830°F)}$: $\hat{H} = \hat{H}_{CO}(1830°F) \overset{\text{Table B.9}}{\Rightarrow} 13,280$ Btu/lb-mole

Solid $(1830°F)$: $\hat{H} = \dfrac{0.24 \text{ Btu}}{\text{lb}_m \cdot °F} \bigg| \dfrac{(1830-77)°F}{} = 420$ Btu/lb$_m$

Mass of solids (emerging)

$$= \dfrac{7.00(1-x) \text{ lb-moles C}}{} \bigg| \dfrac{12.0 \text{ lb}_m}{1 \text{ lb-mole}} + 16 \text{ lb}_m = (100-84x) \text{ lb}_m$$

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	(lb–moles)	(Btu/lb-mole)	(lb–moles)	(Btu/lb-mole)
CO_2	7.00	3130	$7.00(1-x)$	20,890
CO	–	–	$14.0x$	13,280
	(lb$_m$)	(Btu/lb$_m$)	(lb$_m$)	(Btu/lb$_m$)
solid	100	0	$100-84x$	420

Extent of reaction: $n_{CO} = (n_{CO})_o + \nu_{CO}\xi \Rightarrow 14.0x = 2\xi \Rightarrow \xi(\text{lb-moles}) = 7.0x$

Energy balance:

$$Q = \Delta H = \xi\Delta\hat{H}_r^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i$$

$$585,900 \text{ Btu} = \dfrac{7.0x \text{ (lb-moles)}}{} \bigg| \dfrac{74,210 \text{ Btu}}{\text{lb-mole}} + 7.00(1-x)(20,880)$$

$$+(14.0x)(13,280)+(100-84x)(420)-(7.00)(3130)$$

$$\Downarrow$$

$$x = 0.801 \Rightarrow \underline{\underline{80.1\% \text{ conversion}}}$$

**b.**

Advantages of CO. Gases are easier to store and transport than solids, and the product of the combustion is CO_2, which is a much lower environmental hazard than are the products of coke combustion.
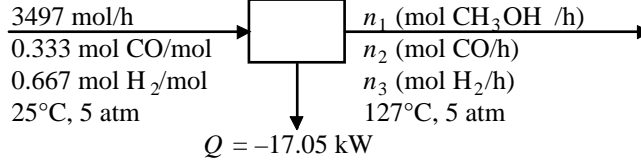
Disadvantages of CO. It is highly toxic and dangerous if it leaks or is not completely burned, and it has a lower heating value than coke. Also, it costs something to produce it from coke.

9.33

$$\text{Basis}: \frac{17.1 \text{ m}^3}{\text{h}} \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \frac{273 \text{ K}}{298 \text{ K}} \left| \frac{5.00 \text{ atm}}{1.00 \text{ atm}} \right| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} = 3497 \text{ mol/h feed}$$

$$CO(g) + 2H_2(g) \rightarrow CH_3OH(g),$$
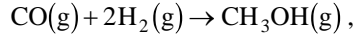
$$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{CH_3OH(g)} - \left(\Delta\hat{H}_f^o\right)_{CO(g)} = -90.68 \text{ kJ/mol}$$

```
3497 mol/h          ┌──────┐   n₁ (mol CH₃OH /h)
0.333 mol CO/mol ──→│      │──→ n₂ (mol CO/h)
0.667 mol H₂/mol    │      │    n₃ (mol H₂/h)
25°C, 5 atm         └──┬───┘    127°C, 5 atm
                       ↓
                  Q = −17.05 kW
```

Let f = fractional conversion of CO (which also equals the fractional conversion of H_2, since CO and H_2 are fed in stoichiometric proportion).

$$\underline{\text{CO reacted}}: = \frac{(3497)(0.333) \text{ mol CO feed}}{} \left| \frac{f(\text{mol react})}{\text{mol feed}} \right. = 1166f \text{ (mol CO react)}$$

$$\underline{\text{CH}_3\text{OH produced}}: \dot{n}_1 = \frac{1166f \text{ mol CO react}}{} \left| \frac{1 \text{ mol CH}_3\text{OH}}{1 \text{ mol CO}} \right. = 1166f \text{ mol CH}_3\text{OH/h}$$

$$\underline{\text{CO remaining}}: \dot{n}_2 = 1166(1-f) \text{ mol CO/h}$$

$$\underline{\text{H}_2 \text{ remaining}}: \dot{n}_3 = (3497)(0.667) \text{ mol H}_2 \text{ fed} - \frac{1166f \text{ mol CO react}}{} \left| \frac{2 \text{ mol H}_2 \text{ react}}{1 \text{ mol CO react}} \right.$$

$$= 2332(1-f) \text{ mol H}_2/\text{h}$$

Reference states : CO(g), $H_2(g)$, $CH_3OH(g)$ at 25°C

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
	(mol/h)	(kJ/mol)	(mol/h)	(kJ/mol)
CO	1166	0	$1166(1-f)$	$\hat{H}_1$
H_2	2332	0	$2332(1-f)$	$\hat{H}_2$
CH_3OH	–	–	$1166f$	$\hat{H}_3$

$$CO(g,127°C): \hat{H}_1 = \hat{H}_{CO}(127°C) \overset{\underset{\text{Table B.8}}{\downarrow}}{=} 2.99 \text{ kJ/mol}$$

$$H_2(g,127°C): \hat{H}_2 = \hat{H}_{H_2}(127°C) \overset{\underset{\text{Table B.8}}{\downarrow}}{=} 2.943 \text{ kJ/mol}$$

$$CH_3OH(g,127°C): \hat{H}_3 = \int_{25}^{122} C_p dT \overset{\underset{\text{Table B.2}}{\downarrow}}{=} 5.009 \text{ kJ / mol}$$

$$\underline{\text{Energy balance}}: \dot{Q} = \Delta\dot{H} = \xi\Delta\hat{H}_r^o + \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i$$

$$\Rightarrow \frac{-17.05 \text{ kJ}}{s} \left| \frac{3600 \text{ s}}{1 \text{ h}} \right. = (1166f)(-90.68)\frac{\text{kJ}}{\text{h}} + [1166(1-f)](2.99)$$

$$+[2332(1-f)](2.993) + [1166f(5.009)](\text{kJ/h})$$

$$\Rightarrow 1.102 \times 10^5 f = 7.173 \times 10^4 \Rightarrow \underline{\underline{f = 0.651 \text{ mol CO(or } H_2) \text{ converted/mol fed}}}$$
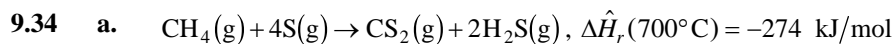
9.33 (cont'd)

$$\dot{n}_1 = 1166(0.651) = 759.1 \text{ mol/h}$$

$$\dot{n}_2 = 1166(1 - 0.651) = 406.9 \text{ mol/h}$$

$$\dot{n}_3 = 2332(1 - 0.651) = 813.9 \text{ mol/h}$$

$$\Downarrow$$

$$\dot{n}_{tot} = 1980 \frac{\text{mol}}{\text{h}} \Rightarrow V_{out} = \frac{1980 \text{ mol}}{\text{h}} \left| \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} \right| \frac{400 \text{ K}}{273 \text{ K}} \left| \frac{1.00 \text{ atm}}{5.00 \text{ atm}} \right| \frac{1 \text{ m}^3}{10^3 \text{ L}} = \underline{\underline{13.0 \text{ m}^3/\text{h}}}$$

9.34   **a.** $CH_4(g) + 4S(g) \rightarrow CS_2(g) + 2H_2S(g)$, $\Delta\hat{H}_r(700°C) = -274 \text{ kJ/mol}$

<u>Basis</u> : 1 mol of feed
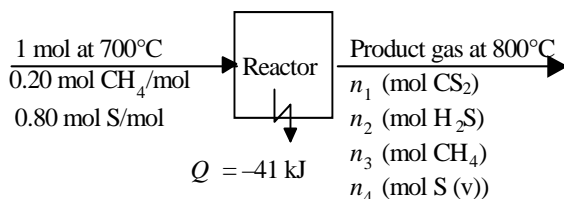
Let f = fractional conversion of CH_4 (which also equals fractional conversion of S, since the species are fed in stoichiometric proportion)

Moles CH_4 reacted $= 0.20f$, Extent of reaction $= \xi(\text{mol}) = 0.20f$

$n_3 = 0.20(1 - f) \text{ mol } CH_4$

$$n_4 = 0.80 \text{ mol S fed} - \frac{0.20f \, (\text{mol } CH_4 \text{ react})}{} \left| \frac{4 \text{ mol S react}}{1 \text{ mol } CH_4 \text{ react}} \right| = 0.80(1 - f) \text{ mol S}$$

$$n_1 = \frac{0.20f \, \text{mol } CH_4 \text{ react}}{} \left| \frac{1 \text{ mol } CS_2}{1 \text{ mol } CH_4} \right| = 0.20f \, \text{mol } CS_2$$

$$n_2 = \frac{0.20f \, \text{mol } CH_4 \text{ react}}{} \left| \frac{2 \text{ mol } H_2S}{1 \text{ mol } CH_4} \right| = 0.40f \, \text{mol } H_2S$$

<u>References</u>: $CH_4(g), S(g), CS_2(g), H_2S(g)$ at 700°C   (temperature at which $\Delta\hat{H}_r$ is known)

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
CH_4	0.20	0	$0.20(1 - f)$	$\hat{H}_1$
S	0.80	0	$0.80(1 - f)$	$\hat{H}_2$
CS_2	–	–	$0.20f$	$\hat{H}_3$
H_2S	–	–	$0.40f$	$\hat{H}_4$

$$\hat{H}_{out} = C_{pi}(800 - 700) \Rightarrow \begin{cases} CH_4(g, \, 800°C): \hat{H}_1 = 7.14 \text{ kJ / mol} \\ S(g, \, 800°C): \hat{H}_2 = 3.64 \text{ kJ / mol} \\ CS_2(g, \, 800°C): \hat{H}_3 = 3.18 \text{ kJ / mol} \\ H_2S(g, \, 800°C): \hat{H}_4 = 4.48 \text{ kJ / mol} \end{cases}$$

9.34 (cont'd)

Energy balance on reactor:

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r + \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = 41\frac{kJ}{s}$$

$$= \frac{(0.20f)(-274.0)}{(1)} + \left[0.20(1-f)(7.140) + 0.80(1-f)(3.640) + 0.20f(3.180) + 0.40f(4.480)\right]$$

$$\Rightarrow \underline{\underline{f = 0.800}}$$

b.
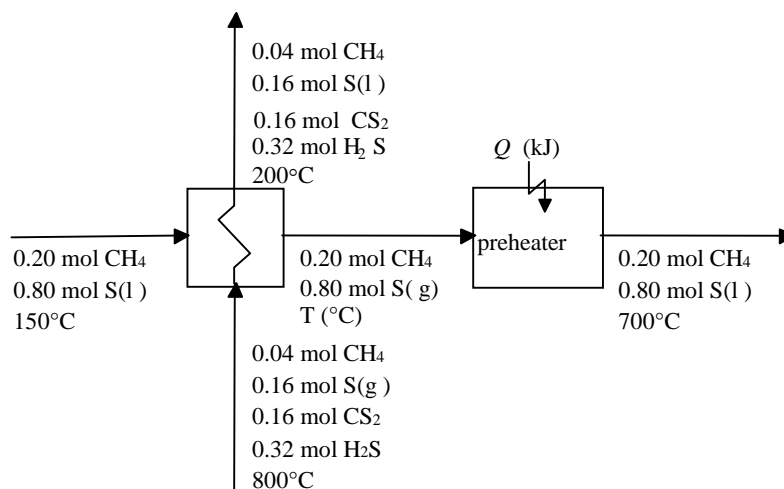
System: Heat exchanger-preheater combination. Assume the heat exchanger is adiabatic, so that the only heat transferred to the system from its surroundings is Q for the preheater.

References : $CH_4(g), S(l), CS_2(g), H_2S(g)$ at 200°C

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	(mol)	(kJ/mol)	(mol)	(kJ/mol)
$(CH_4)_{150°,700°}$	0.20	$\hat{H}_1$	0.20	$\hat{H}_7$
$(CH_4)_{800°,200°}$	0.04	$\hat{H}_2$	0.04	0
$S(l)$	0.80	$\hat{H}_3$	0.16	0
$S(g)$	0.16	$\hat{H}_4$	0.80	$\hat{H}_8$
CS_2	0.16	$\hat{H}_5$	0.16	0
H_2S	0.32	$\hat{H}_6$	0.32	0

$\hat{H}_i = C_{pi}(T-200)$ for all substances but S

$\quad = (C_p)_{S(l)}(T-200)$ for S(l)

$\quad = (C_p)_{S(l)}\left(\underset{T_b}{444.6-200}\right) + \underset{=83.7kJ/mol}{\Delta\hat{H}_v}(T_b) + (C_p)_{S(g)}(T-444.6)$ for S(g)

9- 44

$CH_4(g, 150°C): \hat{H}_1 = -3.57 \text{ kJ / mol}$ $CS_2(g, 800°C): \hat{H}_5 = 19.08 \text{ kJ / mol}$

$CH_4(g, 800°C): \hat{H}_2 = 42.84 \text{ kJ / mol}$ $H_2S(g, 800°C): \hat{H}_6 = 26.88 \text{ kJ / mol}$

$S(l, 150°C): \hat{H}_3 = -1.47 \text{ kJ / mol}$ $CH_4(g, 700°C): \hat{H}_7 = 35.7 \text{ kJ / mol}$

$S(g, 800°C): \hat{H}_4 = 103.83 \text{ kJ / mol}$ $S(g, 700°C): \hat{H}_8 = 100.19 \text{ kJ / mol}$

Energy balance: $Q(\text{kJ}) = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i \Rightarrow Q = 59.2 \text{ kJ} \Rightarrow \underline{\underline{59.2 \text{ kJ/mol feed}}}$

c.   The energy economy might be improved by insulating the reactor better. The reactor effluent will
emerge at a higher temperature and transfer more heat to the fresh feed in the first preheater,
lowering (and possibly eliminating) the heat requirement in the second preheater.

9.35   <u>Basis</u> : 1 mol C_2H_6 fed to reactor

1 mol C_2H_6 | → | n (mols) @ T(K), P atm
1273 K, P atm | | $n_{C_2H_6}$ (mol C_2H_6)
| | $n_{C_2H_4}$ (mol C_2H_4)
| | n_{H_2} (mol H_2)
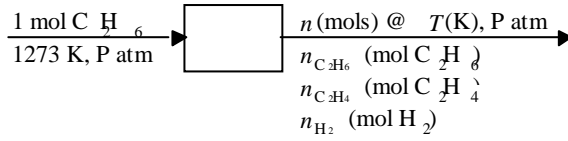
a. $C_2H_6 \Leftrightarrow C_2H_4 + H_2$, $K_p = \dfrac{x_{C_2H_4}\, x_{H_2}}{x_{C_2H_6}}\, P = 7.28 \times 10^6\, \exp[-17{,}000/T(K)]$ (1)

<u>Fractional conversion</u> $= f$ $\left(\text{mols } C_2H_6 \text{ react/mol fed}\right)$

$$\left. \begin{array}{l} \xi(\text{mol}) = f \\ n_{C_2H_6} = (1-f)(\text{mol } C_2H_6) \\ n_{C_2H_4} = f(\text{mol } C_2H_4) \\ n_{H_2} = f(\text{mol } H_2) \\ \hline n = 1 + f\,(\text{mols}) \end{array} \right\} \Rightarrow \begin{array}{l} x_{C_2H_6} = \dfrac{1-f}{1+f}\ \dfrac{\text{mol } C_2H_6}{\text{mol}} \\[2mm] x_{C_2H_4} = \dfrac{f}{1+f}\ \dfrac{\text{mol } C_2H_4}{\text{mol}} \\[2mm] x_{H_2} = \dfrac{f}{1+f}\ \dfrac{\text{mol } H_2}{\text{mol}} \end{array}$$

$$K_p = \frac{x_{C_2H_4}\, x_{H_2}}{x_{C_2H_4}}\, P \Rightarrow K_p = \frac{\dfrac{f^2}{(1+f)^2}\, P}{\dfrac{(1-f)}{(1+f)}} = \frac{f^2\, P}{(1-f)(1+f)} = \frac{f^2}{1-f^2}\, P$$

$$\left(1 - f^2\right)K_p = f^2 P \Rightarrow \underline{\underline{f = \left(\frac{K_p}{P + K_p}\right)^{1/2}}}\quad (2)$$

b.   <u>References</u> : $C_2H_6(g),\ C_2H_4(g),\ H_2(g)$ at 1273 K

<u>Energy balance:</u>

$$\Delta H = 0 \Rightarrow \xi\, \Delta\hat{H}_r(1273\text{ K}) + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$\left(\hat{H}_i\right)_{\text{in}} = 0$ $\left(\text{inlet temperature} = \text{reference temperature}\right)$

$\left(\hat{H}_i\right)_{\text{out}} = \displaystyle\int_{1273}^{T} C_{pi}\, dT$

$\Downarrow$ energy balance

$$f\, \Delta\hat{H}_r(1273\text{ K})\text{kJ} + (1-f)\int_{1273}^{T}\left(C_p\right)_{C_2H_6} dT + f\int_{1273}^{T}\left(C_p\right)_{C_2H_4} dT + f\int_{1273}^{T}\left(C_p\right)_{H_2} dT = 0$$

$\Big\Downarrow$ rearrange, reverse limits and change signs of integrals

$$\frac{1-f}{f} = \underbrace{\frac{\Delta\hat{H}_r(1273K) - \displaystyle\int_{T}^{1273}\left(C_p\right)_{C_2H_4} dT - \int_{T}^{1273}\left(C_p\right)_{H_2} dT}{\displaystyle\int_{T}^{1273}\left(C_p\right)_{C_2H_6} dT}}_{\phi(T)}\quad (3)$$

$$\frac{1-f}{f} = \phi(T) \Rightarrow 1 - f = f\phi(T) \Rightarrow f = \frac{1}{1 + \phi(T)}\quad (4)$$

9.35 (cont'd)

$$\phi(T) = \frac{145600 - \int_T^{1273}(9.419 + 0.1147T)dT - \int_T^{1273}\left(26.90 + 4.167 \times 10^{-3}\,T\right)dT}{\int_T^{1273}(11.35 + 0.1392T)dT}$$

$$\Rightarrow \phi(T) = \frac{3052 + 36.2T + 0.05943T^2}{127240 - 11.3T - 0.0696T^2}$$

c. $$\left(\frac{K_p}{1 + K_p}\right)^{1/2} = \frac{1}{1 + \phi(T)} \Rightarrow \left(\frac{K_p}{1 + K_p}\right)^{1/2} - \frac{1}{1 + \phi(T)} = \psi(T) = 0$$

$\phi(T)$ given by expression of Part b. $K_p(T)$ given by Eq. (1)

d.

P	T	f	Kp	Phi	Psi
(atm)	(K)		(atm)		
0.01	794	0.518	0.0037	0.93152	-0.0001115
0.05	847.4	0.47	0.0141	1.12964	-0.0002618
0.1	872.3	0.446	0.025	1.24028	0.00097743
0.5	932.8	0.388	0.0886	1.57826	3.41E-05
1	960.3	0.36	0.1492	1.77566	4.69E-05
5	1026	0.292	0.4646	2.42913	-2.57E-05
10	1055	0.261	0.7283	2.83692	-7.54E-05

Plot of T vs ln P

Plot of f vs. ln P
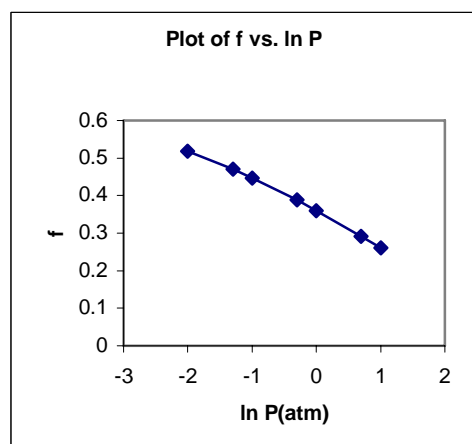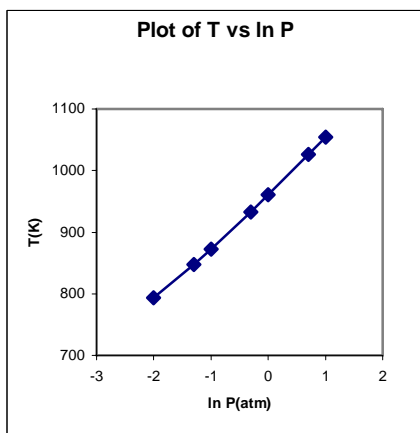
e.
```
C  **PROGRAM FOR PROBLEM 9-35
      WRITE (5, 1)
1     FORMAT ('1', 20X, 'SOLUTION TO PROBLEM 9-35'//)
      T = 1200.0
      TLAST = 0.0
      PSIL = 0.0
```

9.35 (cont'd)

```
      C  **DECREMENT BY 50 DEG. AND LOOK FOR A SIGN IN PSI
            DO 10I =1, 20
            CALL PSICAL (T, PHI, PSI)
            IF ((PSIL*PSI).LT.0.0) GO TO 40
            TLAST = T
            PSIL = PSI
            T = T – 50.
   10       CONTINUE
   40       IF (T.GE.0.0) GO TO 45
            WRITE (3, 2)
    2       FORMAT (1X, 'T LESS THAN ZERO -- ERROR')
            STOP
      C  **APPLY REGULA-FALSI
   45       DO 50 I = 1, 20
            IF (I.NE.1) T2L = T2
            T2 = (T*PSIL-TLAST*PSI)/(PSIL-PSI)
            IF (ABS(T2-T2L).LT.0.01) GO TO 99
            CALL PSICAL (T2, PHIT, PSIT)
            IF (PSIT.EQ.0) GO TO 99
            IF ((PBIT*PBIL).GT.0.0) PSIL = PSIT
            IF ((PSIT*PSIL).GT.0.0) TLAST = T2
            IF ((PSIT*PSI).GT.0.0) PSI = PSIT
            IF ((PSIT*PSI).GT.0.0) T = T2
   50       CONTINUE
            IF (I.EQ.20) WRITE (3, 3)
    3       FORMAT ('0', 'REGULA-FALSI DID NOT CONVERGE IN 20 ITERATIONS')
   93       STOP
            END
            SUBROUTINE PSICAL (T, PHI, PSI)
            REAL KF
            PHI = (3052 + 36.2*T + 36.2*T + 0.05943*T**2)/(127240. – 11.35*T
        *    – 0.0636*T**2)
            KP = 7.28E6*EXP(-17000./T)
            FBI = SQRT((KP/(1. + KP)) – 1./12. + PHI)
            WRITE (3, 1) T, PSI
    1       FORMAT (6X, 'T =', F6.2, 4X, 'PSI =', E11,4)
            RETURN
            END
```

OUTPUT: SOLUTION TO PROBLEM 9-35

T = 1200.00   PSI = 0.8226E + 00

T = 1150.00   PSI = 0.7048E + 00

T = 1100.00   PSI = 0.5551E + 00

T = 1050.00   PSI = 0.3696E + 00

T = 1000.00   PSI = 0.1619E + 00

T = 950.00   PSI = −0.3950E − 01

T = 959.80   PSI = −0.1824E − 02

T = 960.25   PSI = −0.7671E − 04

T = 960.27   PSI = −0.3278E − 05

Solution: $T = 960.3$ K, $f = 0.360$ mol C_2H_6 reacted/mol fed

9.36

$$2CH_4 \rightarrow C_2H_2 + 3H_2$$
$$C_2H_2 \rightarrow 2C(s) + H_2$$

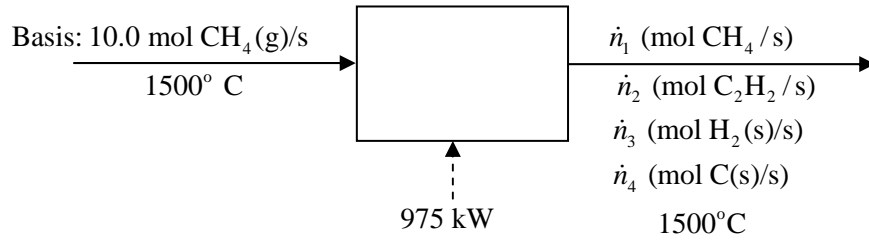Basis: 10.0 mol $CH_4(g)$/s
1500° C

[reactor box]

$\dot{n}_1$ (mol CH_4/s)
$\dot{n}_2$ (mol C_2H_2/s)
$\dot{n}_3$ (mol $H_2(s)$/s)
$\dot{n}_4$ (mol $C(s)$/s)
1500°C

975 kW
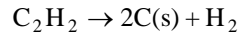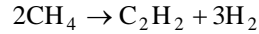
a.

60% conversion $\Rightarrow \dot{n}_1 = 10(1 - 0.600) = \underline{\underline{4.00 \text{ mol } CH_4/s}}$

C balance: $10(1) = 4(1) + 2\dot{n}_2 + \dot{n}_4 \Rightarrow 2\dot{n}_2 + \dot{n}_4 = 6$ (1)
H balance: $10(4) = 4(4) + 2\dot{n}_2 + 2\dot{n}_3 \Rightarrow 2\dot{n}_2 + 2\dot{n}_3 = 24$ (2)

References for enthalpy calculations : $C(s)$, $H_2(g)$ at 25°C

$$H_i = \left(\Delta\hat{H}_f^o\right)_i + C_{pi}(1500 - 25), \ i = CH_4, C_2H_2, C, H_2$$

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
$CH_4(g)$	10	41.68	4	41.68
$C_2H_2(g)$	–	–	$\dot{n}_2$	303.45
$H_2(g)$	–	–	$\dot{n}_3$	45.72
$C(s)$	–	–	$\dot{n}_4$	32.45

Energy Balance: $Q = \Delta H \Rightarrow 975 \text{ kJ}/s = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i$ (3)

Solve (1) - (3) simultaneously $\Rightarrow$
$\begin{cases} \dot{n}_2 = \underline{\underline{2.50 \text{ mol } C_2H_2/s}} \\ \dot{n}_3 = \underline{\underline{9.50 \text{ mol } H_2/s}} \\ \dot{n}_4 = \underline{\underline{1.00 \text{ mol } C/s}} \end{cases}$

Yield of acetylene $= \dfrac{2.50 \text{ mol } C_2H_2/s}{6.00 \text{ mol } CH_4 \text{ consumed}/s} = \underline{\underline{0.417 \text{ mol } C_2H_2/\text{mol } CH_4 \text{ consumed}}}$

b.

If no side reaction,

$\dot{n}_1 = 10.0(1 - 0.600) = \underline{\underline{4.00 \text{ mol } CH_4/s}}$

$\dot{n}_3 = 0 \Rightarrow \dot{n}_2 = \underline{\underline{3.00 \text{ mol } C_2H_2/s}}, \ \dot{n}_4 = \underline{\underline{9.00 \text{ mol } H_2/s}}$

Yield of acetylene $= \dfrac{3.00 \text{ mol } C_2H_2/s}{6.00 \text{ mol } CH_4 \text{ consumed}/s} = \underline{\underline{0.500 \text{ mol } C_2H_2/\text{mol } CH_4 \text{ consumed}}}$

Reactor Efficiency $= \dfrac{0.417}{0.500} = \underline{\underline{0.834}}$

9.37 $C_3H_8(g) + 3H_2O(v) \rightarrow 3CO(g) + 7H_2(g)$

$CO(g) + H_2O(v) \rightarrow CO_2(g) + H_2(g)$

<u>Basis</u> : 1 mol C_3H_8 fed

Heating gas
4.94 m³ at 1400°C, 1 atm
n_g (mol)

n_g (mol), 900°C

1 mol $C_3H_8(g)$
6 mol $H_2O(g)$
125°C

Product gas, 800°C
n_1 (mol C_3H_8) = 0
n_2 (mol H_2O)
n_3 (mol CO)
n_4 (mol CO_2)
n_5 (mol H_2)
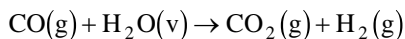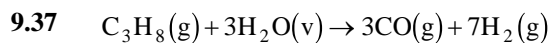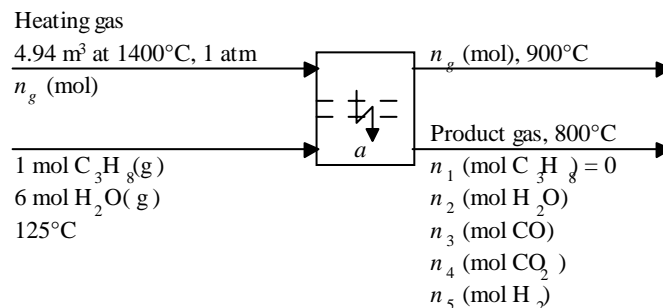
$$n_g = \frac{4.94 \text{ m}^3}{} \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \frac{273 \text{ K}}{1673 \text{ K}} \left| \frac{1 \text{ mol}}{22.4 \text{ L}} \right. = 35.99 \text{ mol heating gas}$$

Let ξ_1 and ξ_2 be the extents of the two reactions.

$n_1 = 1 - \xi_1 \overset{n_1 = 0}{\Rightarrow} \xi_1 = 1 \text{ mol}$ $\qquad\qquad n_4 = \xi_2$

$n_2 = 6 - 3\xi_1 - \xi_2 \overset{\xi_1 = 1}{\Rightarrow} n_2 = 3 - \xi_2$ $\qquad n_5 = 7\xi_1 + \xi_2 \overset{\xi_1 = 1}{\Rightarrow} n_5 = 7 + \xi_2$

$n_3 = 3\xi_1 - \xi_2 \overset{\xi_1 = 1}{\Rightarrow} n_3 = 3 - \xi_2$

<u>References</u> : C(s), $H_2(g), O_2(g)$ at 25°C, heating gas at 900°C

$$\hat{H}_i = \Delta\hat{H}_{fi}^o + \int_{25}^{T} C_{pi} dT \qquad \text{for } C_3H_8$$

$= $ Table B.8 for CO_2, H_2, H_2O, CO

$$= \int_{900}^{T} C_p dT = C_p(T - 900) \quad \text{for heating gas}$$

Substance	n_{in} mol	$\hat{H}_{in}$ kJ / mol	n_{out} mol	$\hat{H}_{out}$ kJ / mol
C_3H_8	1	−95.39	0	−
H_2O	6	−238.43	$3 - \xi_2$	−212.78
CO	−	−	$3 - \xi_2$	−86.39
CO_2	−	−	ξ_2	−356.15
H_2	−	−	$7 + \xi_2$	22.85
heating gas	35.99	200.00	35.99	0

<u>Energy Balance</u> :

$$\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0 \Rightarrow \xi_2 = 2.00 \text{ mol} \Rightarrow n_2 = 1 \text{ mol } H_2O, \ n_3 = 1 \text{ mol CO},$$

$n_4 = 1 \text{ mol } CO_2, n_5 = 9 \text{ mol } H_2 \Rightarrow \underline{7.7 \text{ mol } \% \ H_2O, \ 7.7\% \ CO, \ 15.4\% \ CO_2, \ 69.2\% \ H_2}$

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_2O)

0.500 kg H20
$\Rightarrow$

1.0 kg coal
0.105 kg H_2O/kg coal
0.226 kg ash/kg coal

$\left\{ \begin{array}{l} 0.669 \text{ kg combustible / kg coal} \\ 0.812 \text{ kg C / kg combustible} \\ 0.134 \text{ kg O / kg combustible} \\ 0.054 \text{ kg H / kg combustible} \end{array} \right.$

n_{f1} (mol C)
n_{f2} (mol O)
n_{f3} (mol H)
n_{f4} (mol H_2O)
0.226 kg ash
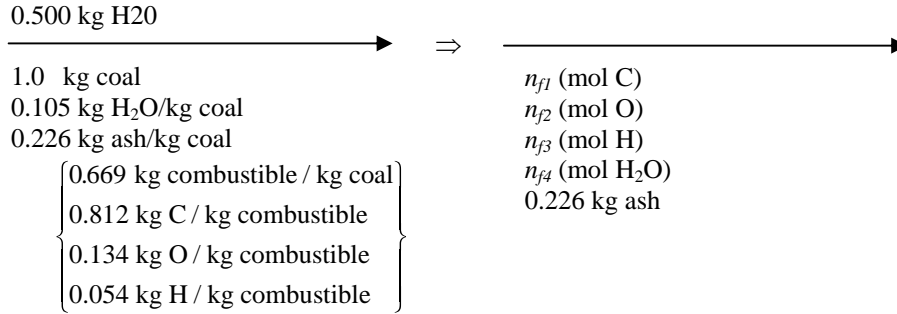
$n_{f1} = [(1.00)(0.669)(0.812) \text{ kg C}][1 \text{ mol C} / 12.01 \times 10^{-3} \text{ kg}] = 45.23 \text{ mol C}$

$n_{f2} = (1.00)(0.669)(0.134) / 16.0 \times 10^{-3} = 5.6 \text{ mol O}$

$n_{f3} = (1.00)(0.669)(0.054) / 1.01 \times 10^{-3} = 35.77 \text{ mol H}$

$n_{f4} = [(0.500+0.105) \text{ kg}][1 \text{ mol } H_2O / 18.016 \times 10^{-3} \text{ kg}] = 33.58 \text{ mol } H_2O$

n_0 (mol O_2) 25°C

Product gas at 2500°C
n_1 (mol CO_2)
n_2 (mol CO)
n_3 (mol H_2)
n_4 (mol H_2O)

1 kg coal + H_2O, 25°C
45.23 mol C
5.60 mol O
35.77 mol H
33.58 mol H_2O
0.226 mol kg ash

0.226 kg slag
2500°C
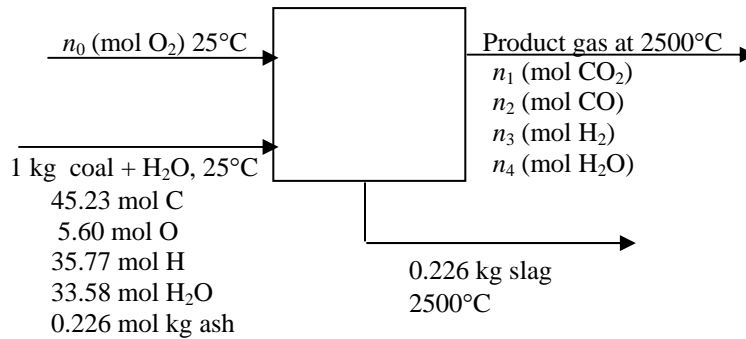
Reactive oxygen (O) available $= (2n_0 + 5.60) \text{ mol O}$

Oxygen consumed by H ($2H + O \rightarrow H_2O$) : $\dfrac{35.77 \text{ mol H}}{} \left| \dfrac{1 \text{ mol O}}{2 \text{ mol H}} \right. = 17.88 \text{ mol O}$

$\Rightarrow$ Reactive O remaining $= (2n_0 + 5.60) - 17.88 = (2n_0 - 12.28) \text{ mol O}$

CO_2 formed ($C + 2O \rightarrow CO_2$) : $n_1 = \dfrac{(2n_0 - 12.28) \text{ mol O}}{} \left| \dfrac{1 \text{ mol } CO_2}{2 \text{ mol O}} \right. = \underline{\underline{(n_0 - 6.14) \text{ mol } CO_2}}$

C balance : $45.23 = n_1 + n_2 \overset{n_1 = n_0 - 6.14}{\Longrightarrow} n_2 = \underline{\underline{(51.37 - n_0) \text{ mol CO}}}$

O balance : $2n_0 + 5.60 + 33.58 = 2n_1 + n_2 + n_4 \overset{n_1 = n_0 - 6.14}{\underset{n_2 = 51.37 - n_0}{\Longrightarrow}} n_4 = \underline{\underline{(n_0 + 0.06) \text{ mol } H_2O}}$

H balance : $35.77 + 2(33.58) = 2n_3 + 2n_4 \overset{n_4 = n_0 + 0.06}{\Longrightarrow} n_3 = \underline{\underline{(51.37 - n_0) \text{ mol } H_2}}$

9.38 (cont'd)

c. 1 kg coal contains 45.23 mol C and 35.77 mol H

$$\Rightarrow \ 1 \text{ kg coal} + nO_2 \rightarrow 45.23 \ CO_2 + (35.77 \, / \, 2) \text{ mol } H_2O \text{ (l)}$$
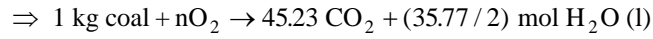
$$\Delta \hat{H}_r = -21{,}400 \text{ kJ} = 45.23 (\Delta \hat{H}_f^o)_{CO_2} + (35.77 \, / \, 2)(\Delta \hat{H}_f^o)_{H_2O(l)} - (\Delta \hat{H}_f^o)_{coal}$$

$$\Rightarrow \underline{\underline{(\Delta \hat{H}_f^o)_{coal} = -1510 \text{ kJ} \, / \, \text{kg}}}$$

Re ferences : $C(s)$, $O_2(g)$, $H_2(g)$, ash(s) at $25^o C$

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
CO_2	–	–	$n_0 - 6.14$	$\hat{H}_1$
CO	–	–	$51.37 - n_0$	$\hat{H}_2$
H_2	–	–	$51.37 - n_0$	$\hat{H}_3$
H_2O	33.58	$\hat{H}_0$	$n_0 + 0.06$	$\hat{H}_4$
Coal	1 kg	−1510 kJ/kg	–	–
Ash(slag)	(in coal)	0	0.266 kg	$\hat{H}_5$ (kJ/kg)

$$\hat{H}_i = \Delta \hat{H}_{fi}^o + C_{pi}(2500 - 25), \ i = 1,3$$

$$\hat{H}_1 = -393.5 + 0.0508(2475) = -267.8 \text{ kJ/mol } CO_2$$

$$\hat{H}_2 = -110.52 + 0.0332(2475) = -28.35 \text{ kJ/mol CO}$$

$$\hat{H}_3 = 0.0300(2475) = 74.25 \text{ kJ/mol } H_2$$

$$\hat{H}_4 = -241.83 + 0.0395(2475) = -144.07 \text{ kJ/mol } H_2O$$

$$\hat{H}_5 = (\Delta \hat{H}_m)_{ash} + 1.4(2475) = 710 + 1.4(2475) = 4175 \text{ kJ/kg ash}$$

Energy Balance

$$\Delta H = \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in} = 0 \ \Rightarrow \ \underline{\underline{n_0 = 35.4 \text{ mol } O_2}}$$

9.39

$$\underline{\text{Mass of } H_2SO_4} = \frac{3 \text{ m}^3}{} \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \frac{1 \text{ mol } H_2SO_4}{L} \right| = 3000 \text{ mol } H_2SO_4 \left(\frac{98.02 \text{ g}}{1 \text{ mol}} \right) = 2.941 \times 10^5 \text{ g } H_2SO_4$$

$$\underline{\text{Mass of solution}} = \frac{3 \text{ m}^3}{} \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \frac{10^3 \text{ mL}}{L} \left| \frac{1.064 \text{ g}}{1 \text{ mL}} \right| = 3.192 \times 10^6 \text{ g solution}$$

$$\Rightarrow \underline{\text{Moles of } H_2O} = (3.192 \times 10^6 - 2.941 \times 10^5) \text{g } H_2O (\frac{1 \text{ mol}}{18.02 \text{ g}}) = 1.61 \times 10^5 \text{ mol } H_2O$$

$$n \left(\frac{\text{mol } H_2O}{\text{mol } H_2SO_4} \right) = \frac{1.61 \times 10^5 \text{ mol } H_2O}{3000 \text{ mol } H_2SO_4} = 53.6 \text{ mol } H_2O/\text{mol } H_2SO_4$$

$$\left(\Delta \hat{H}_f \right)_{H_2SO_4(aq., r=53.6)} = \left(\Delta \hat{H}_f^o \right)_{\substack{H_2SO_4(l) \\ \uparrow \\ \text{Table B.1}}} + \left(\Delta \hat{H}_s \right)_{\substack{H_2SO_4(aq., r=53.6) \\ \uparrow \\ \text{Table B.11}}} = (-811.32 - 73.39) \frac{kJ}{mol} = \underline{\underline{-884.7 \text{ kJ/mol}}}$$

$$H = (3000 \text{ mol } H_2SO_4)(-884.7 \text{ kJ/mol } H_2SO_4) = \underline{\underline{-2.65 \times 10^6 \text{ kJ}}}$$

9.40

$$\underline{\text{HCl (aq):}} \ \Delta \hat{H}_f^o = \left(\Delta \hat{H}_f^o \right)_{HCl(g)} + \left(\Delta \hat{H}_s^o \right)_\infty \overset{\text{Tables B.1, B11}}{=} -92.31 - 75.14 = -167.45 \text{ kJ/mol}$$

$$\underline{\text{NaOH (aq):}} \ \Delta \hat{H}_f^o = \left(\Delta \hat{H}_f^o \right)_{NaOH(s)} + \left(\Delta \hat{H}_s^o \right)_\infty \overset{\substack{\text{Tables B1, B.11} \\ \downarrow}}{=} -426.6 - 42.89 = -469.49 \text{ kJ/mol}$$

$$\underline{\text{NaCl (aq):}} \ \Delta \hat{H}_f^o = \left(\Delta \hat{H}_f^o \right)_{NaCl(s)} + \left(\Delta \hat{H}_s^o \right)_\infty \overset{\substack{\text{Table B.1} \quad \text{Given} \\ \downarrow \qquad \downarrow}}{=} -411.0 + 4.87 = -406.1 \text{ kJ/mol}$$
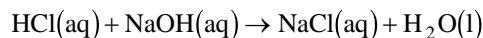
$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$
$$\Delta \hat{H}_r^o = \left[-406.1 - 285.84 - (-167.45) - (-469.49) \right] = \underline{\underline{-55.0 \text{ kJ/mol}}}$$
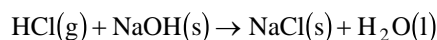
$$HCl(g) + NaOH(s) \rightarrow NaCl(s) + H_2O(l)$$
$$\Delta \hat{H}_r^o = \sum_{\text{products}} v_i \Delta \hat{H}_f^o - \sum_{\text{reactants}} v_i \Delta \hat{H}_f^o$$
$$= \left[-411.0 - 285.84 - (-92.31) - (-426.6) \right] \text{ kJ/mol} = \underline{\underline{-177.9 \text{ kJ/mol}}}$$

The difference between the two calculated values equals
$$\left\{ \left(\Delta \hat{H}_s \right)_{NaCl} - \left(\Delta \hat{H}_s \right)_{HCl} - \left(\Delta \hat{H}_s \right)_{NaOH} \right\}.$$

9.41 **a.** $\quad H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(l)$

$$\underline{\text{Basis:}} \ 1 \text{ mol } H_2SO_4 \text{ soln} \Rightarrow \left. \begin{array}{l} 0.10 \text{ mol } H_2SO_4 \times (98.08 \text{ g/mol}) = 9.808 \text{ g } H_2SO_4 \\ 0.90 \text{ mol } H_2O \times (18.02 \text{ g/mol}) = 16.22 \text{ g } H_2O \end{array} \right\}$$

$$\Rightarrow \frac{26.03 \text{ g soln}}{} \left| \frac{1 \text{ cm}^3}{1.27 \text{ g}} \right. = 20.49 \text{ cm}^3$$

$$\Rightarrow \frac{0.10 \text{ mol } H_2SO_4}{} \left| \frac{2 \text{ mol NaOH}}{1 \text{ mol } H_2SO_4} \right| \frac{1 \text{ liter caustic soln}}{3 \text{ mol NaOH}} \left| \frac{10^3 \text{ cm}^3}{1 \text{ L}} \right. = 66.67 \text{ cm}^3 \text{ NaOH(aq)}$$

9.41 (cont'd)

$$\underline{\text{Volume ratio}} = \frac{66.67 \text{ cm}^3 \text{ NaOH(aq)}}{20.49 \text{ cm}^3 \text{ H}_2\text{SO}_4 \text{ (aq)}} = \underline{\underline{3.25 \text{ cm}^3 \text{caustic solution} / \text{cm}^3 \text{ acid solution}}}$$

b. $\underline{\text{H}_2\text{SO}_4(\text{aq})}$: $r = 9 \text{ mol H}_2\text{O} / 1 \text{ mol H}_2\text{SO}_4$

$$\left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{soln}} = \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{H}_2\text{SO}_4(\text{l})} + \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{H}_2\text{SO}_4(\text{aq., } r=9)} = \left(-811.32 - 65.23\right)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-877 \text{ kJ/mol H}_2\text{SO}_4}}$$

$\underline{\text{NaOH(aq)}}$: The solution fed contains $\left(66.67 \text{ cm}^3\right)\left(1.13 \text{ g/cm}^3\right) = 75.34 \text{ g}$, and

$(0.2 \text{ mol NaOH})(40.00 \text{ g/mol}) = 8.00 \text{ g NaOH}$

$\Rightarrow (75.34 - 8.00) \text{ g H}_2\text{O} \Rightarrow (67.39 \text{ g H}_2\text{O})(1 \text{ mol}/18.02 \text{ g}) = 3.74 \text{ mol H}_2\text{O}$

$\Rightarrow r = 3.74 \text{ mol H}_2\text{O}/0.20 \text{ mol NaOH} = 18.7 \text{ mol H}_2\text{O} / \text{mol NaOH}$

$$\left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{soln}} = \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{NaOH(s)}} + \left(\Delta\hat{H}_{\text{s}}^{\,\text{o}}\right)_{\text{NaOH(s)(aq., } r=18.7)} = \left(-426.6 - 42.8\right)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-469.4 \text{ kJ/mol NaOH}}}$$

$\underline{\text{Na}_2\text{SO}_4(\text{aq})}$:

$$\left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{soln}} = \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{Na}_2\text{SO}_4(\text{s})} + \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{Na}_2\text{SO}_4(\text{aq})} = \left(-1384.5 - 1.17\right)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-1385.7 \text{ kJ/mol Na}_2\text{SO}_4}}$$

$\underline{\text{Extent of reaction:}}$ $(n_{\text{H}_2\text{SO}_4})_{\text{final}} = (n_{\text{H}_2\text{SO}_4})_{\text{fed}} + \nu_{\text{H}_2\text{SO}_4}\xi \Rightarrow 0 = 0.10\text{mol} - (1)\xi \Rightarrow \xi = 0.10 \text{ mol}$

$\underline{\text{Energy Balance:}}$

$$Q = \Delta H = \xi\Delta\hat{H}_{\text{r}}^{\,\text{o}} = \xi\left[(\Delta\hat{H}_{\text{f}}^{\,\text{o}})_{\text{Na}_2\text{SO}_4(\text{aq})} + 2(\Delta\hat{H}_{\text{f}}^{\,\text{o}})_{\text{H}_2\text{O}(\text{l})} - (\Delta\hat{H}_{\text{f}}^{\,\text{o}})_{\text{H}_2\text{SO}_4(\text{aq})} - 2(\Delta\hat{H}_{\text{f}}^{\,\text{o}})_{\text{NaOH(aq)}}\right]$$

$$= (0.10 \text{ mol})\left[-1385.7 + 2(-285.84) - (-876.55) - (2)(-469.4)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-14.2 \text{ kJ}}}$$

9.42   **a.**

$\underline{\text{NaCl(aq):}}$ $\Delta\hat{H}_{\text{f}}^{\,\text{o}} = \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{NaCl(s)}} + \left(\Delta\hat{H}_{\text{s}}^{\,\text{o}}\right)_{\infty} \overset{\underset{\text{Table B.1,}}{\underset{\text{given}}{\downarrow}}}{=} (-411.0 + 4.87)\text{kJ} / \text{mol} = \underline{\underline{-406.1 \text{ kJ/mol}}}$

$\underline{\text{NaOH(aq):}}$

$\Delta\hat{H}_{\text{f}}^{\,\text{o}} = \left(\Delta\hat{H}_{\text{f}}^{\,\text{o}}\right)_{\text{NaOH(s)}} + \left(\Delta\hat{H}_{\text{s}}^{\,\text{o}}\right)_{\infty} \overset{\underset{\text{Table B.1}}{\downarrow}}{=} (-426.6 - 42.89)\text{kJ} / \text{mol} = \underline{\underline{-469.5 \text{ kJ/mol}}}$

$$\text{NaCl(aq)} + \text{H}_2\text{O(l)} \rightarrow \frac{1}{2}\text{H}_2(\text{g}) + \frac{1}{2}\text{Cl}_2(\text{g}) + \text{NaOH(aq)}$$
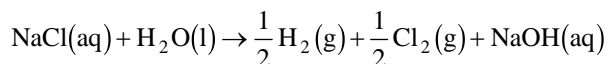
$$\Delta\hat{H}_{\text{r}}^{\,\text{o}} = \left[-469.5 - (-406.1) - (-285.84)\right]\text{kJ/mol} = \underline{\underline{222.44 \text{ kJ/mol}}}$$

b.

$$\frac{8500 \text{ ktonne Cl}_2}{\text{yr}} \left| \frac{10^3 \text{ tonne}}{1 \text{ ktonne}} \right| \frac{10^3 \text{ kg}}{1 \text{ tonne}} \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \frac{1 \text{ mol Cl}_2}{70.91 \text{ g Cl}_2} \left| \frac{222.44 \text{ kJ}}{0.5 \text{ mol Cl}_2} \right|$$

$$\frac{10^3 \text{ J}}{1 \text{ kJ}} \left| \frac{2.778 \times 10^{-7} \text{ kW} \cdot \text{h}}{1 \text{ J}} \right| \frac{1 \text{ MW} \cdot \text{h}}{10^3 \text{ kW} \cdot \text{h}} = \underline{\underline{1.48 \times 10^7 \text{ MW} \cdot \text{h} / \text{yr}}}$$

9.43 **a.**

$CaCl_2(s) + 10H_2O(l) \rightarrow CaCl_2(aq, r = 10)$ (1) $\Delta \hat{H}_{r1}^o = -64.85$ kJ/mol

$CaCl_2 \cdot 6H_2O(s) + 4H_2O(l) \rightarrow CaCl_2(aq, r = 10)$ (2) $\Delta \hat{H}_{r2}^o = +32.41$ kJ/mol

$(1) - (2) \Rightarrow CaCl_2(s) + 6H_2O(l) \rightarrow CaCl_2 \cdot 6H_2O(s)$ (3)

$\Rightarrow \Delta \hat{H}_{r3}^o = \Delta \hat{H}_{r1}^o - \Delta \hat{H}_{r2}^o \, (\text{Hess's law}) = \underline{\underline{-97.26 \text{ kJ/mol}}}$

b.
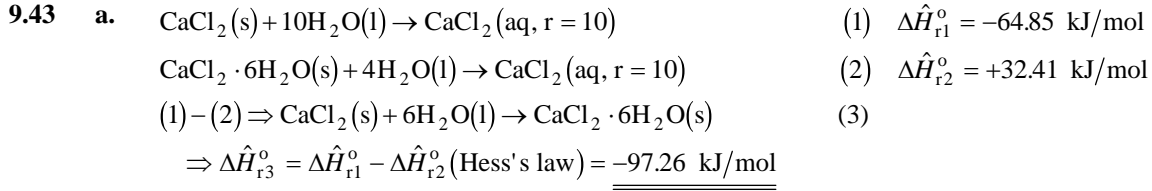
From (1), $\Delta \hat{H}_{r1}^o = \left(\Delta \hat{H}_f^o\right)_{CaCl_2(aq, \, r=10)} - \left(\Delta \hat{H}_f^o\right)_{CaCl_2(s)}$

$\Rightarrow \left(\Delta \hat{H}_f^o\right)_{CaCl_2(aq, \, r=10)} = (-64.85 - 794.96) \text{ kJ/mol} = \underline{\underline{-859.81 \text{ kJ/mol}}}$

9.44   Basis: 1 mol $(NH_4)_2 SO_4$ produced

2 mol NH₃ (g), 75°C, 1mol H₂SO₄ (aq), 25°C → 1 mol (NH₄)₂SO₄ (aq), 25°C

$2NH_3(g) + H_2SO_4(aq) \rightarrow (NH_4)_2 SO_4(aq)$
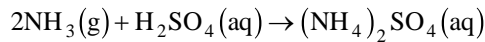
a.

References : Elements at 25°C

$\underline{NH_3(g, 75°C)}: \hat{H} = \Delta \hat{H}_f^o + \int_{25}^{75} C_p \, dT = \left(-46.19 + 1.83\right) \text{kJ/mol} = -44.36 \text{ kJ/mol} \text{ (Table B.1, B.2)}$

$\underline{H_2SO_4(aq, 25°C)}: \hat{H} = \left(\Delta \hat{H}_f^o\right)_{H_2SO_4(aq)} = -907.51 \text{ kJ/mol } H_2SO_4 \text{ (Table B.1)}$

$\underline{(NH_4)_2 SO_4(aq, 25°C)}: \hat{H} = \left(\Delta \hat{H}_f^o\right)_{(NH_4)_2SO_4(aq)} = -1173.1 \text{ kJ/mol } (NH_4)_2 SO_4 \text{ (Table B.1)}$

Energy balance:

$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = (1)(-1173.1) - (2)(-44.36) - (1)(-907.51) \text{ kJ}$

$= -177 \text{ kJ} \Rightarrow \underline{\underline{177 \dfrac{\text{kJ withdrawn}}{\text{mol } (NH_4)_2 SO_4 \text{ produced}}}}$

b.   1 mole % $(NH_4)_2 SO_4$ solution $\Rightarrow \dfrac{1 \text{ mol } (NH_4)_2SO_4 \mid 132 \text{ g}}{\mid \text{mol}} = 132 \text{ g } (NH_4)_2 SO_4$

$\dfrac{99 \text{ mol } H_2O \mid 18 \text{ g}}{\mid \text{mol}} = \dfrac{1782 \text{ g } H_2O}{1914 \text{ g solution}}$

The heat transferred from the reactor in part (a) now goes to heat the product solution from

$25°C \text{ to } T_{final} \Rightarrow 177 \text{ kJ} = \dfrac{1.914g \mid 1 \text{ kg} \mid 4.184 \text{ kJ} \mid (T - 25)°C}{\mid 10^3 \text{ g} \mid \text{kg}°C \mid} \Rightarrow T_{final} = \underline{\underline{47.1°C}}$

c.   In a real reactor, the final solution temperature will be less than the value calculated in part b, due to heat loss to the surroundings. The final temperature will therefore be <u>less</u> than 47.1°C.

9.45 **a.** $H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(aq)$ Basis: 1 mol H_2SO_4 fed
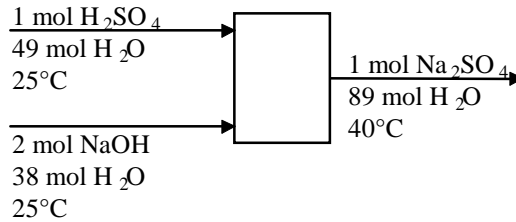
Reference states: Na(s), H_2(g), S(s), O_2(g) at 25°C

$\underline{H_2SO_4\left(aq, r = 49, 25°C\right):}$

$$n\hat{H} = \left(1 \text{ mol } H_2SO_4\right)\left[\left(\Delta\hat{H}_f^o\right)_{H_2SO_4(l)} + \Delta\hat{H}_s^o\left(r = 49\right)\right]\left(kJ/mol\right) + 49\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$$= (1)[-811.3 - 73.3] = -884.6 \text{ kJ} + 49\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$\underline{NaOH\left(aq, r = 19, 25°C\right):}$

$$n\hat{H} = \left(2 \text{ mol } NaOH\right)\left[\left(\Delta\hat{H}_f^o\right)_{NaOH(s)} + \Delta\hat{H}_s^o\left(r = 19\right)\right]\left(kJ/mol\right) + 38\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$$= (2)[-426.6 - 42.8] = -938.8 \text{ kJ} + 38\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$\underline{Na_2SO_4\left(aq, r = 89, 40°C\right):}$

$$\frac{1 \text{ kmol } Na_2SO_4}{} \left|\frac{142.0 \text{ kg}}{1 \text{ kmol}}\right. = 0.142 \text{ kg}, \quad \frac{89 \text{ kmol } H_2O}{} \left|\frac{18.02 \text{ kg}}{1 \text{ kmol}}\right. = 1.604 \text{ kg} \Rightarrow 1.746 \text{ kg}$$

$$n\hat{H} = \left(1 \text{ mol } Na_2SO_4\right)\left[\left(\Delta\hat{H}_f^o\right)_{Na_2SO_4} + \left(\Delta\hat{H}_s^o\right)_{Na_2SO_4}\right] + 89\left(\Delta\hat{H}_f^o\right)_{H_2O(l)} + mC_p\left(40 - 25\right)$$

$\quad\quad\quad\quad\Delta\hat{H}_f^o = -1384.5 \text{ kJ/mol (Table B.1)}$
$\quad\quad\quad\quad\Delta\hat{H}_s^o = -1.2 \text{ kJ/mol}$
$\quad\quad\quad\quad m = 1.746 \text{ kg}, C_p \approx \left(C_p\right)_{H_2O(l)} = 4.814 \text{ kJ}/(kg\cdot°C)$

$$n\hat{H} = -1276 \text{ kJ} + 89\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$\underline{\text{Energy balance:}} \quad Q = \Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 547.4 + 2\overset{-285.84 \text{ kJ/mol}}{\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}} = -24.3 \text{ kJ}$

$\underline{\text{Mass of acid fed}}$

$$\frac{1 \text{ mol } H_2SO_4}{} \left|\frac{98.08 \text{ g } H_2SO_4}{1 \text{ mol}}\right. + \frac{49 \text{ mol } H_2O}{} \left|\frac{18.02 \text{ g } H_2O}{1 \text{ mol}}\right. = 981 \text{ g} = 0.981 \text{ kg}$$

$$\Rightarrow \frac{Q}{M_{acid}} = \frac{-24.3 \text{ kJ}}{0.981 \text{ kg acid}} \Rightarrow \underline{\underline{24.8 \text{ kJ / kg acid transferred from reactor contents}}}$$

b. If the reactor is adiabatic, the heat transferred from the reactor of Part(a) instead goes to heat the product solution from 40°C to T_f

$$\Rightarrow 24.3 \times 10^3 \text{ J} = \frac{1.746 \text{ kg}}{} \left|\frac{4.184 \text{ kJ}}{kg \cdot °C}\right| \left(T_f - 40\right)°C \Rightarrow T_f = \underline{\underline{43°C}}$$

9.46 **a.** $H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(l)$
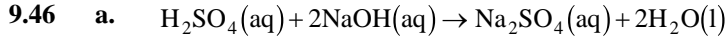
$\underline{H_2SO_4 \text{ solution::}}$

$$75 \text{ ml of 4M } H_2SO_4 \text{ solution} \Rightarrow \frac{4 \text{ mol } H_2SO_4}{1 \text{ L acid soln}} \left| \frac{1 \text{ L}}{10^3 \text{ mL}} \right| \frac{75 \text{ mL}}{} = 0.30 \text{ mol } H_2SO_4$$

$(75 \text{ mL})(1.23 \text{ g/mL}) = 92.25 \text{ g}, \quad (0.3 \text{ mol } H_2SO_4)(98.08 \text{ g/mol}) = 29.42 \text{ g } H_2SO_4$

$\Rightarrow (92.25 - 29.42) \text{ g } H_2O \Rightarrow (62.83 \text{ g } H_2O)(1 \text{ mol}/18.02 \text{ g}) = 3.49 \text{ mol } H_2O$

$\Rightarrow r = 3.49 \text{ mol } H_2O/0.30 \text{ mol } H_2SO_4 = 11.63 \text{ mol } H_2O / \text{mol } H_2SO_4$

$$\left(\Delta\hat{H}_f^o \right)_{\text{soln}} = \left(\Delta\hat{H}_f^o \right)_{H_2SO_4(l)} + \left(\Delta\hat{H}_f^o \right)_{H_2SO_4(aq., \, r=11.63)} \overset{\substack{\text{Table B.1,} \\ \text{Table B.11} \\ \downarrow}}{=} (-811.32 - 67.42)\frac{kJ}{mol}$$

$$= -878.74 \text{ kJ/mol } H_2SO_4$$

$\underline{NaOH \text{ solution required:}}$

$$\frac{0.30 \text{ mol } H_2SO_4}{} \left| \frac{2 \text{ mol NaOH}}{1 \text{ mol } H_2SO_4} \right| \frac{1 \text{ L NaOH(aq)}}{12 \text{ mol NaOH}} \left| \frac{10^3 \text{ mL}}{1 \text{ L}} \right. = 50.00 \text{ mL NaOH(aq)}$$

$(50.00 \text{ mL})(1.37 \text{ g/mL}) = 68.5 \text{ g}$

$$\frac{12 \text{ mol NaOH}}{1 \text{ L NaOH(aq)}} \left| \frac{1 \text{ L}}{10^3 \text{ mL}} \right| \frac{50 \text{ mL}}{} = 0.60 \text{ mol NaOH} \overset{40 \text{ g/mol NaOH}}{\Longrightarrow} 24.00 \text{ g NaOH}$$

$\Rightarrow (68.5 - 24.00) \text{ g } H_2O \Rightarrow (44.5 \text{ g } H_2O)(1 \text{ mol}/18.02 \text{ g}) = 2.47 \text{ mol } H_2O$

$$\Rightarrow r = 2.47 \text{ mol } H_2O/0.6 \text{ mol NaOH} = \frac{4.12 \text{ mol } H_2O}{\text{mol NaOH}}$$

$$\left(\Delta\hat{H}_f^o \right)_{\text{soln}} = \left(\Delta\hat{H}_f^o \right)_{NaOH(s)} + \left(\Delta\hat{H}_s^o \right)_{NaOH(s)(aq., \, r=4.12)} = (-426.6 - 35.10)\frac{kJ}{mol}$$

$$= -461.70 \text{ kJ/mol NaOH}$$

$\underline{Na_2SO_4(aq):}$

$$\left(\Delta\hat{H}_f^o \right)_{\text{soln}} = \left(\Delta\hat{H}_f^o \right)_{Na_2SO_4(s)} + \left(\Delta\hat{H}_f^o \right)_{Na_2SO_4(aq)} = (-1384.5 - 1.17)\frac{kJ}{mol} = -1385.7 \text{ kJ/mol } Na_2SO_4$$

$m_{total} = \text{total mass of reactants or products} = (92.25 \text{g } H_2SO_4 \text{ soln} + 68.5 \text{g NaOH}) = 160.75 \text{g} = 0.161 \text{ kg}$

$\underline{\text{Extent of reaction:}} \ (n_{H_2SO_4})_{\text{final}} = (n_{H_2SO_4})_{\text{fed}} + \nu_{H_2SO_4}\xi \Rightarrow 0 = 0.30 \text{ mol} - (1)\xi \Rightarrow \xi = 0.30 \text{ mol}$

$\underline{\text{Standard heat of reaction}}$

$$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o \right)_{Na_2SO_4(aq)} + 2\left(\Delta\hat{H}_f^o \right)_{H_2O(l)} - \left(\Delta\hat{H}_f^o \right)_{H_2SO_4(aq)} - 2\left(\Delta\hat{H}_f^o \right)_{NaOH(aq)}$$

$\underline{\text{Energy Balance}}: \ Q = \Delta H = \xi\Delta\hat{H}_r^o + m_{total}C_p(T - 25)^\circ C$

$$= (0.30 \text{ mol})(155.2 \text{ kJ / mol}) + (0.161 \text{ kg})\left(4.184 \ \frac{kJ}{kg \ ^\circ C} \right)(T - 25)^\circ C = 0 \Rightarrow T = \underline{\underline{94 \ ^\circ C}}$$

b. Volumes are additive.
Heat transferred to and through the container wall is negligible.

9.47   Basis : 50,000 mol flue gas/h
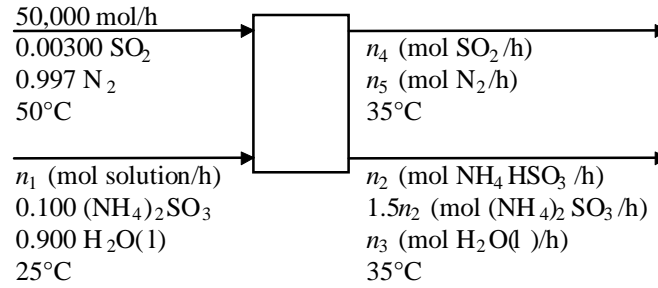
90% SO_2 removal: $\dot{n}_4 = 0.100(0.00300)(50,000 \text{ mol/h}) = 15.0 \text{ mol } SO_2/h$

N_2 balance: $\dot{n}_5 = (0.997)(50,000 \text{ mol/h}) = 49,850 \text{ mol } N_2/h$

NH_4^+ balance: $(2)(0.100)(\dot{n}_1) = \dot{n}_2 + (1.5)(2)\dot{n}_2 \Rightarrow \dot{n}_1 = 20\dot{n}_2$ ⎫ $\dot{n}_1 = 5400 \text{ mol/h}$

S balance: $0.100\dot{n}_1 + (0.00300)(50,000) = 15.0 + \dot{n}_2 + 1.5\dot{n}_2$ ⎭ $\Rightarrow$ $\dot{n}_2 = 270 \text{ mol } NH_4HSO_3/h$

H_2O balance: $\dot{n}_3 = (0.900)(5400) - \dfrac{270 \text{ mol } NH_4HSO_3 \text{ produced}}{h} \Bigg| \dfrac{1 \text{ mol } H_2O \text{ consumed}}{2 \text{ mol } NH_4HSO_3 \text{ produced}}$

$= 4725 \text{ mol } H_2O(l)/h$

Heat of reaction:

$\Delta\hat{H}_r^o = 2\left(\Delta\hat{H}_f^o\right)_{NH_4HSO_4(aq)} - \left(\Delta\hat{H}_f^o\right)_{(NH_4)_2SO_3(aq)} - \left(\Delta\hat{H}_f^o\right)_{SO_2(g)} - \left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$

$= 2(-760) - (-890) - (-296.90) - (-285.84) \text{ kJ/mol} = -47.3 \text{ kJ/mol}$

References : $N_2(g), SO_2(g), (NH_4)_2SO_3(aq), NH_4HSO_3(aq), H_2O(l)$ at 25°C

$\underline{SO_2(g, 50°C)}$: $\hat{H} = \int\limits_{25}^{50}(C_p)_{SO_2} dT = 1.01 \text{ kJ/mol}$ (C_p from Table B.2)

$\underline{SO_2(g, 35°C)}$: $\hat{H} = \int\limits_{25}^{35}(C_p)_{SO_2} dT = 0.40 \text{ kJ/mol}$

$\underline{N_2(g, 50°C)}$: $\hat{H} = 0.73 \text{ kJ/mol}$ (Table B.8)

$\underline{N_2(g, 35°C)}$: $\hat{H} = 0.292 \text{ kJ/mol}$

Entering solution: $\hat{H} = 0$

Effluent solution at 35°C

$\dot{m}(g/h) = \dfrac{270 \text{ mol } NH_4HSO_3}{h} \Bigg| \dfrac{99 \text{ g}}{\text{mol}}$

$+ \dfrac{1.5 \times 270 \text{ mol }(NH_4)_2SO_3}{h} \Bigg| \dfrac{116 \text{ g}}{\text{mol}} + \dfrac{4725 \text{ mol } H_2O}{h} \Bigg| \dfrac{18 \text{ g}}{1 \text{ mol}} = 159,000 \dfrac{g}{h}$

$\dot{n}\hat{H} = mC_p\Delta T = \dfrac{159,000 \text{ g}}{h} \Bigg| \dfrac{4 \text{ J}}{g \cdot °C} \Bigg| \dfrac{(35-25)°C}{} \Bigg| \dfrac{1 \text{ kJ}}{10^3 \text{ J}} = 6360 \text{ kJ / h}$

Extent of reaction:

$(\dot{n}_{NH_4HSO_3})_{out} = (\dot{n}_{NH_4HSO_3})_{in} + \nu_{NH_4HSO_3}\dot{\xi} \Rightarrow 270 \text{ mol / h} = 0 + 2\dot{\xi} \Rightarrow \dot{\xi} = 135 \text{ mol / h}$

9.47 (cont'd)

Energy balance: $\dot{Q} = \Delta\dot{H} = \xi\Delta\hat{H}_r^o + \sum_{out} \dot{n}_i\hat{H}_i - \sum_{in} \dot{n}_i\hat{H}_i$

$$Q = \frac{135 \text{ mol}}{h}\bigg|\frac{-47.3 \text{ kJ}}{\text{mol}} + \overset{SO_2 \text{ out}}{(15)(0.40)} + \overset{N_2 \text{ out}}{(49,850)(0.292)}$$

$$+ \overset{\text{effluent solution}}{6360} - (50,000)(0.003)(1.01) - (49,850)(0.73) = \frac{-22,000 \text{ kJ}}{h}\bigg|\frac{1 \text{ h}}{3600 \text{ s}}\bigg|\frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-6.11 \text{ kW}}}$$

9.48 **a.** $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v)$
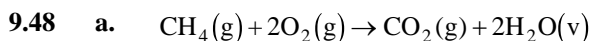
$$HHV = 890.36 \text{ kJ / mol},\ LHV = \overset{\text{Table B.1 HHV}}{-\Delta\hat{H}_c^o} - 2\overset{\text{at 25°C}}{\left(\Delta\hat{H}_v\right)_{H_2O}} = \left[890.36 - 2(44.01)\right]\text{kJ/mol}$$

$$= 802.34 \text{ kJ/mol } CH_4$$

$$C_2H_4(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v)$$
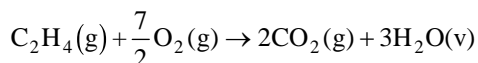
$$HHV = 1559.9 \text{ kJ / mol},\ LHV = \left[1559.9 - 3(44.01)\right]\text{kJ/mol} = 1427.87 \text{ kJ/mol } C_2H_6$$

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(v)$$
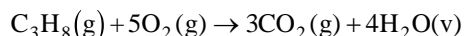
$$HHV = 2220.0 \text{ kJ / mol},\ LHV = \left[2220.0 - 4(44.01)\right]\text{kJ/mol} = 2043.96 \text{ kJ/mol } C_3H_8$$

$$\left(HHV\right)_{\text{natural gas}} = (0.875)(890.36 \text{ kJ/mol}) + (0.070)(1559.9 \text{ kJ/mol}) + (0.020)(2200.00 \text{ kJ/mol})$$

$$= \underline{\underline{933 \text{ kJ/mol}}}$$

$$\left(LHV\right)_{\text{natural gas}} = (0.875)(802.34 \text{ kJ/mol}) + (0.070)(1427.87 \text{ kJ/mol}) + (0.020)(2043.96 \text{ kJ/mol})$$

$$= \underline{\underline{843 \text{ kJ/mol}}}$$

b. $1 \text{ mol natural gas} \Rightarrow [(0.875 \text{ mol } CH_4)\left(16.04\frac{g}{\text{mol}}\right) + (0.070 \text{ mol } C_2H_6)\left(30.07\frac{g}{\text{mol}}\right)$

$$+ (0.020 \text{ mol } C_3H_8)\left(44.09\frac{g}{\text{mol}}\right) + (0.035 \text{ mol } N_2)\left(28.02\frac{g}{\text{mol}}\right)] \times \frac{1 \text{ kg}}{10^3 \text{ g}} = 0.01800 \text{ kg}$$

$$\Rightarrow \frac{843 \text{ kJ}}{\text{mol}}\bigg|\frac{1 \text{ mol}}{0.01800 \text{ kg}} = \underline{\underline{46800 \text{ kJ/kg}}}$$

c. The enthalpy change when 1 kg of the natural gas at 25°C is burned completely with oxygen at 25°C and the products $CO_2(g)$ and $H_2O(v)$ are brought back to 25°C.

9.49

$$C(s) + O_2(g) \rightarrow CO_2(g),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\left(\Delta\hat{H}_f^o\right)_{CO_2(g)}} = \frac{-393.5 \text{ kJ}}{\text{mol}}\bigg|\frac{1 \text{ mol}}{12.01 \text{ g}}\bigg|\frac{10^3 \text{ g}}{1 \text{ kg}} = -32,764 \text{ kJ/kg C}$$

$$S(s) + O_2(g) \rightarrow SO_2(g),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\left(\Delta\hat{H}_f^o\right)_{SO_2}} = -296.90 \text{ kJ/mol} \overset{M_{SO_2}=32.064}{\Rightarrow} -9261 \text{ kJ / kg S}$$

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}} = -285.84 \text{ kJ/mol } H_2 \overset{M_{H_2}=1.008}{\Rightarrow} -141,790 \text{ kJ/kg H}$$
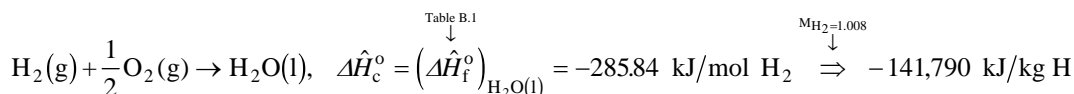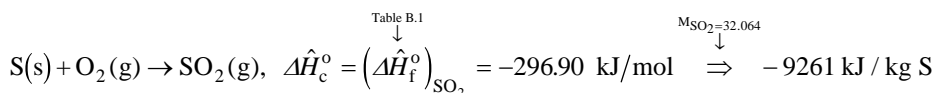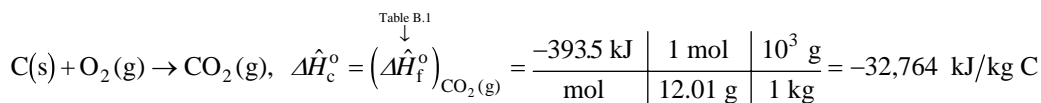
9.49 (cont'd)

a.

H available for combustion = total H – H in H_2O; latter is $\dfrac{x_0 \text{ (kg O)}}{\text{kg coal}} \bigg| \dfrac{2 \text{ kg H}}{16 \text{ kg O}}$

$\underset{\text{in water}}{\uparrow}$

Eq. (9.6-3) $\Rightarrow HHV = 32{,}764C + 141{,}790\left(H - \dfrac{O}{8}\right) + 9261S$

This formula does not take into account the heats of formation of the chemical constituents of coal.

b. $C = 0.758$, $H = 0.051$, $O = 0.082$, $S = 0.016 \Rightarrow (HHV)_{\text{Dulong}} = 31{,}646$ kJ/kg coal

1 kg coal $\Rightarrow \dfrac{0.016 \text{ kg S}}{} \bigg| \dfrac{64.07 \text{ kg } SO_2 \text{ formed}}{32.06 \text{ kg S burned}} = 0.0320$ kg SO_2/kg coal

$\phi = \dfrac{0.0320 \text{ kg } SO_2/\text{kg coal}}{31{,}646 \text{ kJ}/\text{kg coal}} = 1.01 \times 10^{-6}$ kg SO_2/kJ

c. Diluting the stack gas lowers the mole fraction of SO_2, but does not reduce SO_2 emission rates. The dilution does not affect the kg SO_2/kJ ratio, so there is nothing to be gained by it.

9.50

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(l)$, $HHV = -\Delta \hat{H}_c^\circ = 890.36$ kJ/mol (Table B.1)

$C_2H_6 + \dfrac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O(l)$, $HHV = 1559.9$ kJ/mol

$CO + \dfrac{1}{2}O_2 \rightarrow CO_2$, $HHV = 282.99$ kJ/mol
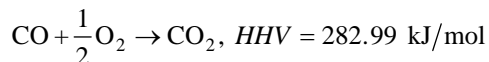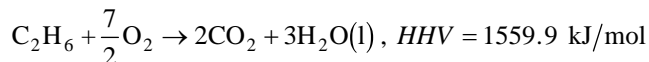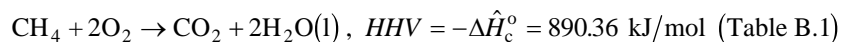
Initial moles charged: $\dfrac{2.000 \text{ L}}{} \bigg| \dfrac{273.2K}{(25+273.2)K} \bigg| \dfrac{2323 \text{ mm Hg}}{760 \text{ mm Hg}} \bigg| \dfrac{1 \text{ mol}}{22.4 \text{ L(STP)}} = 0.25$ mol
(Assume ideal gas)

Average mol. wt.: $(4.929 \text{ g})/(0.25 \text{ mol}) = 19.72$ g / mol

Let $x_1 = $ mol CH_4/mol gas, $x_2 = $ mol C_2H_6/mol gas $\left(\Rightarrow (1 - x_1 - x_2)\text{mol } CO(\text{mol gas})\right)$

$\overline{MW} = 19.72 \Rightarrow x_1(16.04 \text{ g/mol } CH_4) + x_2(30.07) + (1 - x_1 - x_2)(28.01) = 19.72$ (1)

$\overline{HHV} = 963.7$ kJ/mol $\Rightarrow x_1(890.36) + x_2(1559.9) + (1 - x_1 - x_2)(282.99) = 963.7$ (2)

Solving (1) & (2) simultaneously yields

$x_1 = 0.725$ mol CH_4/mol, $x_2 = 0.188$ mol C_2H_6/mol, $1 - x_1 - x_2 = 0.087$ mol CO/mol

9.51 **a.** Basis : 1mol/s fuel gas

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v)$, $\Delta \hat{H}_c^\circ = -890.36$ kJ / mol

$C_2H_6(g) + \dfrac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v)$, $\Delta \hat{H}_c^\circ = -1559.9$ kJ / mol

Excess O_2, 25°C

1 mol/s fuel gas, 25°C
85% CH_4
15% C_2H_6

$\dot{n}_2$, mol CO_2
$\dot{n}_3$, mol H_2O
$\dot{n}_4$, mol O_2
25°C
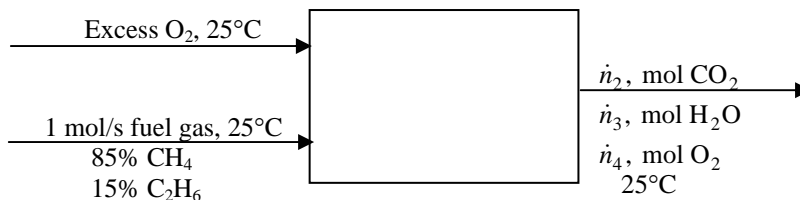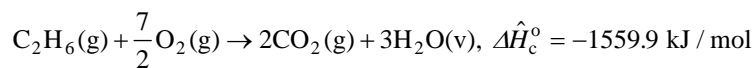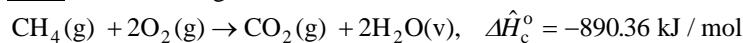
1 mol / s fuel gas $\Rightarrow$ 0.85 mol CH_4 / s , 0.15 mol C_2H_6 / s

$$\text{Theoretical oxygen} = \frac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \Bigg| \frac{0.85 \text{ mol } CH_4}{s} + \frac{3.5 \text{ mol } O_2}{1 \text{ mol } C_2H_6} \Bigg| \frac{0.15 \text{ mol } C_2H_6}{s} = 2.225 \text{ mol } O_2 / s$$

Assume 10% excess $O_2 \Rightarrow O_2$ fed $= 1.1 \times 2.225 = 2.448$ mol O_2 / s

C balance : $\dot{n}_2 = (0.85)(1) + (0.15)(2) \Rightarrow \dot{n}_2 = 1.15$ mol CO_2 / s

H balance : $2\dot{n}_3 = (0.85)(4) + (0.15)(6) \Rightarrow \dot{n}_3 = 2.15$ mol H_2O / s

10% excess $O_2 \Rightarrow \dot{n}_4 = (0.1)(2.225)$ mol O_2 / s $= 0.223$ mol O_2 / s

Extents of reaction: $\dot{\xi}_1 = \dot{n}_{CH_4} = 0.85$ mol / s, $\dot{\xi}_2 = \dot{n}_{C_2H_6} = 0.15$ mol / s

Reference states: $CH_4(g)$, $C_2H_6(g)$, $N_2(g)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at $25^\circ C$

(We will use the values of $\Delta\hat{H}_c^o$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water)

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
	mol	kJ/mol	mol	kJ/mol
CH_4	0.85	0	–	–
C_2H_6	0.15	0	–	–
O_2	2.225	0	0.223	0
CO_2	–	–	1.15	0
$H_2O(v)$	–	–	2.15	H_1

$\hat{H}_1 = \Delta\hat{H}_v(25^\circ C) = 44.01$ kJ / mol

Energy Balance :

$$\dot{Q} = \dot{n}_{CH_4}\left(\Delta\hat{H}_c^o\right)_{CH_4} + \dot{n}_{C_2H_6}\left(\Delta\hat{H}_c^o\right)_{C_2H_6} + \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i$$

$$= (0.85 \text{ mol / s } CH_4)(-890.36 \text{ kJ/mol}) + (0.15 \text{ mol / s } C_2H_6)(-1559.9 \text{ kJ/mol})$$

$$+ (2.15 \text{ mol / s } H_2O)(44.01 \text{ kJ / mol}) = -896 \text{ kW}$$

$\Rightarrow \underline{\underline{-\dot{Q} = 896 \text{ kW}}}$ (transferred from reactor)

b. Constant Volume Process. The flowchart and stoichiometry and material balance calculations are the same as in part (a), except that amounts replace flow rates (mol instead of mol/s, etc.)

1 mol fuel gas $\Rightarrow$ 0.85 mol CH_4, 0.15 mol C_2H_6

Theoretical oxygen $= 2.225$ mol O_2

Assume 10% excess $O_2 \Rightarrow O_2$ fed $= 1.1 \times 2.225 = 2.448$ mol O_2

C balance : $n_2 = (0.85)(1) + (0.15)(2) \Rightarrow n_2 = 1.15$ mol CO_2

H balance : $2n_3 = (0.85)(4) + (0.15)(6) \Rightarrow n_3 = 2.15$ mol H_2O

10% excess $O_2 \Rightarrow n_4 = (0.1)(2.225)$ mol $O_2 = 0.223$ mol O_2

Reference states: $CH_4(g)$, $C_2H_6(g)$, $N_2(g)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at $25^\circ C$

For a constant volume process the heat released or absorbed is determined by the internal energy of reaction.

Substance	n_{in}	$\hat{U}_{in}$	n_{out}	$\hat{U}_{out}$
	mol	kJ/mol	mol	kJ/mol
CH_4	0.85	0	–	–
C_2H_6	0.15	0	–	–
O_2	2.225	0	0.223	0
CO_2	–	–	1.15	0
$H_2O(v)$	–	–	2.15	$\hat{U}_1$

$$\hat{U}_1 = \Delta\hat{U}_v(25^\circ C) = \Delta\hat{H}_v(25^\circ C) - RT = 44.01 \text{ kJ / mol} - \frac{8.314 \text{ J}}{\text{mol K}}\left|\frac{1 \text{ kJ}}{1000 \text{ J}}\right|298 \text{ K} = 41.53 \frac{\text{kJ}}{\text{mol}}$$

Eq. (9.1-5) $\Rightarrow \Delta\hat{U}_c^o = \Delta\hat{H}_c^o - RT\left(\displaystyle\sum_{\substack{\text{gaseous}\\\text{products}}} v_i - \sum_{\substack{\text{gaseous}\\\text{reactants}}} v_i\right)$

$$\Rightarrow \left(\Delta\hat{U}_c^o\right)_{CH_4} = (-890.36 \text{ kJ/mol}) - \frac{8.314 \text{ J}}{\text{mol K}}\left|\frac{298 \text{ K}}{}\right|\frac{(1+2-1-2)}{}\left|\frac{1 \text{ kJ}}{10^3 \text{ J}}\right| = -890.36 \frac{\text{kJ}}{\text{mol}}$$

$$\left(\Delta\hat{U}_c^o\right)_{C_2H_6} = (-1559.9 \text{ kJ/mol}) - \frac{8.314 \text{ J}}{\text{mol K}}\left|\frac{298 \text{ K}}{}\right|\frac{(3+2-3.5-1)}{}\left|\frac{1 \text{ kJ}}{10^3 \text{ J}}\right| = -1561.14 \frac{\text{kJ}}{\text{mol}}$$

Energy balance:

$$Q = \Delta U = n_{CH_4}\left(\Delta\hat{U}_c^o\right)_{CH_4} + n_{C_2H_6}\left(\Delta\hat{U}_c^o\right)_{C_2H_6} + \sum_{out} n_i\hat{U}_i - \sum_{in}\dot{n}_i\hat{U}_i$$

$$= (0.85 \text{ mol / s } CH_4)(-890.36 \text{ kJ/mol}) + (0.15 \text{ mol / s } C_2H_6)(-1561.14 \text{ kJ/mol})$$

$$+ (2.15 \text{ mol / s } H_2O)(41.53 \text{ kJ / mol}) = -902 \text{ kJ}$$

$$\Rightarrow \underline{\underline{-Q = 902 \text{ kJ}}} \text{ (transferred from reactor)}$$

c. Since the O_2 (and N_2 if air were used) are at 25°C at both the inlet and outlet of this process, their specific enthalpies or internal energies are zero and their amounts therefore have no effect on the calculated values of $\Delta\dot{H}$ and ΔU.

9.52 a. $\dot{n}_{fuel}(-\Delta\hat{H}_c^o) = \dot{W}_s - \dot{Q}_l$ (Rate of heat release due to combustion = shaft work + rate of heat loss)

$$\frac{\dot{V}\text{ (gal)}}{\text{h}}\left|\frac{28.317 \text{ L}}{7.4805 \text{ gal}}\right|\frac{0.700 \text{ kg}}{\text{L}}\left|\frac{10^3 \text{ g}}{1 \text{ kg}}\right|\frac{49 \text{ kJ}}{\text{g}}$$

$$= \frac{100 \text{ hp}}{1.341\times10^{-3} \text{ hp}}\left|\frac{1 \text{ J / s}}{}\right|\frac{1 \text{ kJ}}{10^3 \text{ J}}\left|\frac{3600 \text{ s}}{\text{h}}\right| + \frac{15\times10^6 \text{ kJ}}{298 \quad \text{h}} \Rightarrow \underline{\underline{\dot{V} = 2.5 \text{ gal / h}}}$$

b. The work delivered would be less since more of the energy released by combustion would go into heating the exhaust gas.

c. Heat loss increases as T_a decreases.
Lubricating oil becomes thicker, so more energy goes to overcoming friction.

9.53 **a.**

Energy balance: $\Delta U = 0 \Rightarrow \dfrac{n(\text{lb}_\text{m} \text{ fuel burned})}{} \left| \dfrac{\Delta \hat{U}_c^o \text{ (Btu)}}{\text{lb}_\text{m}} + mC_v(T_\text{out} - 77^\circ\text{F}) = 0 \right.$

$\Rightarrow (0.00215)\Delta\hat{U}_c^o + (4.62 \text{ lb}_\text{m})(0.900 \text{ Btu/lb}_\text{m}\cdot^\circ\text{F})(87.06^\circ\text{F} - 77.00^\circ\text{F}) = 0$

$\Rightarrow \varDelta\hat{U}_c^o = \underline{\underline{-19500 \text{ Btu/lb}_\text{m}}}$

b. The reaction for which we determined $\Delta\hat{U}_c^o$ is

$$1 \text{ lb}_\text{m} \text{ oil } + aO_2(g) \rightarrow bCO_2(g) + cH_2O(v) \qquad (1)$$

The higher heating value is $\Delta\hat{H}_r$ for the reaction

$$1 \text{ lb}_\text{m} \text{ oil } + aO_2(g) \rightarrow bCO_2(g) + cH_2O(l) \qquad (2)$$

Eq. (9.1-5) on p. 441 $\Rightarrow \Delta\hat{H}_{c1}^o = \Delta\hat{U}_{c1}^o + RT(b + c - a)$

Eq. (9.6-1) on p. 462 $\Rightarrow \underset{(HHV)}{-\Delta\hat{H}_{c2}^o} = \underset{(LHV)}{-\Delta\hat{H}_{c1}^o} + c\Delta\hat{H}_v(H_2O,\ 77^\circ F)$

To calculate the higher heating value, we therefore need

$\underline{\underline{a = \text{lb-moles of } O_2 \text{ that react with 1 lb}_\text{m} \text{ fuel oil}}}$

$\underline{\underline{b = \text{lb-moles of } CO_2 \text{ formed when 1 lb}_\text{m} \text{ fuel oil is burned}}}$

$\underline{\underline{c = \text{lb-moles of } H_2O \text{ formed when 1 lb}_\text{m} \text{ fuel oil is burned}}}$

9.54 **a.**

$$CH_3OH(v) + \frac{3}{2}O_2(g) \rightarrow CO_2(g) + 2H_2O(l) \qquad \varDelta\hat{H}_r^o = \left(\varDelta\hat{H}_c^o\right)_{CH_3OH(v)} = -764.0\frac{\text{kJ}}{\text{mol}}$$
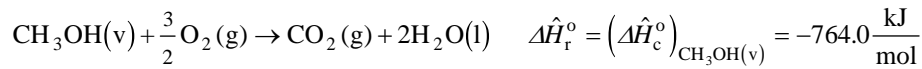
Basis : 1 mol CH_3OH fed and burned
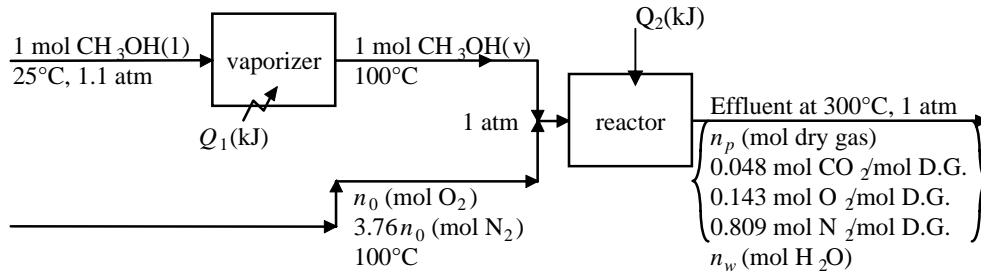
Overall C balance: $\dfrac{1 \text{ mol } CH_3OH}{} \left| \dfrac{1 \text{ mol C}}{1 \text{ mol } CH_3OH} \right. = n_p(0.048)(1) \Rightarrow n_p = 20.83 \text{ mol dry gas}$

N_2 balance: $3.76n_0 = (20.83)(0.809) \Rightarrow n_0 = 4.482 \text{ mol } O_2$

Theoretical O_2: $(1 \text{ mol } CH_3OH)(1.5 \text{ mol } O_2/\text{mol } CH_3OH) = 1.5 \text{ mol } O_2$

% excess air $= \dfrac{(4.482 - 1.5) \text{ mol } O_2}{1.5 \text{ mol } O_2} \times 100\% = \underline{\underline{200\% \text{ excess air}}}$

H balance: $(1 \text{ mol } CH_3OH)(4 \text{ mol H/1 mol } CH_3OH) = n_w(2) \Rightarrow n_w = 2 \text{ mol } H_2O$

(An atomic O balance $\Rightarrow$ 9.96 mol O = 9.96 mol O , so that the results are consistent.)

$p_w^* = \dfrac{n_w}{n_w + n_p} \times P = \dfrac{2 \text{ mol } H_2O}{(2 + 20.83)\text{mol}} \times 760 \text{ mm Hg} = 66.58 \text{ mm Hg} = p_w^*(T_{dp}) \overset{\text{Table B.3}}{\Rightarrow} \underline{\underline{T_{dp} = 44.1^\circ C}}$

b. Energy balance on vaporizer:

$$Q_1 = \Delta H = n\Delta\hat{H} = 1\ \text{mol}\left[\underbrace{\int_{25}^{64.7} C_{pl}\ dT}_{\text{Table B.2}} + \underbrace{\Delta\hat{H}_v}_{\text{Table B.1}} + \underbrace{\int_{64.7}^{100} C_{pv}\ dT}_{\text{Table B.2}}\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{40.33\ \text{kJ}}}$$

References : $CH_3OH(v)$, $N_2(g)$, $O_2(g)$, $CO_2(g)$, $H_2O(l)$ at $25°C$

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)
CH_3OH	1.00	3.603	–	–
N_2	16.85	2.187	16.85	8.118
O_2	4.482	2.235	2.98	8.470
CO_2	–	–	1.00	11.578
H_2O	–	–	2.00	53.58

$\hat{H}(T) = \hat{H}_i$ for N_2, O_2, CO_2 (Table B.8)

$\quad = \Delta\hat{H}_v\left(25°C\right) + \hat{H}_i$ for $H_2O(v)$ (Eq. 9.6-2a on p. 462, Table B.8)

$\quad = \int_{25}^{T} C_p dT$ for $CH_3OH(v)$ (Table B.2)

(Note: $H_2O(l)$ was chosen as the reference state since the given value of $\Delta\hat{H}_c^o$ presumes liquid water as the product.)

Extent of reaction: $(n_{CH_3OH})_{out} = (n_{CH_3OH})_{in} + \nu_{CH_3OH}\xi \Rightarrow 0 = 1\ \text{mol} - \xi \Rightarrow \xi = 1\ \text{mol}$

Energy balance on reactor: $Q_2 = \xi\Delta\hat{H}_c^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i$

$= \underbrace{(1)(-764.0)}_{\text{(Table B.1)}} + \left[(16.85)(8.118) + \ldots - (4.482)(2.235)\right]\text{kJ}$

$= -534\ \text{kJ} \Rightarrow \underline{534\ \text{kJ}}$ transferred from reactor

9.55 **a.** $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O$

Basis : 1000 mol CH_4/h fed
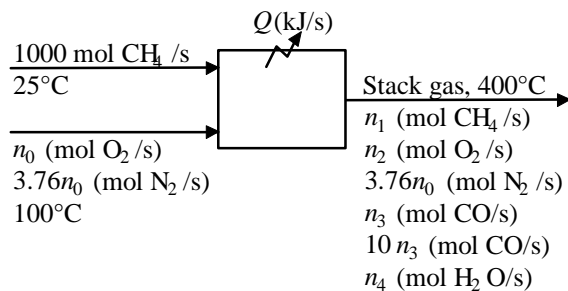
90% combustion $\Rightarrow \dot{n}_1 = 0.10(1000) = 100\ \text{mol}\ CH_4/s$

Theoretical O_2 required $= 2000\ \text{mol/s}$

10% excess $O_2 \Rightarrow O_2$ fed=1.1(2000 mol/s)=2200 mol/s

C balance:

$$(1000 \text{ mol } CH_4/s)(1 \text{ mol } C/mol \text{ } CH_4) = (100)(1) + \dot{n}_3(1) + 10\dot{n}_3(1) \Rightarrow \dot{n}_3 = 81.8 \text{ mol } CO/s$$
$$\Rightarrow 10\dot{n}_3 = 818 \text{ mol } CO_2/s$$

H balance: $(1000)(4) = (100)(4) + 2\dot{n}_4 \Rightarrow \dot{n}_4 = 1800 \text{ mol } H_2O/s$

O balance: $(2200)(2) = 2\dot{n}_2 + (81.8)(1) + (818)(2) + (1800)(1) \Rightarrow \dot{n}_2 = 441 \text{ mol } O_2/s$

References : $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at $25°C$

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
CH_4	1000	−74.85	100	−57.62
O_2	2200	2.24	441	11.72
N_2	8272	2.19	8272	11.15
CO	–	–	81.8	−99.27
CO_2	–	–	818	−377.2
H_2O	–	–	1800	−228.63

$$\hat{H} = \Delta\hat{H}_f^o + \int_{25}^{T} \overset{\text{Table B.2}}{C_p} \, dT \text{ for } CH_4$$

$$= \Delta\hat{H}_f^o + \overset{\text{Table B.8}}{\hat{H}_i(T)} \text{ for others}$$

Energy balance: $\dot{Q} = \Delta\dot{H} = \sum_{out} \dot{n}_i\hat{H}_i - \sum_{in} \dot{n}_i\hat{H}_i = \underline{\underline{-5.85 \times 10^5 \text{ kJ/s (kW)}}}$

b.

(i) $T_{air} \uparrow \text{(increases)} \Rightarrow -\dot{Q}\uparrow$

(ii) $\%XS \uparrow \Rightarrow -\dot{Q}\downarrow$ (more energy required to heat additional O_2 and N_2 to 400°C, therefore less energy transferred.)

(iii) $S_{CO_2/CO} \uparrow \Rightarrow -\dot{Q}\uparrow$ (reaction to form CO2 has a greater heat of combustion and so releases more thermal energy)

(iv) $T_{stack} \uparrow \Rightarrow -\dot{Q}\downarrow$ (more energy required to heat combustion products)

9.56 $$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O, \quad C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$
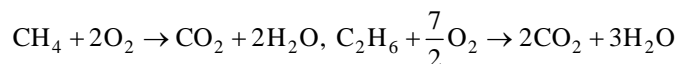
<u>Basis</u> : 100 mol stack gas. Assume ideal gas behavior.

n_1 (mol CH_4)
n_2 (mol C_2H_6)
V_f (m^3 at 25°C, 1 atm)

n_3 (mol O_2)
$3.76n_3$ (mol N_2)
200°C, 1 atm

100 mol at 800°C, 1 atm
0.0532 mol CO_2/mol
0.0160 mol CO/mol
0.0732 mol O_2 /mol
0.1224 mol H_2O/mol
0.7352 mol N_2 /mol
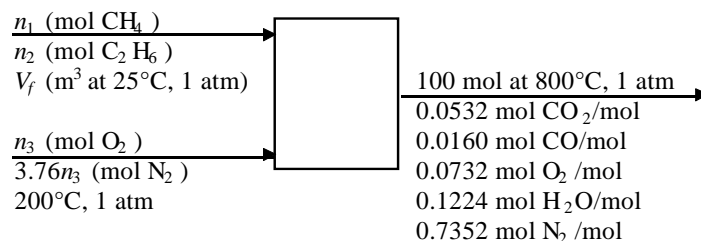
a.

<u>N_2 balance:</u> $3.76n_3 = (100)(0.7352)$mol $N_2 \Rightarrow n_3 = 19.55$ mol O_2 fed

<u>C balance:</u> $n_1(1) + n_2(2) = (100)(0.0532)(1) + (100)(0.0160)(1)$ $\Big\}\Rightarrow$ $n_1 = 3.72$ mol CH_4
<u>H balance:</u> $n_1(4) + n_2(6) = (100)(0.1224)(2)$ $n_2 = 1.60$ mol C_2H_6

$$V_f = \frac{(3.72 + 1.60)\text{mol fuel gas}}{} \left| \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} \right| \frac{298.2 \text{ K}}{273.2 \text{ K}} \left| \frac{1 \text{ m}^3}{10^3 \text{ L}} \right. = 0.130 \text{ m}^3$$

<u>Theoretical O_2 =</u> $\dfrac{3.72 \text{ mol } CH_4}{}\left|\dfrac{2 \text{ mol } O_2}{1 \text{ mol } CH_4}\right. + \dfrac{1.60 \text{ mol } C_2H_6}{}\left|\dfrac{3.5 \text{ mol } O_2}{1 \text{ mol } C_2H_6}\right. = 13.04 \text{ mol } O_2$

<u>Fuel composition:</u> $\left.\begin{array}{l} 3.72 \text{ mol } CH_4 \\ 1.60 \text{ mol } C_2H_6 \end{array}\right\} \Rightarrow \dfrac{69.9 \text{ mole\% } CH_4}{30.1 \text{ mole\% } C_2H_6}$

<u>% Excess air:</u> $\dfrac{(19.55 - 13.04)\text{mol } O_2 \text{ in excess}}{13.04 \text{ mol } O_2 \text{ required}} \times 100\% = \underline{\underline{50\% \text{ excess air}}}$

b.

<u>References</u> : $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	mol	kJ / mol	mol	kJ / mol
CH_4	3.72	−74.85	−	−
C_2H_6	1.60	−84.67	−	−
O_2	19.55	5.31	7.32	25.35
N_2	73.52	5.13	73.52	23.86
CO	−	−	1.60	−86.39
CO_2	−	−	5.32	−356.1
H_2O	−	−	12.24	−212.78

9.56 (cont'd)

$$\hat{H} = \overset{\text{Table B.1}}{\underset{\downarrow}{\varDelta\hat{H}_f^o}} + \int_{25}^T \overset{\substack{\text{Table B.2, for} \\ \text{CH}_4, \text{C}_2\text{H}_6}}{\underset{\downarrow}{C_p}} \ dT$$

$$= \varDelta\hat{H}_f^o + \overset{\text{Table B.8}}{\underset{\downarrow}{\hat{H}_i}}(T) \ \text{ for O}_2, \text{ N}_2, \text{ CO, CO}_2, \text{ H}_2\text{O(v)}$$

Energy balance:

$$Q = \varDelta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \frac{-2764 \text{ kJ}}{0.130 \text{ m}^3 \text{ fuel}} = \underline{\underline{-2.13 \times 10^4 \ \text{kJ}/\text{m}^3 \text{ fuel}}}$$

9.57

$\underline{\text{Basis}:}$ 50000 lb_m coal fed/h $\Rightarrow \dfrac{(0.730)(50000)\text{lb}_m C}{h} \Big| \dfrac{1 \text{ lb - mole C}}{12.01 \text{ lb}_m} = 3039$ lb - mole C/h

$(0.047)(50000)/1.01 = 2327$ lb - moles H/h (does not include H in water)

$(0.037)(50000)/32.07 = 57.7$ lb - moles S/h

$(0.068)(50000)/18.02 = 189$ lb - moles H_2O/h

$(0.118)(50000) = 5900 \text{ lb}_m$ ash/h

$50,000 \text{ lb}_m$coal/h	Stack gas at 600°F, 1 atm <u>(assume)</u>
3039 lb-moles C/h	n_2 (lb-moles CO_2 /h)
2327 lb-moles H/h	n_3 (lb-moles H_2O/h)
57.7 lb-moles S/h	n_4 (lb-moles SO_2/h)
189 lb-moles H_2O/h	n_5 (lb-moles O_2 /h)
5900 lb_mash/h	n_6 (lb-moles N_2 /h)
77°F, 1 atm <u>(assume)</u>	m_7(lb$_m$ fly ash/h)
n_1 (lb-moles air/h)	m_8(lb$_m$ slag/h) at 600°F
$0.210 \ O_2$	$0.287 \text{ lb }_mC/\text{lb }_m$
$0.790 \ N_2$	$0.016 \text{ lb }_mS/\text{lb }_m$
77°F, 1 atm <u>(assume)</u>	$0.697 \text{ lb }_m\text{ash/lb }_m$
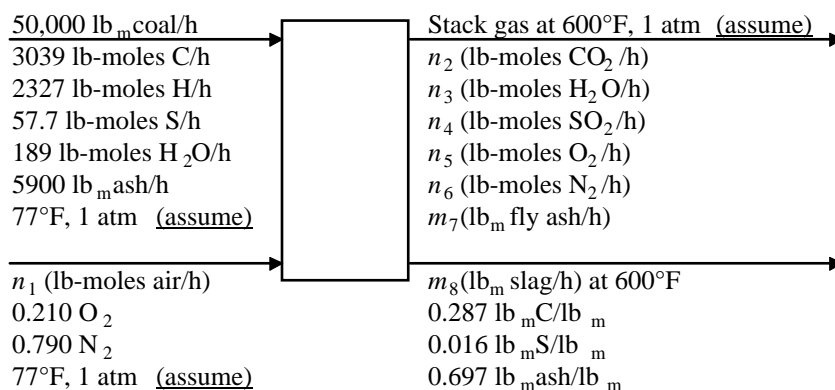
a. $\underline{\text{Feed rate of air :}}$

$\underline{O_2 \text{ required to oxidize carbon}} \ (C + O_2 \to CO_2) = \dfrac{3039 \text{ lb - moles C}}{h} \Big| \dfrac{1 \text{ lb - mole } O_2}{1 \text{ lb - mole C}}$

$$= 3039 \text{ lb - moles } O_2 /h$$

$\underline{\text{Air fed: }} \ \dot{n}_1 = \dfrac{1.5 \times 3039 \text{ lb - moles } O_2 \text{ fed}}{h} \Big| \dfrac{1 \text{ mole air}}{0.210 \text{ mole } O_2} = 21710$ lb - moles air/h

$\underline{\text{30\% ash in coal emerges in slag}} \Rightarrow 0.697 \dot{m}_8 = 0.30(5900 \text{ lb}_m /h) \Rightarrow \dot{m}_8 = 2540 \text{ lb}_m$ slag / h

$\quad \Rightarrow \dot{m}_7 = 0.700(5900) = 4130 \text{ lb}_m$ fly ash/h

$\underline{\text{C balance:}}$ $3039(\text{lb - moles C/h}) = \dot{n}_2 + (0.287)(2540)/12.01$

$\quad \Rightarrow \dot{n}_2 = 2978 \text{ lb - moles } CO_2 /h \xRightarrow{M_{CO_2} = 44.01} 1.31 \times 10^5 \text{ lb}_m \ CO_2 /h$

$\underline{\text{H balance:}}$ $2327(\text{lb - moles H/h}) + (189)(2) = 2\dot{n}_3$

$\quad \Rightarrow \dot{n}_3 = 1352.5 \text{ lb - moles } H_2O /h \xRightarrow{M_{H_2O} = 18.02} 2.44 \times 10^4 \text{ lb}_m \ H_2O/h$

$\underline{N_2 \text{ balance:}} \ \dot{n}_6 = (0.790)21710 \text{ lb - moles/h} = 17150 \text{ lb - moles } N_2 /h \xRightarrow{M_{N_2} = 28.02} 4.81 \times 10^5 \text{ lb}_m \ N_2 /h$

$\underline{\text{S balance:}}$ $57.7(\text{lb - moles S/h}) = (1)\dot{n}_4 + 0.016(2540)/32.06$

$\quad \Rightarrow \dot{n}_4 = 56.4 \text{ lb - moles } SO_2 /h \xRightarrow{M_{SO_2} = 64.2} 3620 \text{ lb}_m \ SO_2 /h$

$\underline{\text{O balance:}}$ $\underset{(\text{coal})}{(189)(1)} + \underset{(\text{air})}{(0.21)(21710)(2)} = \underset{(CO_2)}{(2978)(2)} + \underset{(H_2O)}{(1352.5)(1)} + \underset{(SO_2)}{(56.4)(2)} + \underset{(O_2)}{2\dot{n}_5}$

$\quad \Rightarrow \dot{n}_5 = 943 \text{ lb - moles } O_2 /h \Rightarrow 30200 \text{ lb}_m \ O_2 /h$

9.57 (cont'd)

Summary of component mass flow rates

Stack gas at 600° F, 1 atm

$\left.\begin{array}{l}
2978 \text{ lb-moles } CO_2/h \Rightarrow \quad \underline{\underline{131000 \text{ lb}_m \ CO_2/h}} \\[4pt]
1352.5 \text{ lb-moles } H_2O/h \Rightarrow \quad \underline{\underline{24400 \text{ lb}_m \ H_2O/h}} \\[4pt]
56.4 \text{ lb-moles } SO_2/h \Rightarrow \quad \underline{\underline{3620 \text{ lb}_m \ SO_2/h}} \\[4pt]
943 \text{ lb-moles } O_2/h \Rightarrow \quad \underline{\underline{30200 \text{ lb}_m \ O_2/h}} \\[4pt]
17150 \text{ lb-moles } N_2/h \Rightarrow \quad \underline{\underline{48100 \text{ lb}_m \ N_2/h}} \\[4pt]
\qquad\qquad\qquad\qquad \underline{\underline{4130 \text{ lb}_m \ \text{fly ash}/h}}
\end{array}\right\}$ 674,350 lb_m stack gas/h

Check: $\left[50000 + (21710)(29)\right]_{in} \Leftrightarrow \left[674350 + 2540\right]_{out}$

$\Rightarrow (679600)_{in} \Leftrightarrow (676900)_{out}$ (0.4% roundoff error)

Total molar flow rate = 22480 lb-moles/h at 600°F, 1 atm (excluding fly ash)

$$\Rightarrow V = \frac{22480 \text{ lb-moles}}{h} \left| \frac{359 \text{ ft}^3(\text{STP})}{1 \text{ lb-mole}} \right| \frac{1060°R}{492°R} = \underline{\underline{1.74 \times 10^7 \ \text{ft}^3/h}}$$

b. References: Coal components, air at 77°F $\Rightarrow \sum\limits_{in} n_i \hat{H}_i = 0$

Stack gas: $n\hat{H} = \dfrac{674350 \text{ lb}_m}{h} \left| \dfrac{7.063 \text{ Btu}}{\text{lb-mole}\cdot°F} \right| \dfrac{1 \text{ lb-mole}}{28.02 \text{ lb}_m} \left| \dfrac{(600-77)°F}{} \right| = 8.90 \times 10^7 \ \text{Btu/h}$

Slag: $n\hat{H} = \dfrac{2540 \text{ lb}_m}{h} \left| \dfrac{0.22 \text{ Btu}}{\text{lb}_m \cdot °F} \right| \dfrac{(600-77)°F}{} = 2.92 \times 10^5 \ \text{Btu/h}$

Energy balance: $Q = \Delta H = n_{\text{coal burned}} \Delta\hat{H}_c^o (77°F) + \sum\limits_{out} n_i \hat{H}_i - \sum\limits_{in} n_i \hat{H}_i$

$$= \frac{5 \times 10^4 \ \text{lb}_m}{h} \left| \frac{-1.8 \times 10^4 \ \text{Btu}}{\text{lb}_m} \right| + \left(8.90 \times 10^7 + 2.92 \times 10^5\right) \ \text{Btu/h}$$

$$= -8.11 \times 10^8 \ \text{Btu/h}$$

Power generated $= \dfrac{(0.35)\left(8.11 \times 10^8\right)\text{Btu}}{h} \left| \dfrac{1 \text{ hr}}{3600 \text{ s}} \right| \dfrac{1 \text{ W}}{9.486 \times 10^{-4} \ \text{Btu/s}} \left| \dfrac{1 \text{ MW}}{10^6 \ \text{W}} \right| = \underline{\underline{83.1 \text{ MW}}}$

c. $\hat{Q} = \left(-8.11 \times 10^8 \ \text{Btu/h}\right)/\left(5000 \text{ lb}_m \text{ coal}/h\right) = -1.62 \times 10^4 \ \text{Btu/lb}_m \text{ coal}$

$$\Rightarrow \frac{-\hat{Q}}{HHV} = \frac{1.62 \times 10^4 \ \text{Btu/lb}_m}{1.80 \times 10^4 \ \text{Btu/lb}_m} = \underline{\underline{0.901}}$$

Some of the heat of combustion goes to vaporize water and heat the stack gas.

d. $-\hat{Q}/HHV$ would be closer to 1. Use heat exchange between the entering air and the stack gas.

9.58 **b.** <u>Basis</u> : 1 mol fuel gas/s

$\dot{n}_0$ (mol O_2/s)

$3.76\dot{n}_0$ (mol N_2/s)

T_a (°C)

1 mol / s @ 25°C

x_m (mol CH_4 / mol)

x_a (mol Ar / mol)

$(1-x_m-x_a)$ (mol C_2H_6 / mol)

Stack gas, T_s (°C)

$\dot{n}_{O_2}$ (mol O_2 / s)

$3.76\dot{n}_0$ (mol N_2 / s)

$\dot{n}_{CO}$ (mol CO / s)

$\dot{m}_{CO}$ (mol CO_2 / s)

$\dot{n}_{H_2O}$ (mol H_2O / s)

$\dot{n}_{Ar}$ (mol Ar / s)

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + \frac{7}{2} O_2 \rightarrow 2CO_2 + 3H_2O$$
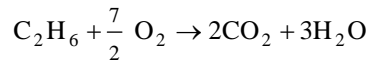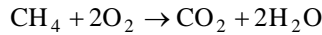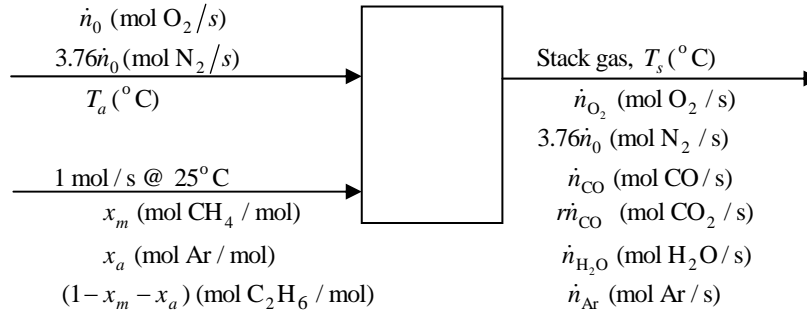
<u>Percent excess air</u>: $\dot{n}_0 = (1+\frac{P_{xs}}{100})\left[2x_m + 3.5(1-x_m-x_a)\right]$

<u>C balance</u>: $x_m + 2(1-x_m-x_a) = (1+r)\dot{n}_{CO} \Rightarrow \dot{n}_{CO} = \dfrac{x_m + 2(1-x_m-x_a)}{(1+r)}$

<u>H balance</u>: $4x_m + 6(1-x_m-x_a) = 2\dot{n}_{H_2O} \Rightarrow \dot{n}_{H_2O} = 2x_m + 3(1-x_m-x_a)$

<u>O balance</u>: $2\dot{n}_0 = 2\dot{n}_{O_2} + \dot{n}_{CO} + 2\,r\,\dot{n}_{CO} + \dot{n}_{H_2O} \Rightarrow \dot{n}_{O_2} = \dot{n}_0 - \dot{n}_{CO}(1+2r)/2 - \dot{n}_{H_2O}/2$

<u>References</u> : C(s), H_2(g), O_2(g), N_2(g) at 25°C

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
CH_4	x_m	0	–	–
C_2H_6	$(1-x_m-x_A)$	0	–	–
A	x_A	0	x_A	$\hat{H}_3$
O_2	n_o	$\hat{H}_1$	n_{O_2}	$\hat{H}_4$
N_2	$3.76n_o$	$\hat{H}_2$	$3.76n_o$	$\hat{H}_5$
CO	–	–	n_{CO}	$\hat{H}_6$
CO_2	–	–	$r\,n_{CO}$	$\hat{H}_7$
H_2O	–	–	n_{H_2O}	$\hat{H}_8$

c.

$$\hat{H}_i = (\Delta\hat{H}_f)_i + \int_{25}^{T_a \text{ or } T_s \overset{\text{Table B.2}}{\downarrow}} C_{p,i}\ dT$$

<u>Given</u> : $x_m = 0.85$, $x_a = 0.05$, $Px_s = 5\%$, $r = 10.0$, $T_a = 150°C$, $T_s = 700°C$

$\Rightarrow n_o = 2.153$, $n_{CO} = 0.0955$, $n_{H_2O} = 2.00$, $n_{O_2} = 0.1500$

$\hat{H}_1$(kJ / mol) = 8.091, $\hat{H}_2 = 29.588$, $\hat{H}_3 = 0.702$, $\hat{H}_4 = 3.279$,

$\hat{H}_5 = 166.72$, $\hat{H}_6 = -8.567$, $\hat{H}_7 = -345.35$, $\hat{H}_8 = -433.82$

<u>Energy balance</u>: $\dot{Q} = \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} = \underline{\underline{-655 \text{ kW}}}$

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	-
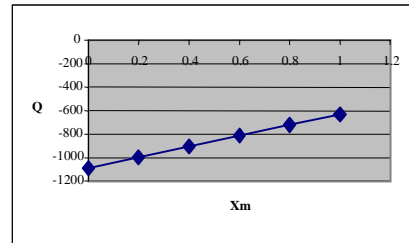
Xa	Pxs	r	Ta	Ts	Q
0.1	5	10	150	700	-
0.1	10	10	150	700	-
0.1	20	10	150	700	-
0.1	50	10	150	700	-
0.1	100	10	150	700	-
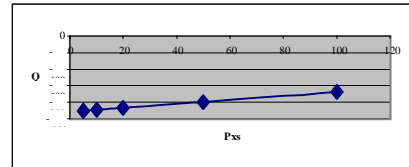
Xa	Pxs	r	Ta	Ts	Q
0.1	5	10	150	700	-
0.2	5	10	150	700	-
0.3	5	10	150	700	-
0.4	5	10	150	700	-
0.5	5	10	150	700	-
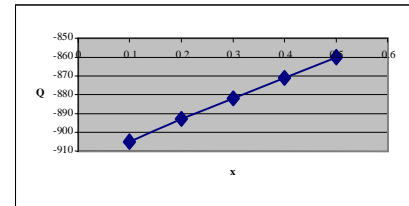
Xa	Pxs	r	Ta	Ts	Q
0.1	5	1	150	700	-722
0.1	5	2	150	700	-796
0.1	5	3	150	700	-834
0.1	5	4	150	700	-856
0.1	5	5	150	700	-871
0.1	5	10	150	700	-905
0.1	5	20	150	700	-924
0.1	5	50	150	700	-936
0.1	5	100	150	700	-941
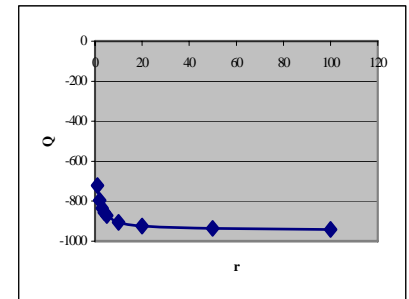
Xa	Pxs	r	Ta	Ts	Q
0.1	5	10	25	700	-852
0.1	5	10	100	700	-883
0.1	5	10	150	700	-905
0.1	5	10	200	700	-926
0.1	5	10	250	700	-948
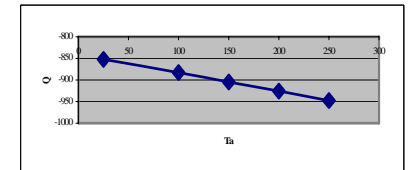
Xa	Pxs	r	Ta	Ts	Q
0.1	5	10	150	500	-1014
0.1	5	10	150	600	-960
0.1	5	10	150	700	-905
0.1	5	10	150	800	-848
0.1	5	10	150	900	-790
0.1	5	10	150	1000	-731
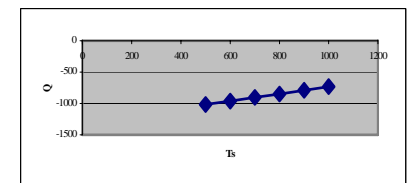
9.59   **a.**

Basis: $\dfrac{207.4 \text{ liters}}{\text{s}} \left| \dfrac{273.2 \text{ K}}{278.2 \text{ K}} \right| \dfrac{1.1 \text{ atm}}{1.0 \text{ atm}} \left| \dfrac{1 \text{ mol}}{22.4 \text{ liters(STP)}} \right. = 10.0 \text{ mols/s fuel gas to furnace}$

$H = C_6H_{14}; \; M = CH_4$

$\dot{m}_w$ (kg H_2O(l)/s) $\dot{m}_w$ (kg H_2O(v)/s)
25°C   10 bars, sat'd

$\dot{Q}_c$ (kW)

$\dot{n}_0$ (mol/s)
y_0 (mol C_6H_{14}/mol)
$(1 - y_0)$ (mol CH_4/mol)
60°C, 1.2 atm
$T_{dp} = 55°C$

condenser

10.0 mol/s at 5°C, 1.1 atm
y_2 (mol C_6H_{14}/mol)
$(1 - y_2)$ (mol CH_4/mol)
sat'd with C_6H_{14}

reactor

Stack gas at 400°C, 1 atm
n_3 (mol O_2/s)
n_4 (mol N_2/s)
n_5 (mol CO_2/s)
n_6 (mol H_2O(v)/s)

n_b (mol C_6H_{14}(l)/s)

n_a (mol air/s) @ 200°C
0.21 mol O_2/mol
0.79 mol N_2/mol
100% excess
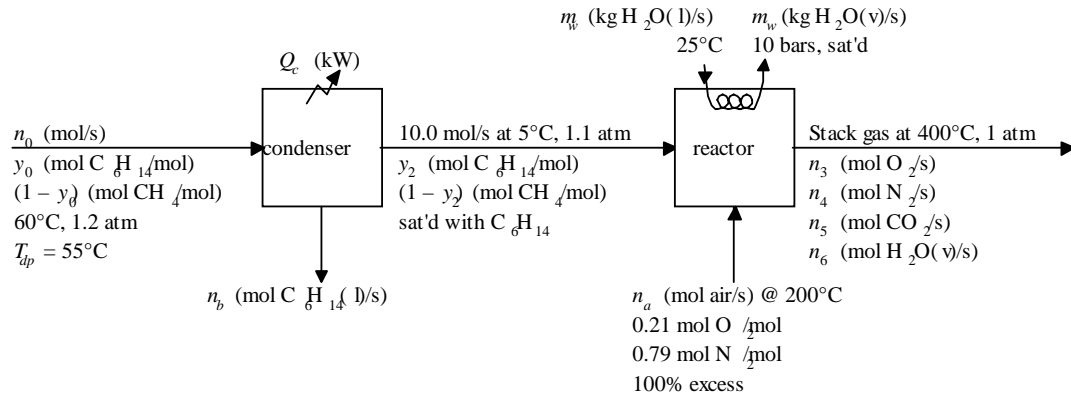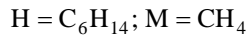
Antoine Eq.
$T_{dp} = 55°C \Rightarrow y_0 P = p_H^\alpha(55°C) = 483.3 \text{ mm Hg}$

$\Rightarrow y_0 = \dfrac{483.3 \text{ mm Hg}}{1.2 \times 760 \text{ mm Hg}} = \underline{\underline{0.530 \text{ mol } C_6H_{14}/\text{mol}}} \Rightarrow 0.470 \text{ mol } CH_4/\text{mol}$

Saturation at condenser outlet:

$y_2 = \dfrac{p_H^*(5°C)}{P} = \dfrac{58.89 \text{ mm Hg}}{1.1 \times 760 \text{ mm Hg}} = \underline{\underline{0.070 \text{ mol } C_6H_{14}/\text{mol}}} = 0.93\% \text{ mol } CH_4/\text{mol}$

Methane balance on condenser: $\dot{n}_0(1 - y_0) = 10.0(1 - y_2) \underset{y_2=0.070}{\overset{y_0=0.530}{\Rightarrow}} \dot{n}_0 = 19.78 \text{ mol/s}$

Hexane balance on condenser: $\dot{n}_0 y_0 = \dot{n}_b + 10.0 y_2 \underset{\substack{\dot{n}_0=19.78 \\ y_0=0.530 \\ y_2=0.070}}{\Rightarrow} \dot{n}_b = 9.78 \text{ mol } C_6H_{14}/\text{s condensed}$

Volume of condensate $= \dfrac{9.78 \text{ mol } C_6H_{14}(l)}{s} \left| \dfrac{86.17 \text{ g}}{\underset{\substack{\uparrow \\ \text{Table B.1}}}{\text{mol}}} \right| \dfrac{cm^3}{\underset{\substack{\uparrow \\ \text{Table B.1}}}{0.659 \text{ g}}} \left| \dfrac{1L}{10^3 \text{ cm}^3} \right| \dfrac{3600 \text{ s}}{1 \text{ h}}$

$= \underline{\underline{4600 \text{ L } C_6H_{14}(l)/\text{h}}}$

b.   References : $CH_4(g, 5°C), \; C_6H_{14}(l, 5°C)$

Substance	$\dot{n}_{in}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
CH_4	9.30	1.985	9.30	0
$C_6H_{14}(v)$	10.48	41.212	0.70	32.940
$C_6H_{14}(l)$	–	–	9.78	0

Table B.2

$CH_4(g): \; \hat{H} = \displaystyle\int_5^T C_p \, dT$ Table B.1   Table B.1

$C_6H_{14}(v): \; \hat{H} = \displaystyle\int_5^{T_b} C_{pR} \, dT + \Delta\hat{H}_v + \int_{T_b}^T C_{pv} dT$

Condenser energy balance: $\dot{Q}_c = \Delta\dot{H} = \displaystyle\sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = \underline{\underline{-427 \text{ kW}}}$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O, \quad C_6H_{14} + \frac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O$$
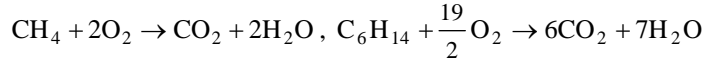
Theoretical O_2: $\quad \dfrac{9.30 \text{ mol } CH_4}{s} \left| \dfrac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} + \dfrac{0.70 \text{ mol } C_6H_{14}}{s} \right| \dfrac{9.5 \text{ mol } O_2}{1 \text{ mol } C_6H_{14}} = 25.3 \text{ mol } O_2/s$

100% excess $\Rightarrow (O_2)_{fed} = 2 \times (O_2)_{theor.} \Rightarrow 0.21\dot{n}_a = 2 \times 25.3 \Rightarrow \dot{n}_a = 240.95 \text{ mol air}/s$

N_2 balance: $0.79(240.95) = \dot{n}_4 \Rightarrow \dot{n}_4 = 190.35 \text{ mol } N_2/s$

C balance:

$$\dfrac{9.30 \text{ mol } CH_4}{s} \left| \dfrac{1 \text{ mol } C}{1 \text{ mol } CH_4} + \dfrac{0.70 \text{ mol } C_6H_{14}}{} \right| \dfrac{6 \text{ mol } C}{1 \text{ mol } C_6H_{14}} = \dfrac{\dot{n}_5 (\text{mol } CO_2)}{} \left| \dfrac{1 \text{ mol } C}{1 \text{ mol } CO_2} \right.$$

$\Rightarrow \dot{n}_5 = 13.5 \text{ mol } CO_2/s$

H balance:

$(9.30 \text{ mol } CH_4/s)(4 \text{ mol } H/\text{mol } CH_4) + (0.70)(14) = \dot{n}_6(2) \Rightarrow \dot{n}_6 = 23.5 \text{ mol } H_2O$

Since combustion is complete, $(O_2)_{remaining} = (O_2)_{excess} = \dfrac{1}{2}(O_2)_{fed} \Rightarrow \dot{n}_3 = 25.3 \text{ mol } O_2/s$

References : C(s), $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C for reactor side, $H_2O(l)$ at triple point for steam side (reference state for steam tables)

Substance	$\dot{n}_{in}$ mol / s	$\hat{H}_{in}$ kJ / mol	$\dot{n}_{out}$ mol / s	$\hat{H}_{out}$ kJ / mol
CH_4	9.30	−75.553	–	–
$C_6H_{14}(v)$	0.70	−170.07	–	–
O_2	50.6	5.31	25.3	11.72
N_2	190.35	5.13	190.35	11.15
CO_2	–	–	13.5	−377.15
$H_2O(v)$	–	–	23.5	−228.60
H_2O(boiler water)	$\dot{m}_w$ (kg / s) 104.8		$\dot{m}_w$ (kg / s) 2776.2	

$$\hat{H}(T) \overset{\overset{\text{Table B.1 and B.2}}{\downarrow}}{=} \Delta\hat{H}_f^o + \int_{25}^{T} C_p dT \quad \text{for } CH_4, C_6H_{14}$$

$$\overset{\overset{\text{Table B.1 and B.8}}{\downarrow}}{=} \Delta\hat{H}_f^o + \hat{H}_i(T) \text{ for } O_2, N_2, CO_2, H_2O(v)$$

Energy balance on reactor (assume adiabatic):

$$\Delta\dot{H} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = 0 \Rightarrow -8468 + \dot{m}_w (2776.2 - 104.8) = 0 \Rightarrow \dot{m}_w = 3.2 \text{ kg steam}/s$$

9.60   **a.**   Basis: 450 kmol CH_4 fed/h $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
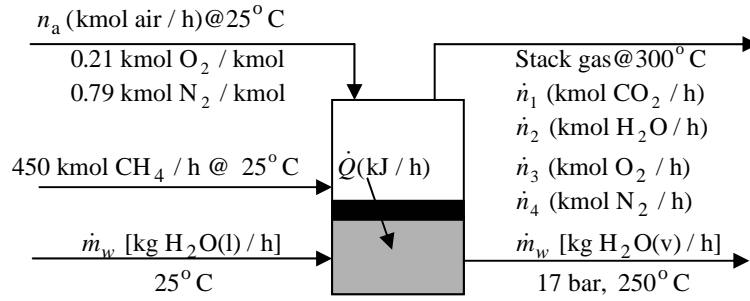
Air fed: $\dot{n}_a = \dfrac{450 \text{ kmol } CH_4}{h} \left|\dfrac{2 \text{ kmol } O_2 \text{ req'd}}{1 \text{ kmol } CH_4}\right| \dfrac{1.2 \text{ kmol } O_2 \text{ fed}}{1 \text{ kmol } O_2 \text{ req'd}} \left|\dfrac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2}\right.$

$= 5143 \text{ kmol air/h}$

$450 \text{ kmol / h } CH_4 \text{ react} \Rightarrow \dot{n}_1 = 450 \text{ kmol } CO_2/h, \ \dot{n}_2 = 900 \text{ kmol } H_2O/h$

N_2 balance: $\dot{n}_4 = (0.79)(5.143 \times 10^6 \ \text{mol/h}) = 4060 \text{ kmol } N_2/h$

Molecular O_2 balance:

$$\dot{n}_3 = (0.21)(5143)\dfrac{\text{mol } O_2 \text{ fed}}{h} - \dfrac{450 \text{ kmol } CH_4 \text{ react}}{h}\left|\dfrac{2 \text{ mol } O_2}{1 \text{ mol } CH_4}\right. = 180 \text{ kmol } O_2/h$$

$$\left.\begin{array}{l} 450 \text{ kmol } CO_2/h \\ 900 \text{ kmol } H_2O/h \\ 4060 \text{ kmol } N_2/h \\ 180 \text{ kmol } O_2/h \end{array}\right\} \Rightarrow \begin{array}{l} y_{CO_2} = \underline{\underline{0.0805}} \\ y_{H_2O} = \underline{\underline{0.161}} \\ y_{N_2} = \underline{\underline{0.726}} \\ y_{O_2} = \underline{\underline{0.0322}} \end{array}$$

5590 kmol / h

Mean heat capacity of stack gas

$$\overline{C}_p = \sum y_i C_{pi} = (0.0805)(0.0423) + (0.161)(0.0343) + (0.726)(0.0297) + (0.0322)(0.0312)$$
$$= \underline{\underline{0.0315 \text{ kJ/mol} \cdot {}^\circ C}}$$

Energy balance on furnace (combustion side only)

References: $CH_4(g), CO_2(g), O_2(g), N_2(g), H_2O(l)$ at $25^\circ C$

Substance	$\dot{n}_{in}$ (kmol / h)	$\hat{H}_{in}$ (kJ / kmol)	$\dot{n}_{out}\hat{H}_{out}$ (kJ / h)
CH_4	450	0	–
Air	5143	0	–
Stack gas	–	–	$\dot{H}_p$

Extent of reaction:

$$\dot{\xi} = \dot{n}_{CH_4} = 450 \text{ kmol / h}$$

9.60 (cont'd)

$$\dot{H}_p = \dot{n}_2(\Delta\hat{H}_v)_{\text{H}_2\text{O}(25°\text{C})} + \dot{n}_{\text{stack gas}}(\bar{C}_p)_{\text{stack gas}}(T_{\text{stack gas}} - 25°\text{C})$$

$$= \frac{180 \text{ kmol H}_2\text{O}}{\text{h}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{44.01 \text{ kJ}}{\text{mol}} + \frac{5590 \text{ kmol}}{\text{h}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{0.0315 \text{ kJ}}{\text{mol} \cdot °\text{C}} \left| (300\text{-}25)°\text{C} \right.$$

$$= \underline{5.63 \times 10^7 \text{ kJ/h}}$$

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}(\Delta\hat{H}_c^o)_{\text{CH}_4} + \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i$$

$$= \left(450 \frac{\text{kmol}}{\text{h}}\right)\left(1000 \frac{\text{mol}}{\text{kmol}}\right)\left(-890.36 \frac{\text{kJ}}{\text{mol}}\right) + 5.63 \times 10^7 \frac{\text{kJ}}{\text{h}} = \underline{\underline{-3.44 \times 10^8 \frac{\text{kJ}}{\text{h}}}}$$

Energy balance on steam boiler

Table B.7   Table B.6

$$\dot{Q} = \dot{m}_w \Delta\hat{H}_w \Rightarrow +3.44 \times 10^8 \frac{\text{kJ}}{\text{h}} = \left[\dot{m}_w\left(\frac{\text{kg}}{\text{h}}\right)\right]\left[(2914 - 105)\frac{\text{kJ}}{\text{kg}}\right]$$

$$\Rightarrow \dot{m}_w = \underline{\underline{1.23 \times 10^5 \text{ kg steam/h}}}$$

b.
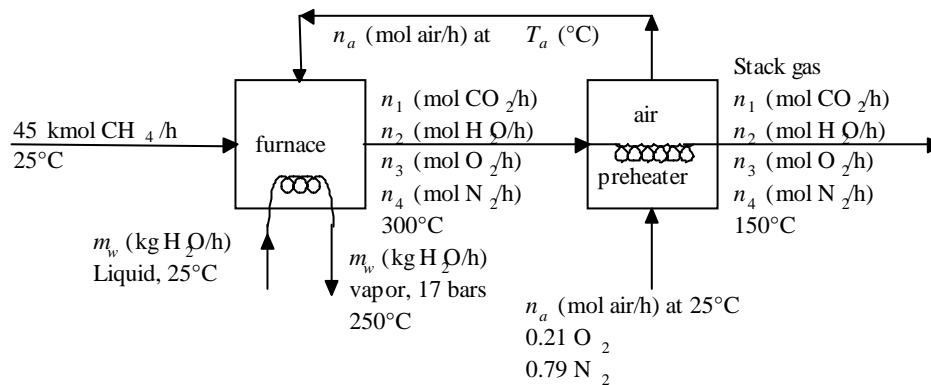
E.B. on overall process: The material balances and the energy balance are identical to those of part (a), except that the stack gas exits at 150°C instead of 300°C.

References: $\text{CH}_4(g), \text{CO}_2(g), \text{O}_2(g), \text{N}_2(g), \text{H}_2\text{O}(l)$ at $25°\text{C}$ (furnace side)

$\text{H}_2\text{O}(l)$ at triple point (steam table reference) (steam tube side)

Substance	$\dot{n}_{\text{in}}$ (kmol / h)	$\hat{H}_{\text{in}}$ (kJ / kmol)	$\dot{n}_{\text{out}}\hat{H}_{\text{out}}$ (kJ / h)
CH_4	450	0	–
Air	5143	0	–
Stack gas	–	–	$\dot{H}_p$
H_2O	$\dot{m}_w$ (kg / h) 105 kJ / kg		$\dot{m}_w$ (kg / h) 2914 kJ / kg

$$\dot{H}_p = \dot{n}_2(\Delta\hat{H}_v)_{\text{H}_2\text{O}(25°\text{C})} + \dot{n}_{\text{stack gas}}(\bar{C}_p)_{\text{stack gas}}(T_{\text{stack gas}} - 25°\text{C})$$

$$= \frac{180 \text{ kmol H}_2\text{O}}{\text{h}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{44.01 \text{ kJ}}{\text{mol}} + \frac{5590 \text{ kmol}}{\text{h}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{0.0315 \text{ kJ}}{\text{mol} \cdot °\text{C}} \left| (150\text{-}25)°\text{C} \right.$$

$$= \underline{2.99 \times 10^7 \text{ kJ/h}}$$

9.60 (cont'd)

$$\Delta \dot{H} = \dot{\xi}(\Delta \hat{H}_c^o)_{CH_4} + \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 0$$

$$\Rightarrow \left(450 \ \frac{kmol}{h}\right)\left(1000 \ \frac{mol}{kmol}\right)\left(-890.36 \ \frac{kJ}{mol}\right) + 2.99 \times 10^7 \ \frac{kJ}{h}$$

$$+ \left[\dot{m}_w \left(\frac{kg}{h}\right)\right]\left[(2914 - 105)\frac{kJ}{kg}\right] = 0 \Rightarrow m_w = \underline{\underline{1.32 \times 10^5 \ kg \ steam / h}}$$

Energy balance on preheater: $\Delta \dot{H} = \left(\Delta \dot{H}\right)_{stack \ gas} + \left(\Delta \dot{H}\right)_{air} = 0$

$$\left(\Delta H\right)_{stack \ gas} = n\overline{C}_p \Delta T = \frac{5590 \ kmol}{h} \left| \frac{10^3 \ mol}{1 \ kmol} \right| \frac{0.0315 \ kJ}{mol \cdot ^\circ C} \frac{(150 - 300)^\circ C}{} = -2.64 \times 10^7 \ \frac{kJ}{h}$$

$$\left(-\Delta H\right)_{stack \ gas} = \left(\Delta H\right)_{air} = n_a \hat{H}_{air}(T_a) \Rightarrow \hat{H}_{air}(T_a) = \frac{2.64 \times 10^7 \ kJ / h}{5143 \ kmol / h} \left| \frac{1 \ kmol}{10^3 \ mol} \right| = 5.133 \ \frac{kJ}{mol}$$

$$\hat{H}_{air} = 5.133 \ kJ / mol \qquad \overset{Table \ B.8}{} \qquad \underline{\underline{T_a = 199^\circ C}}$$

c. The energy balance on the furnace includes the term $-\sum n_{in} \hat{H}_{in}$. If the air is preheated and the stack gas temperature remains the same, this term and hence $\dot{Q}$ become more negative, meaning that more heat is transferred to the boiler water and more steam is produced. The stack gas is a logical heating medium since it is available at a high temperature and costs nothing.

9.61

$$\underset{\text{Assume coal enters at 25°C}}{\underline{Basis: \ 40000 \ kg \ coal/h}} \Rightarrow \frac{(0.76 \times 40000)kg \ C}{h} \left| \frac{10^3 \ g}{1 \ kg} \right| \frac{1 \ mol \ C}{12.01 \ g} = 2.531 \times 10^6 \ mol \ C/h$$

$$\left[(0.05 \times 4000)kg \ H/h\right]\left(10^3/1.01\right) = 1.98 \times 10^6 \ mol \ H/h$$

$$\left[(0.08 \times 4000)kg \ O/h\right]\left(10^3/16.0\right) = 2.00 \times 10^5 \ mol \ O/h$$

$$(0.11 \times 40000) = 4400 \ kg \ ash/h$$
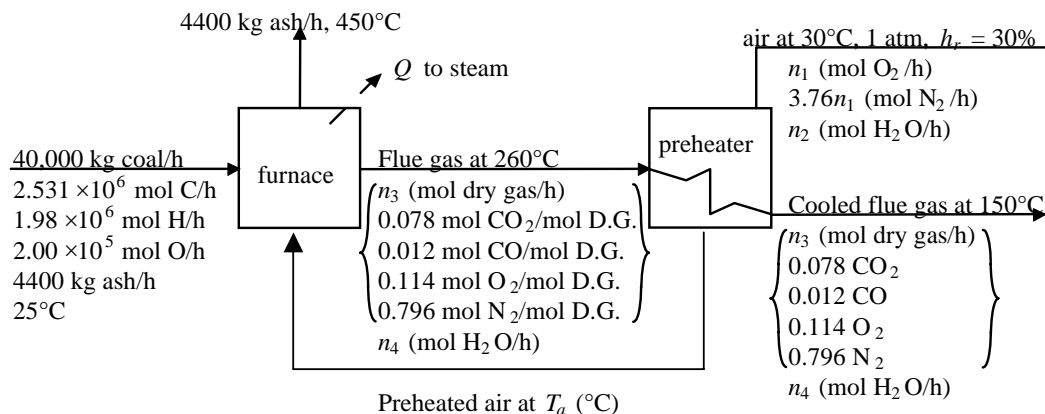
a. Overall system balances

C balance: $2.531 \times 10^6 = 0.078 n_3 + 0.012 n_3 \Rightarrow n_3 = 2.812 \times 10^7 \ mol/h$ dry flue gas

N_2 balance: $3.76 n_1 = (0.796)(2.812 \times 10^7) \Rightarrow n_1 = 5.95 \times 10^6 \ mol \ O_2/h \ (3.76)(5.95 \times 10^6)$

$$= 224 \times 10^7 \ mol \ N_2/h$$

9.61 (cont'd)

30% relative humidity (inlet air):

$$y_{H_2O} P = 0.30 p^*_{H_2O}(30°C) \Rightarrow \frac{\dot{n}_2}{5.95 \times 10^6 + 2.24 \times 10^7 + n_2}(760 \text{ mm Hg}) = 0.300(31.824 \text{ mm Hg})$$

$$\Rightarrow \dot{n}_2 = 3.61 \times 10^5 \text{ mol } H_2O/h$$

Volumetric flow rate of inlet air:

$$\dot{V} = \frac{(5.95 \times 10^6 + 224 \times 10^7 + 3.61 \times 10^5)\text{mol}}{h} \left| \frac{22.4 \text{ liters(STP)}}{1 \text{ mol}} \right| \frac{1 \text{ m}^3}{10^3 \text{ liters}} = 6.43 \times 10^5 \text{ SCMH}$$

Air/fuel ratio: $\dfrac{6.43 \times 10^5 \text{ m}^3 \text{ air/h}}{40000 \text{ kg coal/h}} = 16.1 \text{ SCM air/kg coal}$

H balance: $\underbrace{1.98 \times 10^6 \text{ mol } H/h}_{\text{H in coal}} + \underbrace{2(3.61 \times 10^5)\text{mol } H/h}_{\text{H in water vapor}} = 2\dot{n}_4 \Rightarrow \dot{n}_4 = 1.351 \times 10^6 \text{ mol } H_2O/h$

H_2O content of stack gas $= \dfrac{1.357 \times 10^6 \text{ mol } H_2O/h}{(1.357 \times 10^6 + 2.812 \times 10^7)\text{mol/h}} \times 100\% = 4.6\% \ H_2O$

b. Energy balance on stack gas in preheater

References: CO_2, CO, O_2, N_2, $H_2O(v)$ at $25°C$

Substance	n_{in} mol/h	$\hat{H}_{in}$ kJ/mol	n_{out} mol/h	$\hat{H}_{out}$ kJ/mol
CO_2	2.193×10^6	4.942	2.193×10^6	9.738
CO	0.337×10^6	3669	0.337×10^6	6.961
O_2	3.706×10^6	3758	3.206×10^6	7.193
N_2	22.38×10^6	3655	72.38×10^6	6.918
H_2O	1.357×10^6	4266	1.351×10^6	8135

$\hat{H}_i(T)$ from Table B.8 for inlet $\qquad \hat{H}_i(T) = \int^{\text{Table B.2}} \hat{C}_p \ dT$ for outlet

$$Q = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = -1.01 \times 10^8 \text{ kJ/h} \text{ (Heat transferred from stack gas)}$$

Air preheating

$1.01 \times 10^8 \text{ kJ/hr}$

2.83×10^7 mol dry air/h
3.61×10^5 mol H_2O/h
30°C

2.83×10^7 mol dry air/h
3.61×10^5 mol H_2O/h
T_a (°C)
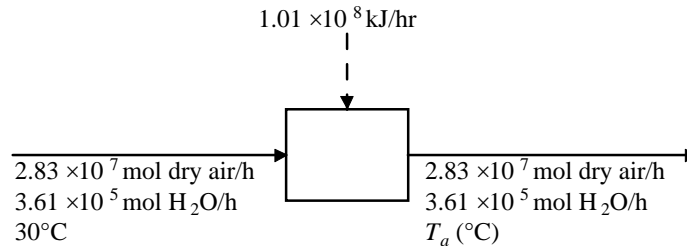
(We assume preheater is adiabatic, so that $Q_{\text{stack gas}} = -Q_{\text{air}}$)

Energy balance on air:

$$Q = \Delta H \Rightarrow 1.01 \times 10^8 \text{ kJ/hr} = \sum \int_{30}^{T_a} n_i (C_p)_i \, dT = \int_{30}^{T_a} n_{\text{dry air}} (C_p)^{\text{Table B.2}}_{\text{dry air}} \, dT + \int_{30}^{T_a} n_{H_2O} (C_p)^{\text{Table B.2}}_{H_2O} \, dT$$

9.61 (cont'd)

$$\Rightarrow 1.01 \times 10^8 = 8.31 \times 10^5 (T_a - 30) + 59.92(T_a^2 - 30^2) + 0.031(T_a^3 - 30^3) - 1.42 \times 10^{-5}(T_a^4 - 30^4)$$

$$\Rightarrow \underline{\underline{T_a = 150°C}}$$

c.

4400 kg ash/h at 450°C

40,000 kg coal/h
25°C

5.95×10^6 mol O_2 /h
2.24×10^7 mol N_2 /h
3.61×10^5 mol $H_2O(v)$/h
150°C(= 149.8°C)

Flue gas at 260°C
2193×10^6 mol CO_2/h
0.337×10^6 mol CO/h
3.206×10^6 mol O_2/h
22.38×10^6 mol N_2/h
1.351×10^6 mol $H_2O(v)$/h

m (kg $H_2O(l)$/h)
50°C

m (kg $H_2O(v)$/h)
30 bars, sat'd
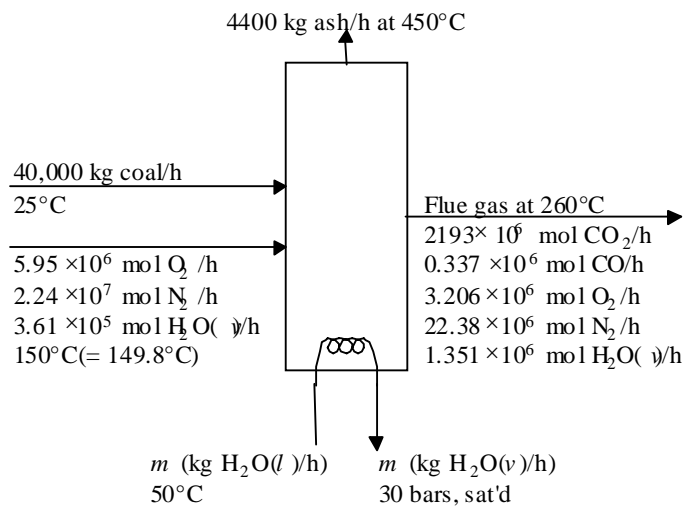
References for energy balance on furnace: CO_2, CO, O_2, N_2, $H_2O(l)$, coal at 25°C

(Must choose $H_2O(l)$ since we are given the higher heating value of the coal.)

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
Coal	40000	0	–	–	$n(kg/h)$
Ash	–	–	4400	412.25	$\hat{H}(kJ/kg)$
O_2	5.95×10^6	3.758	3.206×10^6	7.193	
N_2	2.24×10^6	3.655	2.24×10^7	6.918	$n(mol/h)$
CO_2	–	–	2.193×10^6	9.738	$\hat{H}(kJ/mol)$
CO	–	–	0.337×10^6	6.961	
H_2O	3.61×10^5	48.28	1.351×10^6	52.14	

(Furnace only — exclude boiler water)

Heat transferred from furnace

$$Q = n_{coal}\Delta\hat{H}_i^° + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i$$

$$= \left(4 \times 10^4 \frac{kg}{h}\right)\left(-2.5 \times 10^4 \frac{kJ}{kg}\right) + \left(2.74 \times 10^3 - \underset{\underset{\hat{H} \text{ of preheated air}}{\uparrow}}{1.22 \times 10^8}\right)\frac{kJ}{kg}$$

$$= -8.76 \times 10^8 \ kJ/h$$

Heat transferred to boiler water: $0.60(8.76\mathbf{x}10^8 \ kJ/h) = 5.25\mathbf{x}10^8 \ kJ/h$

Energy balance on boiler: $\dot{Q}(kJ/h) = \dot{m}\left(\frac{kg}{h}\right)\left[\hat{H}(H_2O(l), \ 30b, \ sat'd) - \hat{H}(H_2O(l), \ 50°C)\right]$

$$\Rightarrow 5.25 \times 10^8 \ kJ/h = \dot{m}\left[\underset{\underset{\text{Table B.6}}{\uparrow}}{2802.3} - \underset{\underset{\text{Table B.5}}{\uparrow}}{209.3}\right]\frac{kJ}{kg} \Rightarrow \underline{\underline{\dot{m} = 2.02 \times 10^5 \ kg \ steam/h}}$$

9.62

Basis : 1 mol CO burned. $CO + \frac{1}{2}O_2 \rightarrow CO_2$, $\Delta \hat{H}_c^o = -282.99$ kJ/mol

Block diagram:
- Input: 1 mol CO, n_0 mol O_2, $3.76 n_0$ mol N_2, 25°C
- Output: 1 mol CO_2, $(n_0 - 0.5)$ mol O_2, $3.76 n_0$ mol N_2, 1400°C
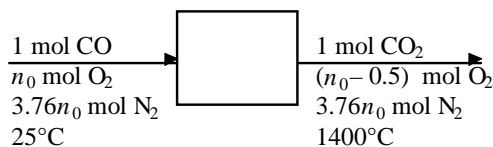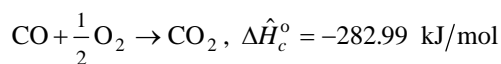
a. <u>Oxygen in product gas:</u> $n_1 = n_0 (\text{mol } O_2 \text{ fed}) - \dfrac{1 \text{ mol CO react}}{} \Big| \dfrac{0.5 \text{ mol } O_2}{1 \text{ mol CO}} = n_0 - 0.5$

<u>References:</u> CO, CO_2, O_2, N_2 at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
CO	1	0	–	–
O_2	n_0	0	$n_0 - 0.5$	$\hat{H}_1$
N_2	$3.76 n_0$	0	$3.76 n_0$	$\hat{H}_2$
CO_2	–	–	1	$\hat{H}_3$

$O_2 (g, 1400°C)$: $\hat{H}_1 = \hat{H}_{O_2} (1400°C) \overset{\text{Table B.8}}{=} 47.07$ kJ/mol

$N_2 (g, 1400°C)$: $\hat{H}_2 = \hat{H}_{N_2} (1400°C) \overset{\text{Table B.8}}{=} 44.51$ kJ/mol

$CO_2 (g, 1400°C)$: $\hat{H}_3 = \hat{H}_{CO_2} (1400°C) \overset{\text{Table B.8}}{=} 71.89$ kJ/mol

<u>E.B.:</u>

$\Delta H = n_{CO} \Delta \hat{H}_c^o + \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = -282.99 + 47.07(n_0 - 0.5) + 44.51(3.76 n_0) + 71.89 = 0$

$\Rightarrow n_0 = 1.094$ mol O_2

<u>Theoretical</u> $O_2 = (1 \text{ mol CO})(0.5 \text{ mol } O_2 / \text{mol CO}) = 0.500 \text{ mol } O_2$

<u>Excess oxygen:</u> $\dfrac{1.094 \text{ mol fed} - 0.500 \text{ mol reqd.}}{0.500 \text{ mol}} \times 100\% = \underline{\underline{119\% \text{ excess oxygen}}}$

b. Increase %XS air $\Rightarrow T_{ad}$ would <u>decrease</u>, since the heat liberated by combustion would go into heating a larger quantity of gas (i.e., the additional N_2 and unconsumed O_2).

9.63 **a.** <u>Basis :</u> 100 mol natural gas $\Rightarrow$ 82 mol CH_4, 18 mol C_2H_6

$CH_4 (g) + 2O_2 (g) \rightarrow CO_2 (g) + 2H_2O(v)$, $\Delta \hat{H}_c^o = -890.36$ kJ / mol

$C_2H_6 (g) + \frac{7}{2}O_2 (g) \rightarrow 2CO_2 (g) + 3H_2O(v)$, $\Delta \hat{H}_c^o = -1559.9$ kJ / mol

Block diagram:
- Input: 82 mol CH_4, 18 mol C_2H_6, 298 K
- Input: n_0 (mol air) at 423 K, 0.21 O_2 (20% XS), 0.79 N_2
- Output: Stack gas at $T(°C)$, n_2 (mol CO_2), n_3 (mol H_2O (v)), n_4 (mol O_2), n_5 (mol N_2)
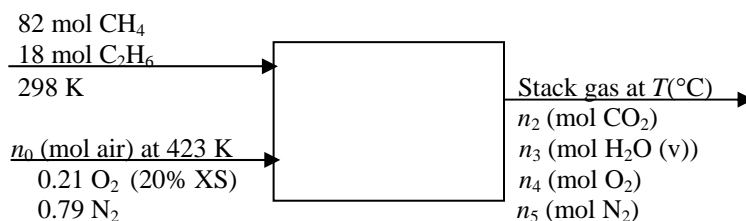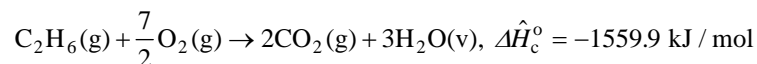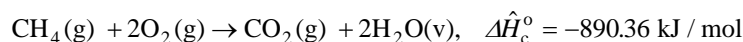
9.63 (cont'd)

$$\underline{\text{Theoretical oxygen}} = \frac{2 \text{ mol O}_2}{1 \text{ mol CH}_4} \left| \frac{82 \text{ mol CH}_4}{} \right. + \frac{3.5 \text{ mol O}_2}{1 \text{ mol C}_2\text{H}_6} \left| \frac{18 \text{ mol C}_2\text{H}_6}{} \right. = 227 \text{ mol O}_2$$

$$\underline{\text{Air fed}} : \ n_1 = \frac{1.2 \times 227 \text{ mol O}_2}{} \left| \frac{1 \text{ mol air}}{0.21 \text{ mol O}_2} \right. = 1297.14 \text{ mol air}$$

$\underline{\text{C balance}} : \ n_2 = (82.00)(1) + (18.00)(2) \Rightarrow n_2 = 118.00 \text{ mol CO}_2$

$\underline{\text{H balance}} : \ 2n_3 = (82.00)(4) + (18.00)(6) \Rightarrow n_3 = 218.00 \text{ mol H}_2\text{O}$

$\underline{\text{20\% excess air, complete combustion}} \Rightarrow n_4 = (0.2)(227) \text{ mol O}_2 = 45.40 \text{ mol O}_2$

$\underline{\text{N}_2 \text{ balance}} : \ n_5 = (0.79)(1297.14) = 1024.63 \text{ mol N}_2$

$\underline{\text{Extents of reaction}} : \ \xi_1 = n_{\text{CH}_4} = 82 \text{ mol}, \ \ \xi_1 = n_{\text{C}_2\text{H}_6} = 18 \text{ mol}$

$\underline{\text{Reference states}} : \ \text{CH}_4(g), \ \text{C}_2\text{H}_6(g), \ \text{N}_2(g), \ \text{O}_2(g), \ \text{H}_2\text{O}(l) \text{ at 298 K}$

(We will use the values of $\Delta \hat{H}_c^o$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water.)

$$\hat{H}_i(T) = C_{pi}(T - 298 \text{ K}) \text{ for all species but water}$$
$$= \Delta \hat{H}_{v,\text{H}_2\text{O}}(298 \text{ K}) + C_{p,\text{H}_2\text{O}}(T - 298 \text{ K}) \text{ for water}$$

Substance	n_{in} mol	$\hat{H}_{\text{in}}$ kJ/mol	n_{out} mol	$\hat{H}_{\text{out}}$ kJ/mol
CH$_4$	82.00	–	–	–
C$_2$H$_6$	18.00	0	–	–
O$_2$	272.40	4.14	45.40	$0.0331(T - 298)$
N$_2$	1024.63	3.91	1024.63	$0.0313(T - 298)$
CO$_2$	–	–	118.00	$0.0500(T - 298)$
H$_2$O(v)	–	–	218.00	$44.013 + 0.0385(T - 298)$

$\underline{\text{Energy balance}} : \ \Delta H = 0$

$$\xi_1 \left(\Delta \hat{H}_c^o \right)_{\text{CH}_4} + \xi_2 \left(\Delta \hat{H}_c^o \right)_{\text{C}_2\text{H}_6} + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0$$

$$\Rightarrow (82.00 \text{ mol CH}_4)(-890.36 \text{ kJ/mol}) + (18.00 \text{ mol C}_2\text{H}_6)(-1559.90 \text{ kJ/mol})$$
$$+ \left[(45.40)(0.0331) + (1024.63)(0.0313) + (118.00)(0.0500) + (218.00)(0.0385) \right](T - 298)$$
$$+ (218.00)(44.01) - (272.40)(4.14) - (1024.63)(3.91) = 0$$

b. Solving for T using E - Z Solve $\Rightarrow \underline{T = 2317 \text{ K}}$

Increase % excess air $\Rightarrow \underline{T_{\text{out}} \text{ decreases.}}$ (Heat of combustion has more gas to heat)

% methane increases $\Rightarrow T_{\text{out}}$ __might__ decrease. (lower heat of combustion, but heat released goes into heating fewer moles of gas.)

9.64 $C_3H_6O(g) + 4O_2(g) \rightarrow 3CO_2(g) + 3H_2O(l)$, $\Delta\hat{H}_i^o = -1821.4$ kJ/mol
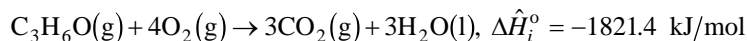
Basis : $\dfrac{1410 \text{ m}^3\text{(STP) feed gas}}{\text{min}} \left|\dfrac{10^3 \text{ mol}}{22.4 \text{ m}^3\text{(STP)}}\right.\left|\dfrac{1 \text{ min}}{60 \text{ s}}\right. = 1049$ mol/s feed gas

Stochiometric proportion:

1 mol $C_3H_6O \Rightarrow 4$ mol $O_2 \Rightarrow 4 \times 3.76 = 15.04$ mol $N_2 \Rightarrow (1+4+15.04) = 20.04$ mol

$y_{C_3H_6O} = \dfrac{1 \text{ mol } C_3H_6O}{20.04 \text{ mol}} = 0.0499 \dfrac{\text{mol } C_3H_6O}{\text{mol}}$, $y_{O_2} = \dfrac{4}{20.04} = 0.1996$ mol O_2/mol

	Preheat		Reaction		Cooling	

Feed gas
1049 mol/s
0.0499 C_3H_6O
0.1996 O_2
0.7505 N_2
T_f (°C), 150 mm Hg
Rel. satn = 12.2%

Q_1 (kW)

Feed gas
562°C

Product gas
n_1 (mol CO_2/s)
n_2 (mol H_2O/s)
n_3 (mol N_2/s)
T_a (°C)

Q_2 (kW)

Product gas
350°C
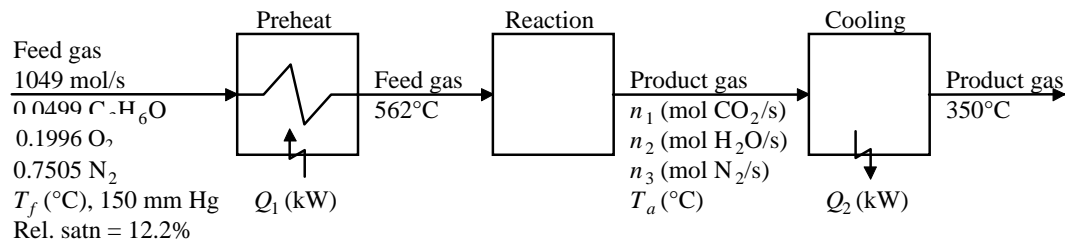
a.

Relative saturation $= 12.2\% \Rightarrow y_{C_3H_6O} P = 0.122 p^*_{C_3H_6O}(T_f)$

$\Rightarrow p^* = \dfrac{(0.0499)(1500 \text{ mm Hg})}{0.122} = 613.52$ mm Hg $\xrightarrow{\text{Table B.4}}$ $\underline{\underline{T_f = 50.0^o \text{ C}}}$

b.

Feed contains $(1049 \text{ mol/s})(0.0499 \text{ } C_3H_6O/\text{mol}) = 52.34$ mol C_3H_6O/s

$(1049)(0.1996) = 209.4$ mol O_2/s

$(1049)(0.7505) = 787.3$ mol N_2/s

$\Rightarrow$ Product contains $\begin{array}{l} n_1 = (52.34)(3) = 157.0 \text{ mol } CO_2/\text{s} \\ n_2 = (52.34)(3) = 157.0 \text{ mol } H_2O/\text{s} \\ n_3 = 787.3 \text{ mol } N_2/\text{s} \end{array}\Big\} \Rightarrow \begin{array}{l} \underline{\underline{14.25 \text{ mole\% } CO_2}} \\ \underline{\underline{14.25\% \text{ } H_2O}} \\ \underline{\underline{71.5\% \text{ } N_2}} \end{array}$

References : $C_3H_6O(g)$, O_2, N_2, $H_2O(l)$, CO_2 at 25° C

Substance	$\dot{n}_{in}$ (mols)	$\hat{H}_{in}$ (kJ/mol) (562°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	$44.013 + 0.040(T_a - 25)$

Energy balance on reactor:

$\Delta H = n_{C_3H_6O}\Delta\hat{H}_c^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 0$ (kJ/s)

$\Rightarrow (5234 \text{ mol/s})\left(-1821.1\dfrac{\text{kJ}}{\text{mol}}\right) + 39.638(T_a - 25) + 157.0(44.013) - 2.078 \times 10^4 = 0 \Rightarrow \underline{\underline{T_a = 2780°C}}$

    c.

        Preheating step: References: $C_3H_6(g)$, O_2, N_2 at 25°C

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol) (50°C)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol) (562°C)
C_3H_6O	52.34	3.15	52.34	67.66
O_2	209.4	0.826	209.4	17.72
N_2	787.3	0.775	787.3	16.65

E.B. $\Rightarrow \dot{Q}_1 = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = \underline{1.94 \times 10^4 \text{ kW}}$

Cooling step. References: $CO_2(g)$, $H_2O(v)$, $N_2(g)$ at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol) $\left(2871°C\right)$	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol) $\left(350°C\right)$
CO_2	157.0	142.3	157.0	16.25
H_2O	157.0	108.15	157.0	12.35
N_2	787.3	88.23	787.3	10.08

E.B. $\Rightarrow Q_2 = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = \underline{-9.64 \times 10^4 \text{ kW}}$

Exchange heat between the reactor feed and product gases.

9.65   **a.**   Basis : 1 mol C_5H_{12} (l)

$C_5H_{12}(l) + 8O_2(g) \rightarrow 5CO_2(g) + 6H_2O(v)$, $\Delta\hat{H}_c^o = -3509.5 \text{ kJ/mol}$

    1 mol C_5H_{12} (l) → [box] → n_2(mol CO_2) / n_3 (mol H_2O (v)) / n_4 (mol O_2) / T_{ad}(°C)

    n_0 (mol O_2), 75°C / 30% excess →
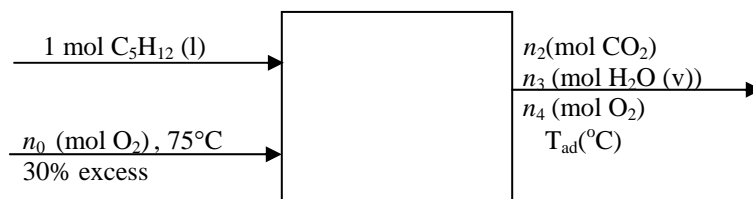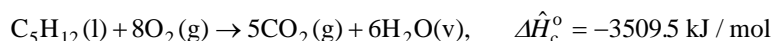
Theoretical oxygen $= \dfrac{1 \text{ mol } C_5H_{12}}{} \left| \dfrac{8 \text{ mol } O_2}{1 \text{ mol } C_5H_{12}} \right. = 8 \text{ mol } O_2$

30% excess $\Rightarrow n_0 = 1.3 \times 8 = 10.4 \text{ mol } O_2$

C balance: $n_2 = (1)(5) \Rightarrow n_2 = 5 \text{ mol } CO_2$

H balance: $2n_3 = (1)(12) \Rightarrow n_3 = 6 \text{ mol } H_2O$

30% excess O_2, complete combustion $\Rightarrow n_4 = (0.3)(8) \text{ mol } O_2 = 2.4 \text{ mol } O_2$

Reference states: $C_5H_{12}(l)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at $25^o C$

(We will use the values of $\Delta\hat{H}_c^0$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water)

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	mol	kJ/mol	mol	kJ/mol
C_5H_{12}	1.00	0	–	–
O_2	10.40	$\hat{H}_1$	2.40	$\hat{H}_2$
CO_2	–	–	5.00	$\hat{H}_3$
H_2O	–	–	6.00	$\hat{H}_4$

$$\hat{H}_i = \int_{25}^{T} (C_p)_i \, dT \qquad i = 2,3$$

$$= \Delta\hat{H}_v\left(25^\circ C\right) + \int_{25}^{T} (C_p)_{H_2O(v)} \, dT \text{ for } H_2O(v)$$

Table B.8
↓
$$\hat{H}_1 = \hat{H}_{O_2}(75^\circ C) = 1.48 \text{ kJ / mol}$$

Substituting $(C_p)_i$ from Table B.2 :

$$\hat{H}_2 = (0.0291 \, T_{ad} + 0.579 \times 10^{-5} \, T_{ad}^2 - 0.2025 \times 10^{-8} \, T_{ad}^3 + 0.3278 \times 10^{-12} \, T_{ad}^4 - 0.7311) \, \frac{kJ}{mol}$$

$$\hat{H}_3 = (0.03611 \, T_{ad} + 2.1165 \times 10^{-5} \, T_{ad}^2 - 0.9623 \times 10^{-8} \, T_{ad}^3 + 1.866 \times 10^{-12} \, T_{ad}^4 - 0.9158) \, \frac{kJ}{mol}$$

$$\hat{H}_4 = 44.01 + (0.03346 \, T_{ad} + 0.3440 \times 10^{-5} \, T_{ad}^2 + 0.2535 \times 10^{-8} \, T_{ad}^3 - 0.8983 \times 10^{-12} \, T_{ad}^4 - 0.838) \, \frac{kJ}{mol}$$

$$\Rightarrow \hat{H}_4 = 43.17 + (0.03346 \, T_{ad} + 0.3440 \times 10^{-5} \, T_{ad}^2 + 0.2535 \times 10^{-8} \, T_{ad}^3 - 0.8983 \times 10^{-12} \, T_{ad}^4) \, \frac{kJ}{mol}$$

<u>Energy balance</u> : $\Delta H = 0$

$$n_{C_5H_{12}}\left(\Delta\hat{H}_c^o\right)_{C_5H_{12}(l)} + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 0$$

$$(1 \text{ mol } C_5H_{12})(-3509.5 \text{ kJ / mol}) + (2.40)\,\hat{H}_2 + (5.00)\,\hat{H}_3 + (6.00)\,\hat{H}_4 - (10.40)(\hat{H}_1) = 0$$

Substitute for $\hat{H}_1$ through $\hat{H}_4$

$$\Delta\dot{H} = (0.4512 \, T_{ad} + 14.036 \times 10^{-5} \, T_{ad}^2 - 3.777 \times 10^{-8} \, T_{ad}^3 + 4.727 \times 10^{-12} \, T_{ad}^4) - 3272.20 \text{ kJ / mol} = 0$$

$$\Rightarrow f(T_{ad}) = -3272.20 + 0.4512 \, T_{ad} + 14.036 \times 10^{-5} \, T_{ad}^2 - 3.777 \times 10^{-8} \, T_{ad}^3 + 4.727 \times 10^{-12} \, T_{ad}^4 = 0$$

<u>Check</u> : $\dfrac{-3272.20}{4.727 \times 10^{-12}} = -6.922 \times 10^{14}$

Solving for T_{ad} using E - Z Solve $\Rightarrow \underline{\underline{T_{ad} = 4414^\circ C}}$

b.

Terms	T_{ad}	% Error
1	7252	64.3%
2	3481	−21.1%
3	3938	−10.8%

9.65 (cont'd)

c.

T	f(T)	f'(T)	Tnew
7252	6.05E+03	3.74	5634
5634	1.73E+03	1.82	4680
4680	3.10E+02	1.22	4426
4426	1.41E+01	1.11	4414
4414	3.11E-02	1.11	4414

d. The polynomial formulas are only applicable for T ≤ 1500°C

9.66

5.5 L/s at 25°C, 1.1 atm
$\dot{n}_1$(mol CH$_4$/s)

25% excess air
$\dot{n}_2$ (mol O$_2$/s)
3.76 $\dot{n}_2$ (mol N$_2$/s) $\dot{n}$
150°C, 1.1 atm

Adiabatic Reactor

$\dot{n}_4$ (mol CO$_2$/s)
$\dot{n}_3$ (mol O$_2$/s)
3.76 $\dot{n}_2$ (mol N$_2$/s)
$\dot{n}_5$ (mol H$_2$O/s)
T(°C), 1.05 atm

$$2CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
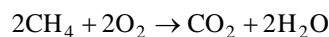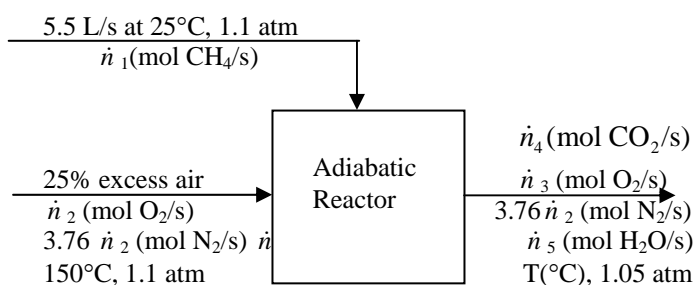
$$\underline{\text{Fuel feed rate}} := \frac{5.50 \text{ L}}{\text{s}} \left| \frac{273 \text{ K}}{298 \text{ K}} \right| \frac{1.1 \text{ atm}}{1.0 \text{ atm}} \left| \frac{\text{mol}}{22.4 \text{ L(STP)}} \right. = 0.247 \text{mol CH}_4 / \text{s}$$

$$\underline{\text{Theoretical O}_2} = 2 \times 0.247 = 0.494 \text{ mol O}_2 / \text{s}$$

$$\underline{\text{25\% excess air}} \Rightarrow \dot{n}_2 = 1.25(0.494) = 0.6175 \text{ mol O}_2 / \text{s} \quad ,$$
$$\Rightarrow 3.76 \times 0.6175 = 2.32 \text{ mol N}_2 / \text{s}$$

$$\underline{\text{Complete combustion}} \Rightarrow \dot{\xi} = n_1 = 0.247 \text{ mol} / \text{s}, \ \dot{n}_4 = 0.247 \text{ mol CO}_2 / \text{s}, \ \dot{n}_5 = 0.494 \text{ mol H}_2\text{O}/\text{s}$$

$$\dot{n}_3 = 0.6175 \text{ mol O}_2 \text{ fed} / \text{s} - 0.494 \text{ mol consumed} / \text{s}$$
$$= 0.124 \text{ mol O}_2 / \text{s}$$

$\underline{\text{References:}}$ CH$_4$, O$_2$, N$_2$, CO$_2$, H$_2$O at 25°C

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
CH$_4$	0.247	0	–	–
O$_2$	0.6175	$\hat{H}_1$	0.124	$\hat{H}_3$
N$_2$	2.32	$\hat{H}_2$	2.32	$\hat{H}_4$
CO$_2$	–	–	0.247	$\hat{H}_5$
H$_2$O	–	–	0.497	$\hat{H}_6$

$$\hat{H}_1 = \hat{H}(O_2, 150°C) \xrightarrow{\text{Table B.8}} 3.78 \text{ kJ/mol}$$

$$\hat{H}_2 = \hat{H}(N_2, 150°C) \xrightarrow{\text{Table B.8}} 3.66 \text{ kJ/mol}$$

$$(\Delta \hat{H}_c^o)_{CH_4} = -890.36 \text{ kJ/mol}$$

$$\hat{H}_i = \int_{25}^{T} C_{pi} dT, \ i = 3-5$$

9.66 (cont'd)

$$\hat{H}_b = (\Delta\hat{H}_v)_{H_2O(25°C)} + \int_{25}^{T} (C_p)_{H_2O(v)} \, dT$$

a. <u>Energy Balance</u>

$$\Delta\dot{H} = \dot{\xi}(\Delta\hat{H}_c^o)_{CH_4} + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} = 0$$

Table B.2 for $C_{pi}(T)$, $(\Delta\hat{H}_v)_{H_2O} = 44.01$ kJ/mol

$$0.247(-890.36) + 0.494(44.01) + 0.0963(T-25) + 1.02\times10^{-5}(T^2-25^2) + 0.305\times10^{-8}(T^3-25^3)$$

$$-1.61\times10^{-12}(T^4-25^4) - 0.6175(3.78) - 2.32(3.66) = 0$$

$$\Rightarrow -211.4 + 0.0963T_{ad} + 1.02\times10^{-5}T_{ad}^2 + 0.305\times10^{-8}T_{ad}^3 - 1.61\times10^{-12}T_{ad}^4 = 0 \Rightarrow \underline{\underline{T = 1832°C}}$$

b. In product gas,

$$T = 1832°C, \ P = 1.05\times760 = 798 \text{ mmHg}$$

$$y_{H_2O} = \frac{0.494 \text{ mol/s}}{(0.124 + 2.32 + 0.247 + 0.494) \text{ mol/s}} = 0.155 \text{ mol } H_2O/\text{mol}$$

Table B.3

<u>Raoult's law</u>: $y_{H_2O}P = p_{H_2O}^*(T_{dp}) \Rightarrow p_{H_2O}^* = (0.155)(798) = 124 \text{ mmHg} \implies \underline{\underline{T_{dp} = 56°C}}$

Degr. superheat $= 1832°C - 56°C = \underline{\underline{1776°C}}$

9.67 a. $CH_4(l) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v)$
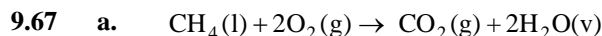
<u>Basis</u>: 1 mol CH_4

<u>Theoretical oxygen</u> $= \dfrac{1 \text{ mol } CH_4}{} \left| \dfrac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \right. = 2.00 \text{ mol } O_2$

<u>30 % excess air</u> $\Rightarrow 1.30\,(2.00) = 2.60 \text{ mol } O_2$, $\Rightarrow 3.76\times2.60 = 9.78 \text{ mol } N_2$

1 mol CH_4		n_2 (mol CO_2)
2.60 mol O_2		n_3 (mol H_2O)
9.78 mol N_2		n_4 (mol O_2)
25° C, 4.00 atm		
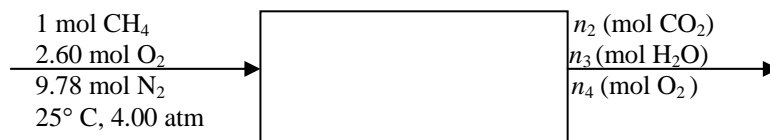
<u>Complete combustion</u> $\Rightarrow n_2 = 1.00 \text{ mol } CO_2$, $n_3 = 2.00 \text{ mol } H_2O$

<u>2.00 mol O_2 consumed</u> $\Rightarrow n_4 = (2.60 - 2.00) \text{ mol } O_2 = 0.60 \text{ mol } O_2$

<u>Internal energy of reaction</u>: Eq. (9.1-5) $\Rightarrow \Delta\hat{U}_c^o = \Delta\hat{H}_c^o - RT\left(\displaystyle\sum_{\substack{\text{gaseous} \\ \text{products}}}\nu_i - \sum_{\substack{\text{gaseous} \\ \text{reactants}}}\nu_i\right)$

$$\Rightarrow \left(\Delta\hat{U}_c^o\right)_{CH_4} = \left(-890.36 \ \frac{kJ}{mol}\right) - \frac{8.314 \text{ J}}{\text{mol K}} \left| \frac{298 \text{ K}}{} \right| \frac{(1+2-1-2)}{} \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right. = -890.36 \ \frac{kJ}{mol}$$

$$\hat{U} = \int_{25}^{T}(C_v)dT \xrightarrow{\text{Ideal Gas}} \int_{25}^{T}(C_p - R_g)dT$$

If C_p is independent of $T \Rightarrow \hat{U} = (C_p - R_g)(T - 25°C)$

b.

Reference states: $CH_4(g)$, $N_2(g)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at $25°C$

(We will use the values of $\Delta\hat{H}_c^0$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water.)

Substance	n_{in} mol	$\hat{U}_{in}$ kJ/mol	n_{out} mol	$\hat{U}_{out}$ kJ/mol
CH_4	1.00	0	–	–
O_2	2.60	0	0.60	$\hat{U}_1$
N_2	9.78	0	9.78	$\hat{U}_2$
CO_2	–	–	1.00	$\hat{U}_3$
$H_2O(v)$	–	–	2.00	$\hat{U}_4$

Part a
$\downarrow$

$\hat{U}_i = (C_p - R_g)(T - 25)$ for all species except $H_2O(v)$

$= \Delta\hat{U}_v\left(25°C\right) + (C_p - R_g)(T - 25) = \left[\Delta\hat{H}_v\left(25°C\right) - R_g T_{ref}\right] + (C_p - R_g)(T - 25)$ for $H_2O(v)$

Substituting given values of $(C_p)_i$ and $R_g = 8.314 \times 10^{-3}$ kJ / mol yields

$\hat{U}_1 = (0.033 - 8.314 \times 10^{-3})(T - 25)$ kJ / mol $= (0.02469T - 0.6172)$ kJ / mol

$\hat{U}_2 = (0.032 - 8.314 \times 10^{-3})(T - 25)$ kJ / mol $= (0.02369T - 0.5922)$ kJ / mol

$\hat{U}_3 = (0.052 - 8.314 \times 10^{-3})(T - 25)$ kJ / mol $= (0.04369T - 1.0922)$ kJ / mol

$\hat{U}_4 = \left[44.01 \frac{kJ}{mol} - \left(8.314 \times 10^{-3} \frac{kJ}{mol \cdot K}\right)(298\ K)\right] + (0.040 - 8.314 \times 10^{-3})(T - 25) \frac{kJ}{mol}$

$\Rightarrow \hat{U}_4 = 41.53 \frac{kJ}{mol} + (0.052 - 8.314 \times 10^{-3})(T - 25) \frac{kJ}{mol} = (0.03167T - 40.74) \frac{kJ}{mol}$

Energy Balance

$Q = n_{CH_4}\left(\Delta\hat{U}_c^o\right)_{CH_4} + \sum_{out} n_i \hat{U}_i - \sum_{in} n_i \hat{U}_i = 0$

$\Rightarrow Q = (1.00)(-890.36\ kJ / mol) + (0.60)\hat{U}_1 + (9.87)\hat{U}_2 + (1.00)\hat{U}_3 + (2.00)\hat{U}_4 = 0$

Substituting $\hat{U}_1$ through $\hat{U}_4$

$0.3557\ T - 816.19 = 0 \Rightarrow \underline{T = 2295°C}$

Ideal Gas Equation of State $\Rightarrow \dfrac{P_f}{P_i} = \dfrac{T_f}{T_i} \Rightarrow P_f = \left(\dfrac{(2295 + 273)\ K}{(25 + 273)\ K}\right) \times 4.00\ atm = \underline{\underline{34.5\ atm}}$

c.
– Heat loss to and through reactor wall
– Tank would expand at high temperatures and pressures

9.68

b. 1 mol natural gas

y_{CH_4} (mol CH_4 / mol)

$y_{C_2H_6}$ (mol C_2H_6 / mol)

$y_{C_3H_8}$ (mol C_3H_8 / mol)

n_{CO_2} (mol CO_2)

n_{H_2O} (mol H_2O)

n_{N_2} (mol N_2)

n_{O_2} mol O_2)

Humid air

n_a (mol air)

y_{wo} (mol $H_2O(v)$/mol)

$(1-y_{wo})$ (mol dry air/mol)

0.21 mol O_2/mol DA

0.79 mol N_2/mol DA
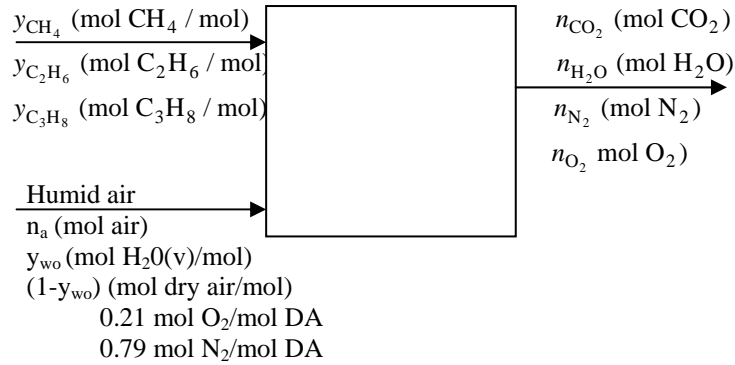
<u>Basis</u> : 1 g-mole natural gas

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + H_2O(v)$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v)$$

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(v)$$
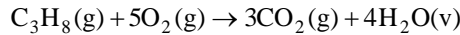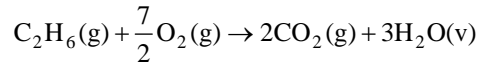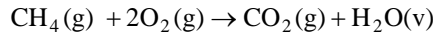
<u>Theoretical oxygen</u> :

$$\frac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \left| \frac{y_{CH_4} (\text{mol } CH_4)}{} + \frac{3.5 \text{ mol } O_2}{1 \text{ mol } C_2H_6} \right| \frac{y_{C_2H_6} (\text{mol } C_2H_6)}{} + \frac{5 \text{ mol } O_2}{1 \text{ mol } C_3H_8} \left| \frac{y_{C_3H_8} (\text{mol } C_3H_8)}{} \right.$$

$$= (2y_{CH_4} + 3.5y_{C_2H_6} + 5 y_{C_3H_8})$$

<u>Excess oxygen:</u> $0.21n_a (1 - y_{wo}) = \left(1 + \frac{P_{xs}}{100}\right)(2y_{CH_4} + 3.5y_{C_2H_6} + 5 y_{C_3H_8})$ mol O_2

$$\Rightarrow n_a = \left(1 + \frac{P_{xs}}{100}\right)(2y_{CH_4} + 3.5y_{C_2H_6} + 5 y_{C_3H_8}) \frac{1}{0.21(1 - y_{w0})} \text{ mol air}$$

<u>Feed components</u>

$$(n_{O_2})_{in} = 0.21n_a (1 - y_{wo}), \quad (n_{N_2})_{in} = 0.79n_a (1 - y_{wo}), \quad (n_{H_2O})_{in} = n_a y_{wo}$$

<u>N_2 in product gas:</u> $n_{N_2} = (n_{N_2})_{in}$ mol N_2

<u>CO_2 in product gas :</u>

$$n_{CO_2} = \frac{1 \text{ mol } CO_2}{1 \text{ mol } CH_4} \left| \frac{n_{CH_4} (\text{mol } CH_4)}{} + \frac{2 \text{ mol } CO_2}{1 \text{ mol } C_2H_6} \right| \frac{n_{C_2H_6} (\text{mol } C_2H_6)}{} + \frac{3 \text{ mol } CO_2}{1 \text{ mol } C_3H_8} \left| \frac{n_{C_3H_8} (\text{mol } C_3H_8)}{} \right.$$

$$= (n_{CH_4} + 2n_{C_2H_6} + 3n_{C_3H_8}) \text{ mol } CO_2$$

<u>H_2O in product gas :</u>

$$n_{H_2O} = \frac{1 \text{ mol } H_2O}{1 \text{ mol } CH_4} \left| \frac{n_{CH_4} (\text{mol } CH_4)}{} + \frac{3 \text{ mol } H_2O}{1 \text{ mol } C_2H_6} \right| \frac{n_{C_2H_6} (\text{mol } C_2H_6)}{} + \frac{4 \text{ mol } O_2}{1 \text{ mol } C_3H_8} \left| \frac{n_{C_3H_8} (\text{mol } C_3H_8)}{} \right.$$

$$= [2n_{CH_4} + 3n_{C_2H_6} + 4n_{C_3H_8} + n_a (1 - y_{wo})] \text{ mol } H_2O$$

<u>O_2 in product gas :</u> $n_{O_2} = \frac{P_{xs}}{100}(2n_{CH_4} + 3.5n_{C_2H_6} + 5 n_{C_3H_8})$ mol O_2

9.68 (cont'd)

c.   <u>References</u> : $C(s)$, $H_2(g)$ at $25^{\circ}C$

$$\hat{H}_{CH_4}(T) = (\Delta H_f^o)_{CH_4} + \int_{25}^{T} (C_p)_{CH_4}\, dT$$

Using $(\Delta H_f^o)_{CH_4}$ from Table B.1 and $(C_p)_{CH_4}$ from Table B.2

$$\hat{H}_{CH_4}(T) = -74.85 \text{ kJ/mol} + \left(\int_{25}^{T} (0.03431 + 5.469 \times 10^{-5} T + 0.3661 \times 10^{-8} T^2 - 11.00 \times 10^{-12} T^3)\, dT \right) \text{kJ/mol}$$

$$\Rightarrow \hat{H}_{CH_4}(T) = [-75.72 + 3.431 \times 10^{-2} T + 2.734 \times 10^{-5} T^2 + 0.122 \times 10^{-8} T^3 - 2.75 \times 10^{-12} T^4]\ \text{kJ/mol}$$

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
	mol	kJ/mol	mol	kJ/mol
CH_4	n_1	$\hat{H}_1$	–	–
C_2H_6	n_2	$\hat{H}_2$	–	–
C_3H_8	n_3	$\hat{H}_3$	–	–
O_2	n_4	$\hat{H}_4$	n_7	$\hat{H}_7$
N_2	n_5	$\hat{H}_5$	n_8	$\hat{H}_8$
CO_2	n_6	–	n_9	$\hat{H}_9$
H_2O	–	–	n_{10}	$\hat{H}_{10}$

$$\Delta H = \sum_{i=4}^{7} (n_i)_{out} (H_i)_{out} - \sum_{i=1}^{6} (n_i)_{in} (H_i)_{in}$$

$$\hat{H}_i = a_i + b_i T + c_i T^2 + d_i T^3 + e_i T^4$$

$$\sum_{i=1}^{6} (n_i)_{in} (H_i)_{in} = \sum_{i=1}^{3} (n_i)_{in} \hat{H}_i(T_f) + \sum_{i=4}^{6} (n_i)_{in} \hat{H}_i(T_a)$$

$$\Rightarrow \Delta H = \sum_{i=4}^{7} (n_i)_{out} (a_i + b_i T + c_i T^2 + d_i T^3 + e_i T^4)_{out} - \sum_{i=1}^{3} (n_i)_{in} \hat{H}_i(T_f) - \sum_{i=4}^{6} (n_i)_{in} \hat{H}_i(T_a)$$

$$\Rightarrow \Delta H = \sum_{i=1}^{7} (n_i)_{out} a_i + \sum_{i=4}^{7} (n_i)_{out} b_i T + \sum_{i=1}^{7} (n_i)_{out} c_i T^2 + \sum_{i=1}^{7} (n_i)_{out} d_i T^3 + \sum_{i=1}^{7} (n_i)_{out} e_i T^4$$

$$- \sum_{i=1}^{3} (n_i)_{in} \hat{H}_i(T_f) - \sum_{i=4}^{6} (n_i)_{in} \hat{H}_i(T_a)$$

$$= \alpha_0 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3 + \alpha_4 T^4$$

where $\quad \alpha_0 = \sum_{i=1}^{7} (n_i)_{out} a_i - \sum_{i=1}^{3} (n_i)_{in} \hat{H}_i(T_f) - \sum_{i=4}^{6} (n_i)_{in} \hat{H}_i(T_a)$

$$\alpha_1 = \sum_{i=1}^{7} (n_i)_{out} b_i \qquad \alpha_2 = \sum_{i=1}^{7} (n_i)_{out} c_i$$

$$\alpha_3 = \sum_{i=1}^{7} (n_i)_{out} d_i \qquad \alpha_4 = \sum_{i=1}^{7} (n_i)_{out} e_i$$

.

9.68 (cont'd)

d.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
yCH4	0.75	0.86	0.75	0.75	0.75	0.75
yC2H6	0.21	0.1	0.21	0.21	0.21	0.21
yC3H8	0.04	0.04	0.04	0.04	0.04	0.04
Tf	40	40	150	40	40	40
Ta	150	150	150	250	150	150
Pxs	25	25	25	25	100	25
ywo	0.0306	0.0306	0.0306	0.0306	0.0306	0.1
nO2i	3.04	2.84	3.04	3.04	4.87	3.04
nN2	11.44	10.67	11.44	11.44	18.31	11.44
nH2Oi	0.46	0.43	0.46	0.46	0.73	1.61
HCH4	-74.3	-74.3	-70	-74.3	-74.3	-74.3
HC2H6	-83.9	-83.9	-77	-83.9	-83.9	-83.9
HC3H8	-102.7	-102.7	-93	-102.7	-102.7	-102.7
HO2i	3.6	3.6	3.6	6.6	3.6	3.6
HN2i	3.8	3.8	3.8	6.9	3.8	3.8
HH2Oi	-237.6	-237.6	-237.6	-234.1	-237.6	-237.6
nCO2	1.29	1.18	1.29	1.29	1.29	1.29
nH2O	2.75	2.61	2.75	2.75	3.02	3.9
nO2	0.61	0.57	0.61	0.61	2.44	0.61
nN2	11.44	10.67	11.44	11.44	18.31	11.44
Tad	**1743.1**	**1737.7**	**1750.7**	**1812.1**	**1237.5**	**1633.6**
alph0	-1052	-978.9	-1057	-1099	-1093	-1058
alph1	0.4892	0.4567	0.4892	0.4892	0.7512	0.5278
alph2	0.0001	1.00E-04	0.0001	0.0001	0.0001	0.0001
alph3	-3.00E-08	-3.00E-08	-3.00E-08	-3.00E-08	-4.00E-08	-2.00E-08
alph4	3.00E-12	3.00E-12	3.00E-12	3.00E-12	4.00E-12	2.00E-12
Delta H	3.00E-07	9.00E-06	-4.00E-07	-1.00E-04	-1.00E-05	6.00E-04

Species	a	b	c	d	e
		x 10^2	x 10^5	x 10^8	x 10^12
CH4	-75.72	3.431	2.734	0.122	-2.75
C2H6	-85.95	4.937	6.96	-1.939	1.82
C3H8	-105.6	6.803	11.3	-4.37	7.928
O2	-0.731	2.9	0.11	0.191	-0.718
N2	-0.728	2.91	0.579	-0.203	0.328
H20	-242.7	3.346	0.344	0.254	-0.898
CO2	-394.4	3.611	2.117	-0.962	1.866

9.69

Absorber off-gas
n_8 (mol H_2/h)
n_{12} (mol N_2/h)
$0.988n_9$ (mol CO/h)
$0.950n_6$ (mol CH_4/h)
$0.006n_7$ (mol C_2H_2/h)

Basis:
5000 kg/h Product gas
n_1 (mol/h)
0.991 mol C_2H_2 (g)/mol
0.00059 mol H_2O/mol
0.00841 mol CO_2/mol

n_{14} (mol CH_4/h)
25°C
Preheaters

n_{13} (mol C(s)/h)

$0.917n_1$ (mol DMF/h)
Lean solvent

Converter
product
T_{ad} (°C)

Converter
product
38°C

converter

quench

filter

absorber   stripper

Feed gas, 650°C
n_{14} (mol CH_4/h)
$0.96n_{15}$ (mol O_2/h)
$0.04n_{15}$ (mol N_2/h)

Rich solvent

n_6 (mol CH_4/h)
n_7 (mol C_2H_2/h)
n_8 (mol H_2/h)
n_9 (mol CO/h)
n_{10} (mol CO_2/h)
n_{11} (mol H_2O/h)
n_{12} (mol N_2/h)
n_{13} (mol C(s)/h)

n_6 (mol CH_4/h)
n_7 (mol C_2H_2/h)
n_8 (mol H_2/h)
n_9 (mol CO/h)
n_{10} (mol CO_2/h)
n_{11} (mol H_2O/h)
n_{12} (mol N_2/h)

n_{15} (mol/h)
0.96 mol O_2/mol
0.04 mol N_2/mol
25°C

Stripper off-gas
n_2 (mol CO/h)
n_3 (mol CH_4/h)
n_4 (mol H_2O(v)/h)
n_5 (mol CO_2/h)

n_1 (mol/h)
0.0155 mol C_2H_2/mol
0.0063 mol CO_2/mol
0.00055 mol CO/mol
0.00055 mol CH_4/mol
0.0596 mol H_2O/mol
0.917 mol DMF/mol

Average M.W. of product gas:

$$\overline{M} = 0.991(26.04) + 0.00059(18.016) + 0.00841(44.01) = 26.19 \text{ g/mol}$$

Molar flow rate of product gas: $n_0 = \dfrac{5000 \text{ kg}}{\text{day}} \left| \dfrac{10^3 \text{ g}}{1 \text{ kg}} \right| \dfrac{1 \text{ mol}}{26.19 \text{ g}} \left| \dfrac{1 \text{ day}}{24 \text{ h}} \right. = 7955 \text{ mol/h}$

Material balances -- plan of attack (refer to flow chart):

Stripper balances: $C_2H_2 \Rightarrow n_1$, $CO \Rightarrow n_2$, $CH_4 \Rightarrow n_3$, $H_2O \Rightarrow n_4$, $CO_2 \Rightarrow n_5$

Absorber balances: $CH_4 \Rightarrow n_6$, $C_2H_2 \Rightarrow n_7$, $CO \Rightarrow n_9$, $CO_2 \Rightarrow n_{10}$, $H_2O \Rightarrow n_{11}$

$\left. \begin{array}{l} 5.67\% \text{ soot formation} \\ \text{converter C balance} \end{array} \right\} \Rightarrow n_{13}, n_{14}$, converter H balance $\Rightarrow n_8$

Converter O balance $\Rightarrow n_{15}$, converter N_2 balance $\Rightarrow n_{12}$

Stripper balances:

C_2H_2: $0.0155n_1 = 0.991(7955 \text{ mol/h}) \Rightarrow n_1 = 5.086 \times 10^5 \text{ mol/h}$

CO: $(0.00055)(5.086 \times 10^5) = n_2 \Rightarrow n_2 = 79.7 \text{ mol CO/h}$

CH_4: $(0.00055)(5.086 \times 10^5) = n_3 \Rightarrow n_3 = 79.7 \text{ mol } CH_4/\text{h}$

H_2O: $(0.0596)(5.086 \times 10^5) = n_4 + (0.00059)(7955) \Rightarrow n_4 = 30308 \text{ mol } H_2O/\text{h}$

CO_2: $(0.0068)(5.086 \times 10^5) = n_5 + (0.00841)(7955) \Rightarrow n_5 = 3392 \text{ mol } CO_2/\text{h}$

Absorber balances

CH_4: $n_6 = 0.950n_6 + (0.00055)(5.086 \times 10^5) = n_6 \Rightarrow 5595 \text{ mol } CH_4/\text{h}$

9.69 (cont'd)

C_2H_2: $n_7 = (0.0155)(5.086 \times 10^5) + 0.006n_7 \Rightarrow n_7 = 7931$ mol C_2H_2/h

CO: $n_9 = 0.988n_9 + (0.00055)(5.086 \times 10^5) \Rightarrow n_9 = 23311$ mol CO/h

CO_2: $n_{10} = (0.0068)(5.086 \times 10^5) = 3458$ mol CO_2/h

H_2O: $n_{11} = (0.0596)(5.086 \times 10^5) = 30313$ mol H_2O/h

<u>Soot formation:</u> $\dfrac{n_{13} = (0.0567)n_{14}\,(\text{mol CH}_4)}{h} \left|\dfrac{1 \text{ mol C}}{1 \text{ mol CH}_4}\right. \Rightarrow n_{13} = 0.0567n_{14}$ (1)

<u>Converter C balance:</u>

$n_{14} = (5595 \text{ mol CH}_4/h)(1 \text{ mol C}/\text{mol CH}_4) + (7931)(2) + (23311)(1) + (3458)(1) + n_{13}$

    $\Rightarrow n_{14} = n_{13} + 48226$ (2)

Solve (1) & (2) simultaneously $\Rightarrow n_{13} = 2899$ mol C(s)/h, $n_{14} = 51120$ mol CH_4/h

<u>Converter H balance:</u> $\dfrac{51120 \text{ mol CH}_4}{h}\left|\dfrac{4 \text{ mol H}}{1 \text{ mol Ch}_4}\right. = \overset{CH_4}{(5595)(4)} + \overset{C_2H_2}{(7931)(2)} + \overset{H_2}{2n_8} + \overset{H_2O}{(30313)(2)}$

        $\Rightarrow n_8 = 52816$ mol H_2/h

<u>Converter O balance:</u> $(0.96n_{15})(2) = \dfrac{23311 \text{ mol CO}}{h}\left|\dfrac{1 \text{ mol O}}{1 \text{ mol CO}}\right. + \overset{CO_2}{(3458)(2)} + \overset{H_2O}{(30313)(1)}$

        $\Rightarrow n_{15} = 31531$ mol/h

<u>Converter N_2 balance:</u> $(0.04)(31531)n_{12} \Rightarrow n_{12} = 1261$ mol N_2/h

a. <u>Feed stream flow rates</u>

$V_{CH_4} = \dfrac{51120 \text{ mol CH}_4}{h}\left|\dfrac{0.0244 \text{ m}^3(\text{STP})}{1 \text{ mol}}\right. = \underline{\underline{1145 \text{ SCMH CH}_4}}$

$V_{O_2} = \dfrac{31531 \text{ mol }(O_2 + N_2)}{h}\left|\dfrac{0.0244 \text{ m}^3(\text{STP})}{1 \text{ mol}}\right. = \underline{\underline{706 \text{ SCMH O}_2(+N_2)}}$

b. <u>Gas feed to absorber</u>

$\left.\begin{array}{l} 5595 \text{ mol CH}_4/h \\ 7931 \text{ mol C}_2H_2/h \\ 23311 \text{ mol CO}/h \\ 3458 \text{ mol CO}_2/h \\ 30313 \text{ mol H}_2O/h \\ 52816 \text{ mol H}_2/h \\ \underline{1261 \text{ mol N}_2/h} \\ \hline 1.2469 \times 10^5 \text{ mol/h} \end{array}\right\}$ $\Rightarrow \underline{\underline{125 \text{ kmol/h}}}$, $\begin{array}{l}\text{4.5 mole\% CH}_4\text{, 6.4 \% C}_2H_2\text{, 18.7\% CO ,} \\ \text{2.8\% CO}_2\text{, 24.3\% H}_2O\text{, 42.4\% H}_2\text{, 1.0\% N}_2\end{array}$

<u>Absorber off-gas</u>

$\left.\begin{array}{l} 52816 \text{ mol H}_2/h \\ 1261 \text{ mol N}_2/h \\ 23031 \text{ mol CO}/h \\ 5315 \text{ mol CH}_4/h \\ \underline{41.6 \text{ mol C}_2H_2/h} \\ \hline 8.2471 \times 10^4 \text{ mol/h} \end{array}\right\}$ $\Rightarrow \underline{\underline{82.5 \text{ kmol/h,}}}$ $\begin{array}{l}\text{64.1 mole\% H}_2\text{, 1.5\% N}_2\text{, 27.9\% CO,} \\ \text{6.4\% CH}_4\text{, 0.06\% C}_2H_2\end{array}$

9.69 (cont'd)

Stripper off-gas

$$\left.\begin{array}{l} 279.7 \text{ mol } CO/h \\ 279.7 \text{ mol } CH_4/h \\ 30308 \text{ mol } H_2O/h \\ 3392 \text{ mol } CO/h \\ \hline 3.4259 \times 10^4 \text{ mol/h} \end{array}\right\} \Rightarrow 34.3 \text{ kmol/h, } 0.82\% \text{ CO, } 0.82\% \text{ CH}_4, \text{ } 88.5\% \text{ H}_2\text{O, } 9.9\% \text{ CO}_2$$

c. $\underline{\text{DMF recirculation rate}} = 0.917 \left(5.086 \times 10^5 \ \frac{\text{mol}}{\text{h}}\right)\left(\frac{1 \text{ kmol}}{10^3 \text{ mol}}\right) = \underline{\underline{466 \text{ kmol DMF/h}}}$

d. $\underline{\text{Overall product yield}} = \dfrac{(0.991)(7955) \text{ mol C}_2\text{H}_2 \text{ in product gas}}{51120 \text{ mol CH}_4 \text{ in feed/h}} = 0.154 \dfrac{\text{mol C}_2\text{H}_2}{\text{mol CH}_4}$

The theoretical maximum yield would be obtained if only the reaction $2CH_4 \rightarrow C_2H_2 + 3H_2$ occurred, the reaction went to completion, and all the C_2H_2 formed were recovered in the product gas. This yield is $(1 \text{ mol C}_2\text{H}_2/2 \text{ mol CH}_4) = 0.500 \text{ mol C}_2\text{H}_2/2 \text{ mol CH}_4$.

The ratio of the actual yield to the theoretical yield is $0.154/0.500 = \underline{0.308}$.

e. Methane preheater

$$\dot{Q}_{CH_4} = \Delta \dot{H} = \dot{n}_{14} \int_{25}^{650} \overset{\text{Table B.2}}{\left(C_p\right)}_{CH_4} dT = \frac{51120 \text{ mol}}{\text{h}} \left| \frac{32824 \text{ J}}{\text{mol}} \right| \frac{1 \text{ h}}{3601 \text{ s}} \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} = \underline{\underline{466 \text{ kW}}}$$

Oxygen preheater

$$\dot{Q}_{O_2} = \Delta \dot{H} = 0.96 \dot{n}_{15} \overset{\text{Table B.8}}{\hat{H}(O_2, 650°C)} + 0.04 \dot{n}_{15} \overset{\text{Table B.8}}{\hat{H}(N_2, 650°C)}$$

$$= \left(31531 \frac{\text{mol}}{\text{h}}\right)\left[(0.96 \times 20.135 + 0.04 \times 18.99) \frac{\text{kJ}}{\text{mol} \cdot °C}\right]\left(\frac{1 \text{ h}}{3600 \text{ s}}\right) = \underline{\underline{176 \text{ kW}}}$$

f. $\underline{\text{References}}$: $C(s), H_2(g), O_2(g), N_2(g)$ at $25°C$

Substance	$\dot{n}_{in}$	$\hat{H}_{in}(650°C)$	$\dot{n}_{out}$	$\hat{H}_{out}(T_{out})$	
CH_4	51120	−42.026	5595	$-74.85 + \int_{25}^{T_a} C_p dT$	
O_2	30270	20.125	−	−	
N_2	1261	18.988	1261	$\int_{35}^{T_a} C_p dT$	
C_2H_2	−	−	7931	$+226.75 \int_{25}^{T_a} C_p dT$	
H_2	−	−	52816	$\int C_p dT$	$n(\text{mol/h})$
CO	−	−	23311	$-110.52 + \int C_p dT$	$\hat{H}(\text{kJ/mol})$
CO_2	−	−	3458	$-393.5 + \int C_p dT$	
H_2O	−	−	30313	$-241.83 + \int C_p dT$	
$C(s)$	−	−	2899	$\int C_p dT$	

9.69 (cont'd)

$$\hat{H}_i = \underset{\text{kJ/mol}}{\Delta \hat{H}_i^0} + \underset{\substack{25 \\ \text{kJ/mol·°C}}}{\int^T} C_{pi} dT$$

$$\sum_{\text{in}} \dot{n}_i \hat{H}_i = -1.575 \times 10^6 \ \text{kJ/h}$$

$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -9.888 \times 10^6 \ \text{kJ/h} + \int_{25}^{T_{out}} \left[5595 \left(C_p \right)_{CH_4} + 1261 \left(C_p \right)_{N_2} + 7931 \left(C_p \right)_{C_3H_2} \right.$$

$$+ 52816 \left(C_p \right)_{H_2} + 23311 \left(C_p \right)_{CO} + 3458 \left(C_p \right)_{CO_2} + 3013 \left(C_p \right)_{H_2O(v)} \left] \frac{1 \ \text{kJ}}{10^3 \ \text{J}} dT \right.$$

$$+ \int_{298}^{T_{ad}+273} \left(C_p \right)_{C(s)} \times \frac{1 \ \text{kJ}}{10^3 \ \text{J}} dT$$

We will apply the heat capacity formulas of Table B.2, recognizing that we will probably push at least some of them above their upper temperature limits

$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -9.888 \times 10^6 \ \text{kJ/h} + \int_{25}^{T_{ad}} \left(3902 + 1.2185 - 5.9885 \times 10^{-4} T^2 - 1.0162 \times 10^{-7} T^3 \right) dT$$

$$+ \int_{298}^{T_{ad}+273} \left(32.411 + 0.031744T - \frac{1.4179 \times 10^6}{T^2} \right) dT$$

$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -1.000 \times 10^7 + 3943T_a + 0.6251T_a^2 - 1.996 \times 10^{-4} T_a^3 - 2.5405 \times 10^{-8} T_a^4 + \frac{1.418 \times 10^6}{T_a + 273}$$

<u>Energy balance:</u> $\Delta \dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 0$

$$\Rightarrow f(T_c) = -8.485 \times 10^6 + 3943T_c + 0.6251T_c^2 - 1.996 \times 10^{-4} T_c^3 - 2.5405 \times 10^{-8} T_c^4 + \frac{1.418 \times 10^6}{T_c + 273} = 0$$

$$\xrightarrow{\text{E-Z Solve}} \underline{\underline{T_c = 2032^\circ \text{C.}}}$$

9.70 a.

W = H₂O $\quad$ **W = H$_2$O**

$\dot{m}_1 [kg\ W(v)/d]$

$100°C$

24,000 kg sludge / d, 22°C

0.35 solids, 0.65 W(l)

DRYER $\quad \dot{Q}_2$

$\dot{m}_2$ (kg conc. sludge/d), 100°C

0.75 solids, 0.25 W(l)

F

INCINERATOR

Waste gas

$\dot{m}_3\ [kg\ W(v)/d]$

4B, sat'd

C

$\dot{m}_3\ [kg\ W(l)/d]$

20°C

BOILER

$\dot{Q}_3$ (kJ / d)

$\dot{m}_3\ [kg\ W(l)/d]$

4B, sat'd

$\dot{m}_6$ (kg gas/d)

$0.90\ \dfrac{kmol\ CH_4}{kmol}$

$0.10\ \dfrac{kmol\ C_2H_6}{kmol}$

110°C

$\dot{Q}_1$

D

$\dot{m}_4$ (kg oil/d)

0.87 C

0.10 H

0.0084 S

0.0216 ash

125°C

Stack gas

CO_2, $H_2O(v)$

SO_2

O_2, N_2

ash

$\dot{Q}_4$ (kJ / d)

$\dot{Q}_0$ (kJ/d)

$\dot{m}_7$ (kg air/d)

25°C

E $\dot{m}_5$ (kg air/d)

25°C
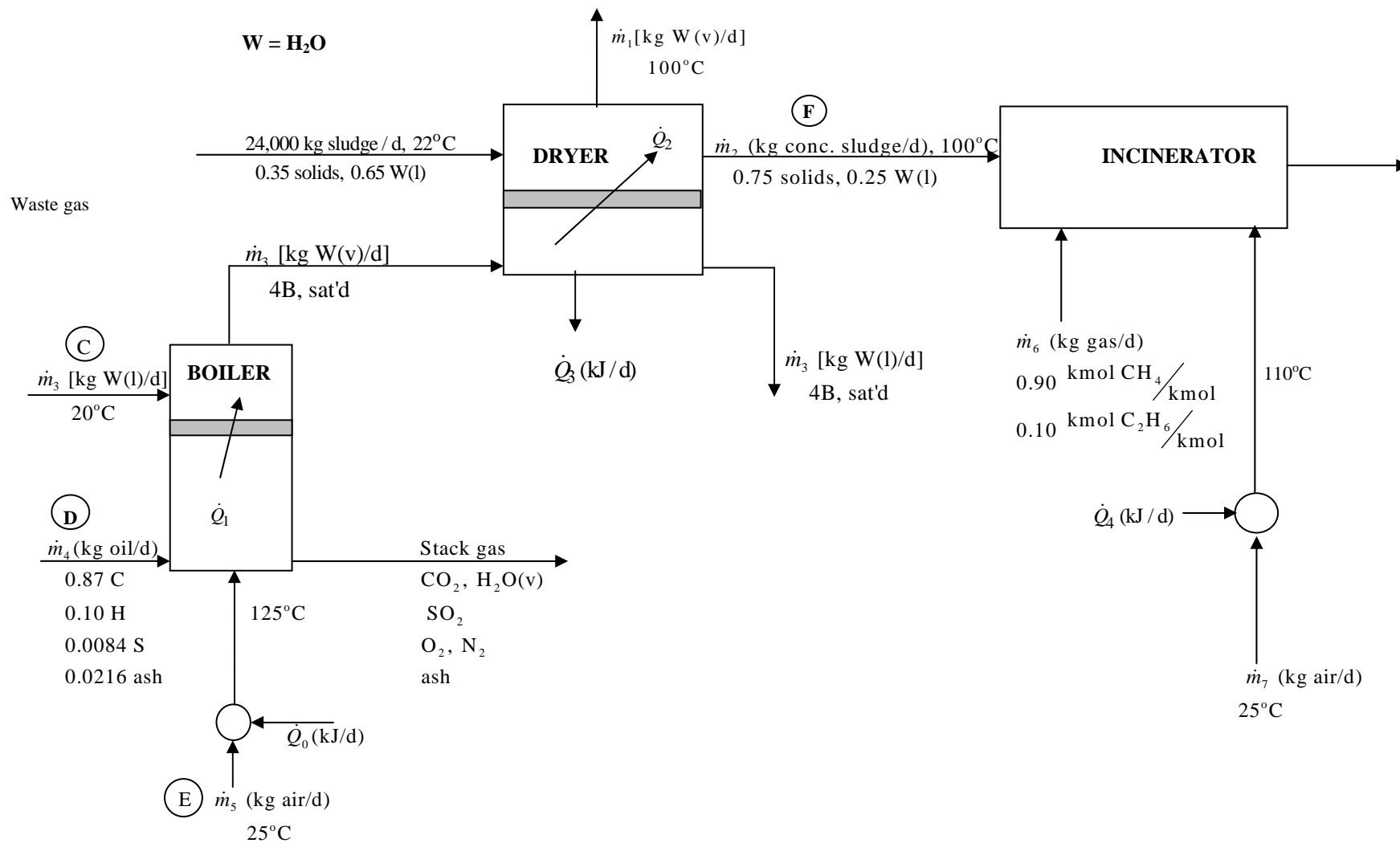
9.70 (cont'd)

Solids balance on dryer:
$$0.35 \times 24{,}000 \text{ kg/d} = 0.75\dot{n}_2 \Rightarrow \dot{n}_2 = 11200 \text{ kg/d} \Rightarrow \underline{\text{ F } \quad 11.2 \text{ tonnes/d }} \text{ (conc. sludge)}$$

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 : $H_2O(l, 22°C)$, Solids($22°C$)

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)

$$\dot{Q}_2 = \sum_{out} \dot{m}_i \hat{H}_i - \sum_{in} \dot{m}_i \hat{H}_i \Rightarrow \underline{\underline{\dot{Q}_2 = 3.56 \times 10^7 \text{ kJ/day}}}$$

$$\dot{Q}_{steam} = \frac{3.56 \times 10^7}{0.55} = 6.47 \times 10^7 \text{ kJ/d} \Rightarrow \underline{\underline{\dot{Q}_3 = 2.91 \times 10^7 \text{ kJ/d}}}$$

Energy balance on steam side of dryer:

$$6.47 \times 10^7 \frac{\text{kJ}}{\text{d}} = \dot{n}_3 \left(\frac{\text{kg}}{\text{d}}\right) \times \overset{\overset{\Delta\hat{H}_v \text{ for}}{H_2O(\text{sat'd, })}}{\underset{\downarrow}{2133}} \left(\frac{\text{kJ}}{\text{kg}}\right) \left(\frac{1 \text{ tonne}}{10^3 \text{ kg}}\right) \Rightarrow \underline{\underline{\dot{n}_3 = 30.3 \text{ tonnes/d}}} \text{ (boiler feedwater)}$$

Energy balance on steam side of boiler:

$$Q_1 = (30300 \frac{\text{kg}}{\text{d}})(2737.6 - 83.9)\frac{\text{kJ}}{\text{kg}} = \underline{\underline{8.04 \times 10^7 \text{ kJ/d}}}$$

<u>62% efficiency</u> $\Rightarrow$ Fuel heating value needed $= \frac{8.04 \times 10^7}{0.62} = 1.3 \times 10^8 \text{ kJ/d}$

$$\Rightarrow \dot{n}_4 = \frac{1.30 \times 10^8 \text{ kJ/d}}{3.75 \times 10^4 \text{ kJ/kg}} = \underline{\underline{3458 \text{ kg/d}}} \Rightarrow \underline{\text{D} = 3.5 \text{ tonnes/day}} \text{ (fuel oil)}$$

Air feed to boiler furnace: $C + O_2 \rightarrow CO_2$, $4H + O_2 \rightarrow 2H_2O$, $S + O_2 \rightarrow SO_2$

$$(n_{O_2})_{theo} = 3458 \frac{\text{kg}}{\text{d}} \left[(0.87 \frac{\text{kgC}}{\text{kg}})(\frac{1 \text{ kmol C}}{12 \text{ kg}})(\frac{1 \text{ kmol O}_2}{1 \text{ kmol C}}) + (0.10)(\frac{1}{1})(\frac{1}{4}) + (0.0084)(\frac{1}{32})(\frac{1}{1}) \right]$$

$$= 338 \text{ kmol O}_2/\text{d}$$

9.70 (cont'd)

$$\text{Air fed (25\% excess)} = 1.25(4.76\frac{\text{kmol air}}{\text{kmol O}_2})(338\frac{\text{kmol O}_2}{\text{d}}) = 2011\frac{\text{kmol air}}{\text{d}}$$

$$\Rightarrow \frac{2011\ \text{kmol}}{\text{d}}\left|\frac{29\ \text{kg}}{\text{kmol}}\right|\frac{1\ \text{tonne}}{10^3\ \text{kg}} \Rightarrow \dot{E} = 58.3\ \text{tonnes}/\text{d (air to boiler)}$$

Energy balance on boiler air preheater:

$$\text{Table B.8} \Rightarrow \hat{H}_{air}(125^\circ\text{C}) = 2.93\frac{\text{kJ}}{\text{mol}} \Rightarrow \dot{Q}_0 = \frac{2011\ \text{kmol}}{\text{d}}\left|\frac{10^3\ \text{mol}}{1\ \text{kmol}}\right|\frac{2.93\ \text{kJ}}{\text{mol}} = 5.89 \times 10^6\ \text{kJ/d}$$

Supplementary fuel for incinerator:

$$\dot{n}_6 = \frac{11.2\ \text{tonne sludge}}{\text{d}}\left|\frac{195\ \text{SCM}}{\text{tonne}}\right|\frac{1\ \text{kmol}}{22.4\ \text{SCM}} = 97.5\ \text{kmol/d}$$

$$\overline{MW}_{gas} = 0.90\overline{MW}_{\text{CH}_4} + 0.10\overline{MW}_{\text{C}_2\text{H}_6} = (0.90)(16) + (0.10)(30) = 17.4\ \text{kg/kmol}$$

$$M_{gas} = (97.5)(17.4) \Rightarrow \dot{G} = 1.7\ \text{tonne}/\text{d}\ \text{(natural gas)}$$

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O},\ \text{C}_2\text{H}_6 + \frac{7}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$$
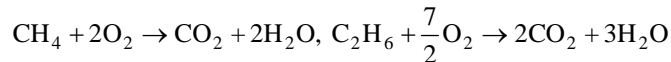
Air feed to incinerator:

$$(\text{air})_{th,sludge}:\ \frac{11200\ \text{kg sludge}}{\text{d}}\left|\frac{0.75\ \text{kg sol}}{\text{kg sludge}}\right|\frac{19000\ \text{kJ}}{1\ \text{kg sol}}\left|\frac{2.5\ \text{m}^3(\text{STP})\ \text{air}}{10^4\ \text{kJ}}\right|\frac{1\ \text{kmol}}{22.4\ \text{m}^3(\text{STP})} = 1781\frac{\text{kmol air}}{\text{d}}$$

$$(\text{air})_{th,gas}:\ 97.5\frac{\text{kmol}}{\text{d}}\left[0.90\frac{\text{kmol CH}_4}{\text{kmol}} \times \frac{2\ \text{kmol O}_2}{\text{kmol CH}_4} + (0.10)(3.5)\right]\left(\frac{4.76\ \text{kmol air}}{1\ \text{kmol O}_2}\right) = 998\frac{\text{kmol air}}{\text{d}}$$

$$100\%\ \text{excess air:}\ \dot{n}_7 = 2(1781 + 998)\frac{\text{kmol air}}{\text{d}} = 5558\ \text{kmol air/d}$$

$$\Rightarrow \frac{5558\ \text{kmol air}}{\text{d}}\left|\frac{29.0\ \text{kg air}}{1\ \text{kmol air}}\right|\frac{1\ \text{tonne}}{10^3\ \text{kg}} = 161\ \text{tonne air/d (incinerator air)}$$

Energy balance on air preheater :

$$\text{Table B.8} \Rightarrow \hat{H}_{air}(110^\circ\text{C}) = 2.486\frac{\text{kJ}}{\text{mol}} \Rightarrow \dot{Q}_4 = \frac{5558\ \text{kmol}}{\text{d}}\left|\frac{10^3\ \text{mol}}{1\ \text{kmol}}\right|\frac{2.486\ \text{kJ}}{\text{mol}} = 1.38 \times 10^7\frac{\text{kJ}}{\text{d}}$$

b. Cost of fuel oil, natural gas, fuel oil and air preheating, pumping and compression, piping, utilities, operating personnel, instrumentation and control, environmental monitoring. Lowering environmental hazard might justify lack of profit.

c. Put hot product gases from boiler and/or incinerator through heat exchangers to preheat both air streams. Make use of steam from dryer.

d. Sulfur dioxide, possibly NO_2, fly ash in boiler stack gas, volatile toxic and odorous compounds in gas effluents from dryer and incinerator.

CHAPTER TEN

10.1 b. Assume no combustion

n_1 (mol gas),T_1 (°C)
x_1 (mol CH$_4$ /mol)
x_2 (mol C$_2$H$_6$ /mol)
$1 - x_1 - x_2$ (mol C$_3$H$_8$ /mol)

n_2 (mol air), T_2 (°C)

n_3 (mol), 200°C
y_1 (mol CH$_4$ /mol)
y_2 (mol C$_2$H$_6$ /mol)
y_3 (mol C$_3$H$_8$ /mol)
$1 - y_1 - y_2 - y_3$ (mol air/mol)

Q (kJ)
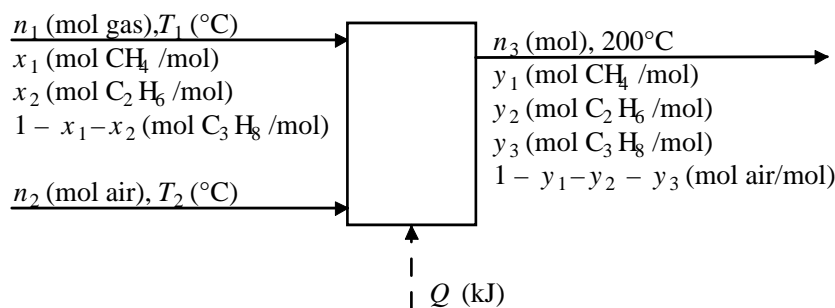
11 variables	$\left(n_1, n_2, n_3, x_1, x_2, y_1, y_2, y_3, T_1, T_2, Q\right)$
-5 relations	$\left(4 \text{ material balances and 1 energy balance}\right)$

6 degrees of freedom

A feasible set of design variables: $\{n_1, n_2, x_1, x_2, T_1, T_2\}$

Calculate n_3 from total mole balance, y_1, y_2, and y_3 from component balances, Q from energy balance.

An infeasible set: $\{n_1, n_2, n_3, x_1, x_2, T_1\}$

Specifying n_1 and n_2 determines n_3 (from a total mole balance)

c.

n_1 (mol gas),T_1, P
y_1 (mol C$_6$H$_{14}$/mol)
$1 - y_1$ (mol N$_2$/mol)

n_2 (mol gas), T_2, P
y_2 (mol C$_6$H$_{14}$/mol)
$1 - y_2$ (mol N$_2$/mol)

n_3 (mol C$_6$H$_{14}$(l)/mol), T_2, P

Q (kJ)
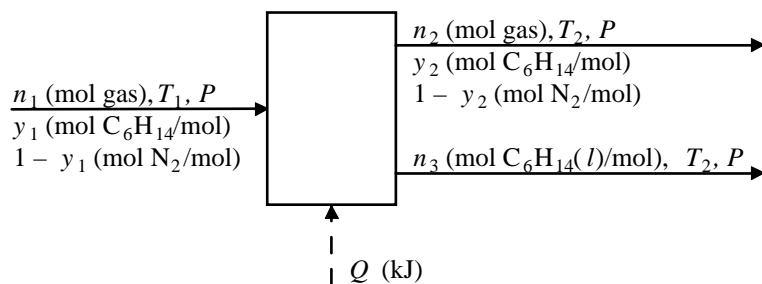
9 variables	$\left(n_1, n_2, n_3, y_1, y_2, T_1, T_2, Q, P\right)$
-4 relations	$\left(2 \text{ material, 1 energy, and 1 equilibrium: } y_2 P = P_{C_6H_{14}}^*\left(T_2\right)\right)$

5 degrees of freedom

A feasible set: $\{n, y_1, T_1, P, n_3\}$

Calculate n_2 from total balance, y_2 from C$_6$H$_{14}$ balance, T_2 from Raoult's law: [$y_2 P = P_{C_6H_4}^*\left(T_2\right)$], Q from energy balance

An infeasible set: $\{n_2, y_2, n_3, P, T_2\}$

Once y_2 and P are specified, T_2 is determined from Raoult's law

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>: $\{n_1, \ n_3, \ n_4, \ x_1, \ x_4, \ T\}$

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>: $\{n_1, \ n_2, \ n_3, \ x_1, \ x_2, \ x_3\}$

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>: $\{n_1, \ n_2, \ n_3, \ n_4, \ T, \ P\}$

Once n_1, n_2, and n_3 are specified, a total mole balance determines n_4.

10.3 $2BaSO_4(s) + 4C(s) \rightarrow 2BaS(s) + 4CO_2(g)$

a.
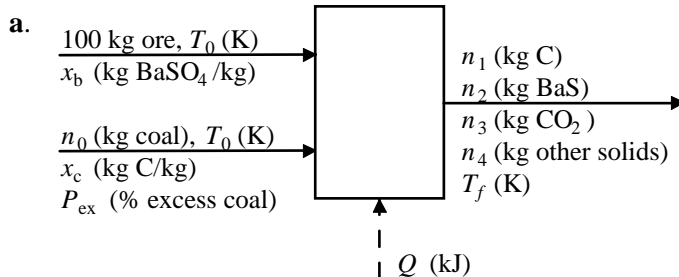
11 variables $(n_0, n_1, n_2, n_3, n_4, x_b, x_c, T_0, T_f, Q, P_{ex})$

-5 material balances$(C, \ BaS, \ CO_2, \ BaSO_4, \ \text{other solids})$

-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>: $\{x_b, \ x_c, \ T_0, \ T_f, \ P_{ex}\}$

Calculate n_0 from x_b, x_c, and P_{ex}; n_1 through n_4 from material balances, Q from energy balance

10.3 (cont'd)

   c. <u>Design set:</u> $\{x_B, x_c, T_0, n_2, Q\}$

      Specifying x_B determines $n_2 \Rightarrow$ impossible design set.

   d. <u>Design set:</u> $\{x_B, x_c, T_0, P_{ex}, Q\}$

      Calculate n_2 from x_B, n_3 from x_B

      n_0 from x_B, x_c and P_{ex}

      n_1 from C material balance, n_4 from total material balance

      T_f from energy balance (trial-and-error probably required)

10.4 $2C_2H_5OH + O_2 \rightarrow 2CH_3CHO + 2H_2O$

      $2CH_3COH + O_2 \rightarrow 2CH_3CHOOH$
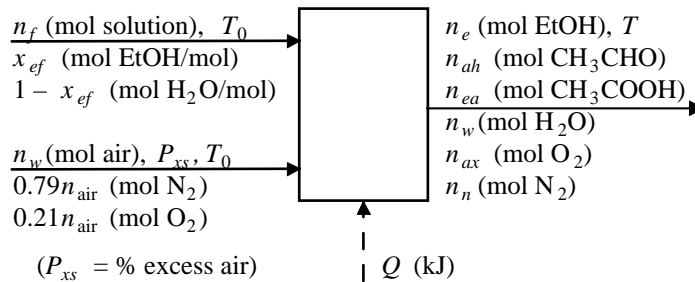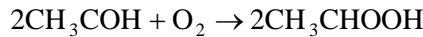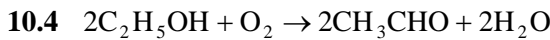
   a. 13 variables $\left(n_f, n_{aw}, n_e, n_{eh}, n_{ea}, n_w, n_{ex}, n_0, x_{ef}, T_0, T, Q, P_{xs}\right)$

      -6 material balances

      -1 energy balance

      -1 relation between P_{xs}, n_f, x_{ef}, and n_{air}

      $+2$ reactions

      ———————————

      $\underline{\underline{7}}$ degrees of freedom

   b. <u>Design set:</u> $\{n_f, x_{ef}, P_{xs}, n_e, n_{ah}, T_0, T\}$

      Calculate n_{air} from n_f, x_{ef} and P_{xs}; n_n from N_2 balance;

      n_{aa} and n_w from n_f, x_{ef}, n_e, n_{ah} and material balances;

      n_{ex} from O atomic balance; Q from energy balance

   c. <u>Design set:</u> $\{n_f, x_{ef}, T_0, n_{air}, Q, n_e, n_w\}$

      Calculate P_{xs} from n_f, x_{ef} and n_{air}; n's from material balances; T from energy

      balance (generally nonlinear in T)

   d. <u>Design set:</u> $\{n_{air}, n_n, ...\}$. Once n_{air} is specified, an N_2 balance fixes n_n

10.5

a.

n_1 (mol CO)
n_2 (mol H$_2$)

n_3 (mol C$_3$H$_6$) → reactor → n_4 (mol C$_3$H$_6$), n_5 (mol CO), n_6 (mol H$_2$), n_7 (mol C$_7$H$_8$O), n_8 (mol C$_4$H$_7$OH), n_9 (kg catalyst) → Flash tank → n_{11}(mol C$_3$H$_6$), n_{12}(mol CO), n_{13}(mol H$_2$), n_{14}(mol C$_7$H$_8$O), n_{15}(mol C$_4$H$_7$OH) → Separation → n_{16}(mol C$_3$H$_6$), n_{17}(mol CO), n_{18}(mol H$_2$)

n_{10} (kg catalyst)

n_{19}(mol C$_7$H$_8$O), n_{20}(mol C$_4$H$_7$OH)

n_{21}(mol H$_2$) → Hydrogenator → n_{22}(mol H$_2$)

n_{20}(mol C$_4$H$_7$OH)
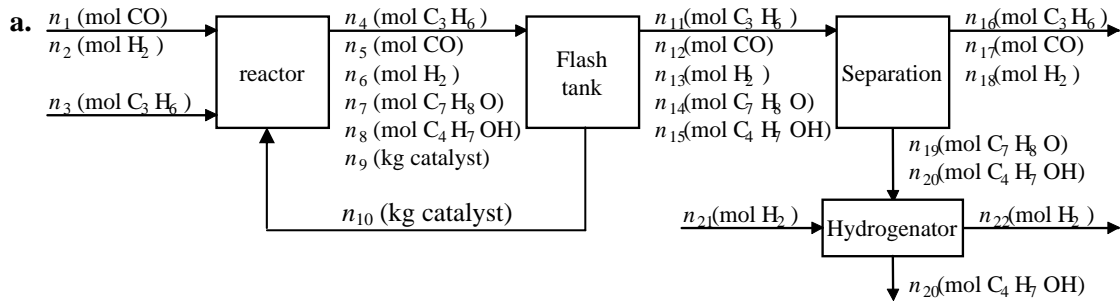
Reactor:	10 variables $(n_1 - n_{16})$
	-6 material balances
	$+2$ reactions
	$\underline{6}$ degrees of freedom

Flash Tank:	12 variables $(n_4 - n_{15})$
	-6 material balances
	$\underline{6}$ degrees of freedom

Separation:	10 variables $(n_{11} - n_{20})$
	-5 material balances
	$\underline{5}$ degrees of freedom

Hydrogenator:	5 variables $(n_{19} - n_{23})$
	-3 material balances
	$+1$ reaction
	$\underline{3}$ degrees of freedom

Process:	20 Local degrees of freedom
	-14 ties
	$\underline{6}$ overall degrees of freedom

The last answer is what one gets by observing that 14 variables were counted two times each in summing the local degrees of freedom. However, one <u>relation</u> also was counted twice: the catalyst material balances on the reactor and flash tank are each $n_9 = n_{10}$. We must therefore <u>add</u> one degree of freedom to compensate for having subtracted the same relation twice, to finally obtain 7 overall degrees of freedom (A student who gets this one has done very well indeed!)

b. The catalyst circulation rate is not included in any equations other than the catalyst balance ($n_9 = n_{10}$). It may therefore not be determined unless either n_9 or n_{10} is specified.

10.6 $n - C_4H_{10} \rightarrow i - C_4H_{10}$ $(n - B = i - B)$
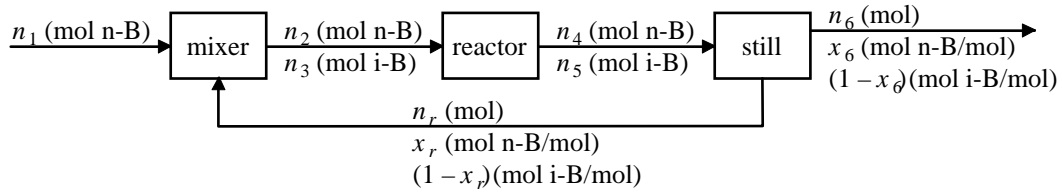
a. Mixer: 5 variables $(n_1, n_2, n_3, n_r, x_r)$

$\underline{-2 \text{ material balances}}$

$\underset{=}{3}$ degrees of freedom

Reactor: 4 variables (n_2, n_3, n_3, n_5)

-2 material balances

$\underline{+1 \text{ reaction}}$

$\underset{=}{3}$ degrees of freedom

Still: 6 variables $(n_4, n_5, n_6, x_6, n_r, x_r)$

$\underline{-2 \text{ material balances}}$

$\underset{=}{4}$ degrees of freedom

Process: 10 Local degrees of freedom

$\underline{- 6 \text{ ties}}$

$\underset{=}{4}$ overall degrees of freedom

b. $n_1 = 100 \text{ mol } n - C_4H_{10}$, $x_6 = 0.115 \text{ mol } n - C_4H_{10}/\text{mol}$, $x_r = 0.85 \text{ mol } n - C_4H_{10}/\text{mol}$

Overall C balance: $(100)(4) = n_6[(0.115)(4) + (0.885)(4)]\text{mol C} \Rightarrow \underset{=}{n_6} = 100 \text{ mol overhead}$

Overall conversion $= \dfrac{100 \text{ mol } n \text{-} B \text{ fed} - (100)(0.115)\text{mol } n \text{-} B \text{ unreacted}}{100 \text{ mol } n \text{-} B \text{ fed}} \times 100\% = \underline{\underline{88.5\%}}$

Mixer n-B balance: $100 + 0.85n_T = n_2$ (1)

35% S.P. conversion: $n_4 = 0.65n_2 \overset{(1)}{\Rightarrow} n_4 = 65 + 0.5525n_r$ (2)

Still $n - B$ balance:

$\quad n_4 = n_6x_6 + n_rx_r \overset{(2)}{\Rightarrow} 65 + 0.5525n_r = (0.115)(100) + 0.85n_r \Rightarrow n_r = 179.83 \text{ mol}$

Recycle ratio $= (179.83 \text{ mol recycle})/(100 \text{ mol fresh feed}) = \underline{\underline{1.79 \dfrac{\text{mol recycle}}{\text{mol fresh feed}}}}$

10.6 (cont'd)

c.

	$k = 1$	$k = 2$	$k = 3$
n_r	100.0	132.3	151.5
$n_2 = 100 + 0.85n_r$	185.0	212.5	228.8
$n_3 = n_r(1 - 0.85)$	15.0	19.85	22.73
$n_4 = 0.65n_2$	120.25	138.1	148.7
$n_5 = n_2 + n_3 - n_4$	79.75	94.21	102.8
$n_4 + n_5 = n_6 + n_r$ $\Rightarrow n_6 =$	67.69	80.76	88.55
$n_4 = 0.115n_6 + 0.85n_r$ $n_r =$	132.3	151.5	163.0

Error: $\dfrac{179.83 - 163.0}{179.83} \times 100 = \underline{\underline{9.3\% \text{ error}}}$

d. $w = \dfrac{151.5 - 132.3}{132.3 - 100.0} = 0.595$

$q = \dfrac{0.595}{0.595 - 1} = -1.470$

$n_r^{(3)} = -1.470(132.3) + (1 - (-1.470))(151.5) = 179.8$

Error: $\dfrac{179.8 - 179.8}{179.8} \times 100 = \underline{\underline{< 0.1\% \text{ error}}}$

e. Successive substitution, Iteration 32: $n_r = 179.8319 \rightarrow n_r = 179.8319$
Wegstein, Iteration 3: $n_r = 179.8319 \rightarrow n_r = 179.8319$

10.7
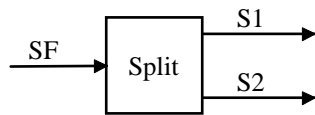
a.

	A	**B**	**C**	**D**
1	X1 =	0.6		
2		Molar flow rates (mol/h)		
3		SF	S1	S2
4	nA	85.5	51.3	34.2
5	nB	52.5	31.5	21.0
6	nC	12.0	7.2	4.8
7	nD	0.0	0.0	0.0
8	T(deg.C)	315	315	315

Formula in C4: = B1*B4
Formula in D4: = B4-C4

10.7 (cont'd)

b.
```
C      **CHAPTER 10 -- PROBLEM 7
       DIMENSION SF(8), S1(8), S2(8)
       FLOW = 150.
       N = 3
       SF(1) = 0.35*FLOW
       SF(2) = 0.57*FLOW
       SF(3) = 0.08*FLOW
       SF(8) = 315.
       X1 = 0.60
       CALL SPLIT (SF, S1, S2, X1, N)
       WRITE (6, 900)' STREAM 1', S1(1), S1(2), S1(3), S1(B)
       WRITE (6, 900)' STREAM 2', S2(1), S2(2), S2(3), S2(B)
900    FORMAT (A10, F8.2,' mols/h n-octane', /,
      *10X, F8.2,' mols/h iso-octane', /,
      *10X, F8.2,' mols/h inerts', /,
       10X, F8.2,' K')
       END

  C
  C    SUBROUTINE SPLIT
  C
       SUBROUTINE SPLIT (SF, S1, S2, X1, N)
       DIMENSION SF(8), S1(8), S2(8)
       D0 100 J = 1, N
       S1(J) = X1*SF(J)
100    S2(J) = SF(J) – S1(J)
       S1(8) = SF (8)
       S2(8) = SF (8)
       RETURN
       END
```

Program Output: Stream 1 31.50 mols/h n-octane

                                         51.30 mols/h iso-octane

                                         7.20 mols/h inerts

                                       315.00 K

                        Stream 2 21.00 mols/h n-octane

                                         34.20 mols/h iso-octane

                                        4.80 mols/h inerts

                                       315.00 K

10.8

a. Let Bz = benzene, Tl = toluene

$\underline{\text{Antoine equations:}}$ $p_{Bz}^* = 10^{6.89272 - 1211.033/(T+220.790)}$ (=1350.491)

$\qquad\qquad\qquad\qquad p_{Tl}^* = 10^{6.95805 - 1346.773/(T+219.693)}$ (=556.3212)

$\underline{\text{Raoult's law:}}$ $x_{Bz} = (P - p_{Tl}^*)/(p_{Bz}^* - p_{Tl}^*)$ (=0.307), $y_{Bz} = x_{Bz} p_{Bz}^*/P$ (= 0.518)

$\underline{\text{Total mole balance:}}$ $100 = n_v + n_l$
$\underline{\text{Benzene balance:}}$ $\quad 40 = y_{Bz} n_v + x_{Bz} n_l$ $\Bigg\}$

$$\Rightarrow n_v = \frac{40 - 100 x_{Bz}}{y_{Bz} - x_{Bz}}\ (=44.13),\ n_l = 100 - n_v\ (=55.87)$$

$\underline{\text{Fractional benzene vaporization}}:\ f_B = n_v y_{Bz}/40\ (=0.571)$

$\underline{\text{Fractional toluene vaporization}}:\ f_T = n_v(1 - y_{Bz})/60\ (=0.354)$

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

$\quad T_{bp} = 96.9°\text{C},\ T_{dp} = 103.2°\text{C}$

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
```

10.8 (cont'd)

```
901     FORMAT ('Heat Required', F7.2,' kW')
        END
  C

        SUBROUTINE FLASN2 (SF, SL, SV, T, P, Q)
        REAL NF, NL, NV
        DIMESION SF(3), SL(3), SV(3)
        COMMON A1, B1, C1, C2, CP1, CP2, NV1, NV2
  C     Vapor Pressure
        PV1 = 10.**(A1 – B1/(T – 273.15 + C1))
        PV2 = 10.**(A2 – B2/(T – 273.15 + C2))
  C     Product fractions
        XL1 = (P – PV2)/(PV1 – PVS)
        XV1 = XL1*PM/P
  C     Feed Variables
        NF = SF(1) + SF(2)
        XF1 = SF(1)/NF
  C     Product flows
        NL = NF*(XF1 – XV1)/(XL1 – XV1)
        NV = NF – NL
        SL(1) = XL1*NL
        SL(2) = NL – SL(1)
        SY(1) = XY1*NY
        SY(2) = NV – SY(1)
        SL(3) = T
        SV(3) = T
  C     Energy Balance
        Q = CP1*SF(1)*SF(1) + CP2*SF(2)
        Q = Q*(T – SF(3)) + (NV1*XV1 + HV2*(1 – XV1))*NV
        RETURN
        END
```

10.9 a. <u>Mass Balance:</u> $NF = NL + NV$ (1)

$$XF(I)* NF = XL(I)* NL + XV(I)* NV \quad I = 1,2\ldots n-1 \quad (2)$$

<u>Energy Balance:</u> $Q = (T - TF)* \sum\limits_{I=1}^{N} CP(I)*\big(XL(I)* NL + XV(I)* NV\big)$

$$+NV* \sum\limits_{I=1}^{N} HV(I)* XV(1) \quad (3)$$

where: $XL(N) = 1 - \sum\limits_{I=1}^{N-1} XL(I) \quad XV(N) = 1 - \sum\limits_{I=1}^{N-1} XV(I)$

<u>Raoult's law:</u> $P = \sum\limits_{I=1}^{N} XL(I)* PV(I) \quad (4)$

$$XV(I)* P = XL(I)* PV(I) \quad I = 1,2,\ldots N-1 \quad (5)$$

10-9

10.9 (cont'd)

where: $PV(I) = 10**\left(A(I) - B(I)\big/\left(C(I) + T\right)\right)$ $I = 1, 2, \ldots N - 1$

$3 + 3(N - 1) + N + 4$ variables $\left(NF, NL, NV, XF(I), XL(I), XV(I), PV(I), TF, T, P, Q\right)$

$-N$ mass balance

-1 energy balances

$-N$ equilibrium relations

$-N$ Antoine equations

$N + 3$ degrees of freedom

Design Set $\left\{TF, \ T, \ P, \ NF, \ XF(I)\right\}$

Eliminate NL form (2) using (1)
Eliminate XV(I) form (2) using (5)
Solve (2) for $XL(I)$

$XL(I) = XF(I)*NF\big/\left(NF + NV*\left(PV(I)\big/P - 1\right)\right)$ (6)

Sum (6) ove I to Eliminate XL(I)

$f(NV) = -1 + NF*\sum\limits_{I=1}^{N} XF(I)\big/\left(NF + NV*\left(PV(I)\big/P - 1\right)\right) = 0$ (7)

Use Newton's Method to solve (7) for NV
Calulate NL from (1)
XL(I) from (2)
XV(I) from (5)
Q from (3)

b.   C **CHAPTER 10 - - PROBLEM 9
          DIMENSION SF(8), SL(8), SV(8)
          DIMENSION A(7), B(7), C(7), CP(7), HV(7)
          COMMON A, B, C, CP, NV
          DATA A/6.85221, 6.87776, 6.402040, 0., 0., 0., 0./
          DATA B/1064.63, 1171.530, 1268.115, 0., 0., 0., 0./
          DATA C/232.00, 224.366, 216.900, 0., 0., 0., 0./
          DATA CP/0.188, 0.216, 0.213, 0., 0., 0., 0./
          DATA NV/25.77, 28.85, 31.69, 0., 0., 0., 0./
          FLOW = 1.0
          N*3
          SF(1) = 0.348*FLOW
          SF(2) = 0.300*FLOW
          SF(3) = 0.352*FLOW
          SF(4) = 363
          SL(4) = 338
          SV(4) = 338
          P*611
          CALL FLASHN (SF, SL, SV, N, P, Q)
          WRITE (6, 900)' Liquid Stream', (SL(I), I = 1, N + 1)
          WRITE (6, 900)' Vapor Stream', (SV(I), I = 1, N + 1)

10.9 (cont'd)

```
900       FORMAT (A15, F7.4,' mols/s n-pentane', /,
        *15X, F7.4,' mols/s n-hexane', /,
        *15X, F7.4,' mols/s n-hephane', /,
         15X, F7.2,' K')
          WRITE (6, 901) Q
901       FORMAT ('Heat Required', F7.2, 'kW')
          END
   C      SUBROUTINE FLASHIN (SF, SL, SV, N, P, Q)
          REAL NF, NL, NV, NVP
          DIMENSION SF(8), SL(8), SV(8)
          DIMENSION XF(7), XL(7), XV(7), PV(7)
          DIMENSION A(7), B(7), C(7), CP(7), HV(7)
          COMMON A, B, C, CP, HV
          TOL = 1,5 – 6
   C      Feed Variables
          NF = 0.
          DO 100 I = 1, N
100       NF = NF + SF(I)
          DO 200 I = 1, N
200       XF(I) = SF(I)/NF
          TF = SF (N + 1)
          T = SL (N + 1)
          TC = T – 273.15
   C      Vapor Pressures
          DO 300 I = 1, N
300       PV(I) = 10.**(A(I) – B(I)/(TC + C(I)))
   C      Find NV -- Initial Guess = NF/2
          NVP = NF/2
          DO 400 ITER = 1, 10
          NV = NVP
          F = –1.
          FP = 0.
          DO 500 I = 1, N
          PPM1 = PV(I)/P – 1.
          F = F + NF*XF(I)/(NF + NV*PPM1)
500       FP = FP – PPM1*XF(I)/(NF + NV*PPM1)**2.
          NVP = NV – F/FP
          IF (ABS((NVP – NV)/NVP).LT.TOL) GOTO 600
400       CONTINUE
          WRITE (6, 900)
900       FORMAT ('FLASHN did not converge on NV')
          STOP
   C      Other Variables
```

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
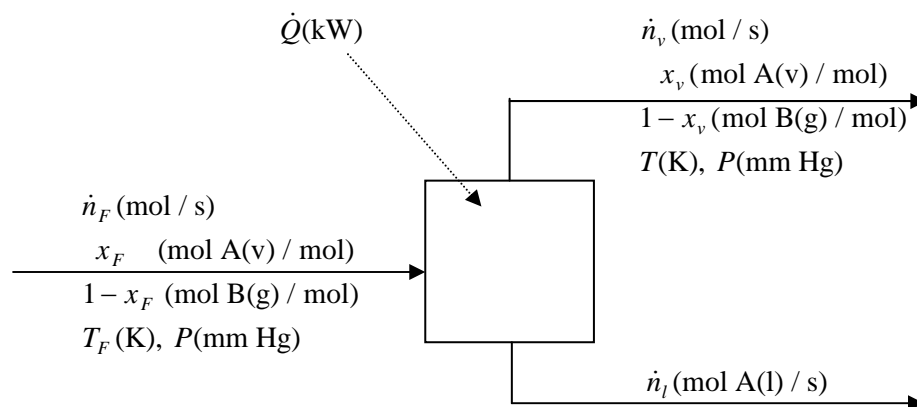
                                                     0.2000 mols/s n-hexane

                                                     0.1509 mols/s n-heptane

                                                     338.00 K

                 Heat Required   13.01 kW

10.10

a.

10.10 (cont'd)

10 variables $(\dot{n}_F, x_F, T_F, P, \dot{n}_v, x_v, T, \dot{n}_l, p_A^*, \dot{Q})$
–2 material balances
–1 Antoine equation
–1 Raoult's law
<u>–1 energy balance</u>
5 degrees of freedom

b.

<u>References:</u> A(l), B(g) at 25°C

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
A(l)	—	—	$\dot{n}_l$	$\hat{H}_3$
A(v)	$\dot{n}_F x_F$	$\hat{H}_1$	$\dot{n}_v x_v$	$\hat{H}_4$
B(g)	$\dot{n}_F(1-x_F)$	$\hat{H}_2$	$\dot{n}_v(1-x_v)$	$\hat{H}_5$

Given $\dot{n}_F$ and x_F (or $\dot{n}_{AF}$ and $\dot{n}_{BF}$), T_F, P, y_c (fractional condensation),

<u>Fractional condensation</u> $\Rightarrow \dot{n}_l = y_c \dot{n}_F x_F$

<u>Mole balance</u> $\Rightarrow \dot{n}_v = \dot{n}_F - \dot{n}_l$

<u>A balance</u> $\Rightarrow x_v = (\dot{n}_F x_F - \dot{n}_l)/\dot{n}_v$

<u>Raoult's law</u> $\Rightarrow p_A^* = x_v P$

<u>Antoine's equation</u> $\Rightarrow T = \dfrac{B}{A - \log_{10} p_A^*} - C$

<u>Enthalpies:</u> $\hat{H}_1 = \Delta \hat{H}_v + C_{pv}(T_F - 25), \hat{H}_2 = C_{pg}(T_F - 25), \hat{H}_3 = C_{pl}(T - 25),$

$\hat{H}_4 = \Delta \hat{H}_v + C_{pv}(T - 25), \hat{H}_5 = C_{pg}(T - 25)$

<u>Energy balance:</u> $Q = \sum \dot{n}_{out} \hat{H}_{out} - \sum \dot{n}_{in} \hat{H}_{in}$

c.

nAF	nBF	nF	xF	TF	P	yc	nL
0.704	0.296	1.00	0.704	333	760	0.90	0.6336
nV	xV	A	B	C	pA*	T	Cpl
0.3664	0.1921	7.87863	1473.11	230	146.0	300.8	0.078
Cpv	Cpg	H1	H2	H3	H4	H5	Q
0.050	0.030	37.02	1.05	0.2183	35.41	0.0839	–23.7

Greater fractional methanol condensation (y_c) $\Rightarrow$ lower temperature (T). ($y_c = 0.10 \Rightarrow$ $T = 328$°C.)

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
```

10.11 $\eta_1 A_1 + \eta_2 A_2 + \eta_3 A_3 + \dots \eta_m A_m = 0$

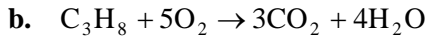**a.** Extent of reaction equations:

$$\xi = -[SF(IX)* X]/NU(IX)$$

$$SP(I) = SF(I) + NU(I)* \xi \quad I = 1,2,\dots N$$

Energy Balance: Reference states are molecular species at 298K.

$$TF = SF(N+1) \quad TP = SP(N+1)$$

$$\Delta\hat{H}_r = \sum_{I=1}^{N} HF(I)* NU(I)$$

$$Q = \xi * \Delta\hat{H}_r + (TP - 298)* \sum_{I=1}^{N} SP(I)* CP(I) - (TF - 298)* \sum_{I=1}^{N} SF(I)* CP(I)$$

b. $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

Subscripts: $1 = C_3H_8$, $2 = O_2$, $3 = N_2$, $4 = CO_2$, $5 = H_2O$

$$\frac{270 \text{ m}^3}{\text{h}} \left| \frac{1 \text{ atm}}{273K} \right| \frac{\text{mol} \cdot K}{0.08206 \text{ liter} \cdot \text{atm}} \left| \frac{1000 \text{ liter}}{\text{m}^3} \right| \frac{\text{h}}{3600 \text{ s}} = 3.348 \text{ mol } C_3H_8/s \text{ [=SF(1)]}$$

$$\frac{3.348 \text{ mol } C_3H_8}{\text{sec}} \left| \frac{1.2(5 \text{ mol } O_2)}{\text{mol } C_3H_8} \right. = 20.09 \text{ mol } O_2/s \text{ [= SF(2)]} \Rightarrow 75.54 \text{ mol } N_2/s \text{ [= SF(3)]}$$

$X_{C_3H_8} = 0.90 \Rightarrow \dot{n}_{C_3H_8} = 0.10(3.348) = 0.3348 \text{ mol } C_3H_8 / s$ in product gas [= SP(1)]

$\xi = -[SF(IX)* X]/NU(IX) = -(3.348 \text{ mol/s})(0.90)/(-1) = 3.013 \text{ mol/s}$

		1-C3H8	2-O2	3-N2	4-CO2	5-H2O(v)
Nu		-1	-5	0	3	4
nin (SF)		3.348	20.09	75.54		
X	0.90					
Xi	3.01					
nout (SP)		0.3348	5.024	75.54	9.0396	12.0528
Cp		0.1431	0.033	0.0308	0.0495	0.0375
Tin	423					
Hin		17.9	4.1	3.9	6.2	4.7
Tout	1050					
Hout		107.6	24.8	23.2	37.2	28.2
HF		-103.8	0	0	-393.5	-241.83
DHr	-2044					
Q	-4006					

For the given conditions, $\underline{Q = -4006 \text{ kJ} / \text{s}}$. As T_{stack} increases, more heat goes into the stack gas so less is transferred out of the reactor: that is, Q becomes <u>less negative</u>.

10.11 (cont'd)

```
C  **CHAPTER 10 PROBLEM 11
      DIMENSION SF(8), SP(8), CP(7), HF(7)
      REAL NU(7)
      DATA NU/–1., –5, 0., 3., 4., 0., 0./
      DATA CP/0.1431, 0.0330, 0.0308, 0.0495, 0.0375, 0., 0./
      DATA HF/–103.8, 0., 0., –393.5, –241.83, 0., 0./
      COMMON CP, HF
      SF(1) = 3.348
      SF(2) = 20.09
      SF(3) = 75.54
      SF(4) = 0.
      SF(5) = 0.
      SF(6) = 423.
      SP(6) = 1050.
      IX = 1
      X = 0.90
      N = 5
      CALL REACTS (SF, SP, NU, N, X, IX, Q)
      WRITE (6, 900) (SP(I), I = 1, N + 1), Q
900   FORMAT ('Product Stream', F7.3, ' mols/s propane', /,
     *15X, F7.3,' mols/s oxygen', /,
     *15X, F7.3,' mols/s nitrogen', /,
     *15X, F7.3,' mols/s carbon dioxide', /,
     *15X, F7.3,' mols/s water', /,
     *15X, F7.2,'K', /,
      Heat required', F8.2, 'kW')
      END
C     SUBROUTINE REACTS (SF, SP, NU, N, X, IX, Q)
      DIMENSION SF(8), SP(8), CP(7), HF(7)
      REAL NU(7)
      COMMON CP, HF
C     Extent of Reaction
      EXT = –SF(IX)*X/NU(IX)
C     Solve Material Balances
      DO 100 I = 1, N
100   SP(I) = SF(I) + EXT = NU(I)
C     Heat of Reaction
      HR = 0
      DO 200 I = 1, N
200   HR = HR + NF(I)*NU(I)
C     Product Enthalpy (ref * inlet)
      HP = 0.
      DO 300 I = 1, N

300   HP = HP + SP(I)*CP(I)
      HP = HP + (SP(N + 1) – SF (N + 1))
      Q = EXT * HR + HP
      RETURN
      END
```

10.12 a. Extent of reaction equations:

$$\xi = -SF(IX)* X/NU(IX)$$

$$SP(I) = SF(I) + NU(I)* \xi \quad I = 1, N$$

<u>Energy Balance</u>: Reference states are molecular species at feed stream temperature.

$$Q = \Delta H = \xi \Delta \hat{H}_r + \sum n_{out} \hat{H}_{out} = 0 \Rightarrow 0 = \xi \sum_{i=1}^{N} NU(I)HF(I) + \sum_{I=1}^{N} SP(I) \int_{T_{feed}}^{T} CP(I) dT$$

$$\Downarrow \quad CP(I) = ACP(I) + BCP(I)*T + CCP(I)*T^2 + DCP(I)*T^3$$

$$f(T) = \xi * \sum_{I=1}^{N} NU(I) * HF(I) + AP*(T - T_{feed}) + \frac{BP}{2}*(T^2 - T_{feed}^2)$$

$$+ \frac{CP}{3}*(T^3 - T_{feed}^3) + \frac{DP}{4}*(T^4 - T_{feed}^4) = 0$$

where: $AP = \sum_{I=1}^{N} SP(I)* ACP(I)$, and similarly for BP, CP, & DP

Use goalseek to solve $f(T) = 0$ for T [= SP(N+1)]

b. $2CO + O_2 \rightarrow 2CO_2$

<u>Temporary basis</u>: 2 mol CO fed

$$\frac{2 \text{ mol CO}}{} \left| \frac{1.25(1 \text{ mol O}_2)}{2 \text{ mol CO}} = 1.25 \text{ mol O}_2 \Rightarrow 4.70 \text{ mol N}_2 \right.$$

$$\Rightarrow \text{Total moles fed} = (2.00 + 1.25 + 4.70) \text{ mol} = 7.95 \text{ mol}$$

<u>Scale to given basis</u>:

$$\frac{(23.0 \ \frac{\text{kmol}}{\text{h}})(\frac{1 \text{ h}}{3600 \text{ s}})(\frac{10^3 \text{ mol}}{1 \text{ kmol}})}{7.95 \text{ mol}} = 0.8036 \Rightarrow$$

$$SF(1) = 1.607 \text{ mol CO fed}/s$$
$$SF(2) = 1.004 \text{ mol O}_2 \text{ fed}/s$$
$$SF(3) = 3.777 \text{ mol N}_2 \text{ fed}/s$$

Solution to Problem 10.12

		1-CO	2-O2	3-N2	4-CO2
Nu		-2	-1	0	2
nin (SF)		1.607	1.004	3.777	0
X	0.45				
Xi	0.36				
nout (SP)		0.88385	0.642425	3.777	0.72315
ACP		0.02895	0.0291	0.029	0.03611
BCP		4.11E-06	1.16E-05	2.20E-06	4.23E-05
CCP		3.55E-09	-6.08E-09	5.72E-09	-2.89E-08
DCP		-2.22E-12	1.31E-12	-2.87E-12	7.46E-12
AP	0.1799				
BP	5.00E-05				
CP	-2.90E-11				
DP	-6.57E-12				
Tfeed	650				
DHF		-110.52	0	0	-393.5
DHr	-566				
T	1560				
f(T)	-4.7E-08				

The adiabatic reaction temperature is $\underline{\underline{1560^\circ C}}$.

As X increases, T increases. (The reaction is exothermic, so more reaction means more heat released.)

d.

```
C **CHAPTER 10 -- PROBLEM 12
      DIMENSION SF(8), SP(B), NU(7), ACP(7), BCP(7), CCP(7), DCP(7), HF(7)
      COMMON ACP, BCP, CCP, DCP, NF
      DATA NU / –2., –1., 0., 2., 0., 0., 0./
      DATA ACP/ 28.95E-3, 29.10E-3, 29.00E-3, 36.11E-3, 0., 0., 0./
      DATA BCP/ 0.4110E-5, 1.158E-5, 0.2199E-5, 4.233E-6, 0., 0., 0./
      DATA CCP/ 0.3548E-B, –0.6076E-8, 0.5723E-8, –2.887E-8, 0., 0., 0./
      DATA DCP/ –2.220 E-12, 1.311E-12, –2.871E-12, 7.464E-12, 0., 0., 0./
      DATA HF / –110.52, 0., 0., –393.5, 0., 0., 0./
      SF(1) = 1.607
      SF(2) = 1.004
      SF(3) = 3.777
      SF(4) = 0.
      SF(5) = 650.
      IX = 1
      X = 0.45
      N = 4
      CALL REACTAD (SF, SP, NU, N, X, IX)
      WRITE (6, 900) (SP(I), I = 1, N + 1)
```

```
900      FORMAT ('Product Stream', F7.3, ' mols/s carbon monoxide', /,
         *15X, F7.3, 'mols/s oxygen', /.
         *
         *15X, F7.3, 'mols/s nitrogen', /.
         *15X, F7.3, 'mols/s carbon dioxide', /,
          15X, F7.2, 'C')
          END
   C      SUBROUTINE REACTAD (SF, SP, NU, N, X, IX)
          DIMENSION SF(8), SP(8), NU(7), ACP(7), BCP(7), CCP(7), DCP(7), HF(7)
          COMMON ACP, BCP, CCP, DCP, NF
          TOL = 1.E-6
   C      Extent of Reaction
          EXT = –SF(IX)*X/NU(IX)
   C      Solve Material Balances
          DO 100 I = 1, N
100       SP(I) = SF(I) + EXT*NU(I)
   C      Heat of Reaction
          HR = 0
          DO 200 I = 1, N
200       HR = HR + HF(I) * NU(I)
          HR = HR * EXT
   C      Product Heat Capacity
          AP = 0.
          BP = 0.
          CP = 0.
          DP = 0.
          DO 300 I = 1, N

          AP = AP + SP(I)*ACP(I)
          BP = BP + BP(I)*BCP(I)
          CP = CP + SP(I)*CCP(I)
300       DP = DP + SP(I)*DCP(I)
   C      Find T
          TIN = SF (N + 1)
          TP = TIN
          D0 400 ITER = 1, 10
          T = TP
          F = HR
          FP = 0.
          F = F +T*(AP + T*(BP/2. + T*(CP/3. + T*DP/4.)))
         *–TIN*(AP + TIN*(BP/2. + TIN*(CP/3. + TIN*DP/4.)))
          FP = FP + AP + T *(BP + T*(CP + T*DP))
          TP = T – F/FP
          IF(ABS((TP – T)/T).LT.TOL) GOTO 500
400       CONTINUE
          WRITE (6, 900)
900       FORMAT ('REACTED did not converge')
          STOP
```

10.12 (cont'd)

```
500   SP(N + 1) = T
      RETURN
      END
```

Program Output:
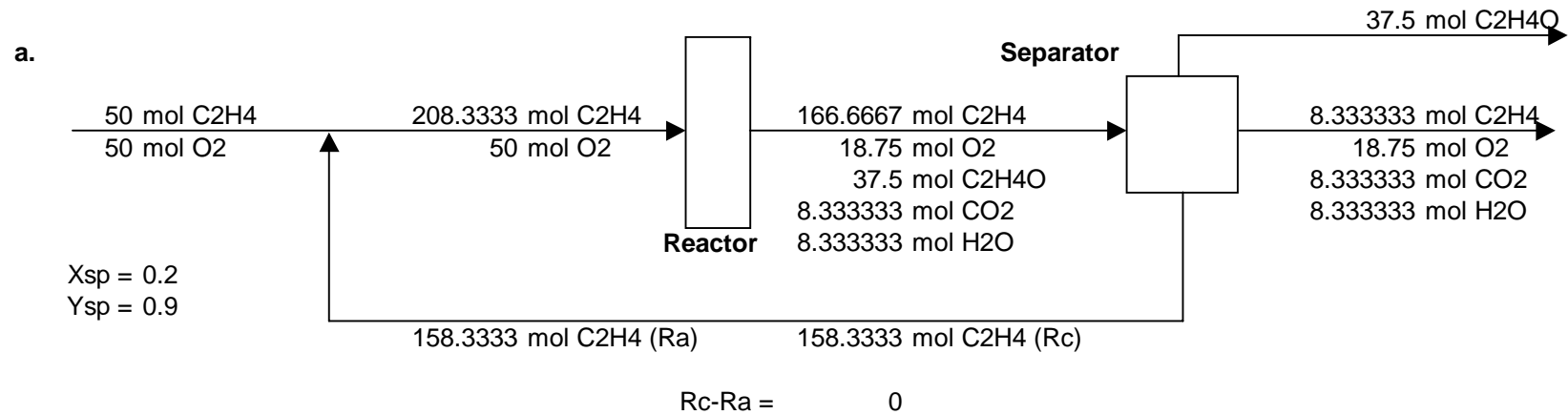0.884 mol/s carbon monoxide
0.642 mol/s oxygen
3.777 mol/s nitrogen
0.723 mol/s carbon dioxide
$T = 1560.43$ C

10.13

a.

37.5 mol C2H4O

Separator

50 mol C2H4   208.3333 mol C2H4   166.6667 mol C2H4   8.333333 mol C2H4
50 mol O2   50 mol O2   18.75 mol O2   18.75 mol O2
                                                                   37.5 mol C2H4O   8.333333 mol CO2
                                                                   8.333333 mol CO2   8.333333 mol H2O
                                                      Reactor 8.333333 mol H2O

Xsp = 0.2
Ysp = 0.9

158.3333 mol C2H4 (Ra)   158.3333 mol C2H4 (Rc)

Rc-Ra =   0

Procedure: Assume Ra, perform balances on mixing point, then reactor, then separator. Rc is recalculated recycle rate.
              Use goalseek to find the value of Ra that drives (Rc-Ra) to zero.

b.

Xsp	Ysp	Yo	no
0.2	0.72	0.6	158.33
0.2	1	0.833	158.33
0.3	0.75333	0.674	99.25
0.3	1	0.896	99.25

The second reaction consumes six times more oxygen per mole of ethylene consumed. The lower the single pass ethylene oxide yield, the more oxygen is consumed in the second reaction. At a certain yield for a specified ethylene conversion, all the oxygen in the feed is consumed. A yield lower than this value would be physically impossible.

10.14   C   **CHAPTER 10 -- PROBLEM 14

```
      DIMENSION XA(3), XC(3)
      N = 2
      EPS = 0.001
      KMAX = 20
      IPR = 1
      XA(1) = 2.0
      XA(2) = 2.0
      CALL CONVG (XA, XC, N, KMAX, EPS, IPR)
      END
  C   SUBROUTINE FUNCGEN(N, XA, XC)
      DIMENSION XA(3), XC(3)
      XC(1) = 0.5*(3. – XA(2) + (XA(1) + XA(2))**0.5
      XC(2) = 4. – 5./(XA(1) + XA(2))
      RETURN
      END
  C   SUBROUTINE CONVG (XA, XC, N, KMAX, EPS, IPR)
      DIMENSION XA(3), XC(3), XAH(3), XCM(3)
      K = 1
      CALL FUNCGEN (N, XA, XC)
      IF (IPR.EQ.1) CALL IPRNT (K, XA, XC, N)
      DO 100 I = 1, N
      XAM(I) = XA(I)
      XA(I) = XC(I)
100   XCM(I) = XC(I)
110   K = K + 1
      CALL FUNCGEN (N, XA, XC)
      IF (IPR.EQ.1) CALL IPRNT (K, XA, XC, N)
      D0 200 I = 1, N
      IF (ABS ((XA(I) - XC(I))/XC(I)).GE.EPS) GOTO 300
200   CONTINUE
  C   Convergence
      RETURN
300   IF(K.EQ.KMAX) GOTO 500
      DO 400 I = 1, N
      W = (XC(I) – XCM(I))/(XA(I) – XAM(I))
      Q = W/(W – 1.)
      IF (Q.GT.0.5) Q = 0.5
      IF (Q.LT.–5) Q = –5.
      XCM(I) = XC(I)
      XAM(I) = XA(I)
400   XA(I) = Q = XAM(I) + (1. – Q)*XCM(I)
      GOTO 110
500   WRITE (6, 900)
900   FORMAT (' CONVG did not converge')
      STOP
      END
```

10.14 (cont'd)

```
C      SUBROUTINE IPRNT (K, XA, XC, N)
       DIMENSION XA(3), XC(3)
       IF (K.EQ.1) WRITE (6, 400)
       IF (K.NE.1) WRITE (6, *)
       DO 100 I = 1, N
100    WRITE (6, 901) K, I, XA(I), XC(I)
       RETURN
900    FORMAT (' K Var Assumed Calculated')
901    FORMAT (I4, I4, 2E15.6)
       END
```

Program Output:	K	Var	Assumed	Calculated
	1	1	0.200000E + 01	0.150000E + 01
	1	2	0.200000E + 01	0.275000E + 01
	2	1	0.150000E + 01	0.115578E + 01
	2	2	0.275000E + 01	0.282353E + 01
	3	1	0.395135E + 00	0.482384E + 00
	3	2	0.283152E + 01	0.245041E + 01
	⋮			
	8	1	0.113575E + 01	0.113289E + 01
	8	2	0.269023E + 01	0.269315E + 01
	4	1	0.113199E + 01	0.113180E + 01
	9	2	0.269186E + 01	0.269241E + 01

CHAPTER ELEVEN

11.1 **a.** The peroxide mass fraction in the effluent liquid equals that in the tank contents, which is:

$$x_p = \frac{M_p}{M}$$

Therefore, the leakage rate of hydrogen peroxide is $\underline{\underline{\dot{m}_1 M_p / M}}$

b. <u>Balance on mass:</u> Accumulation = input – output

$$\Downarrow$$

$$\underline{\frac{dM}{dt} = \dot{m}_0 - \dot{m}_1}$$

$$\underline{\underline{t = 0,\ M = M_0}}\ \text{(mass in tank when leakage begins)}$$

<u>Balance on H_2O_2:</u>   Accumulation = input – output – consumption

$$\Downarrow$$

$$\underline{\underline{\frac{dM_p}{dt} = \dot{m}_0 x_{p0} - \dot{m}_1 \left(\frac{M_p}{M}\right) - kM_p}}$$

$$\underline{\underline{t = 0,\ M_p = M_{p0}}}$$

11.2 **a.** <u>Balance on H_3PO_4:</u> Accumulation = input
Density of H_3PO_4: $\rho = 1.834\ \text{g / ml}$.
Molecular weight of H_3PO_4: $M = 98.00\ \text{g / mol}$.

$$\text{Accumulation} = \frac{dn_p}{dt}\ (\text{kmol / min})$$

$$\text{Input} = \frac{20.0\ \text{L}}{\text{min}}\left|\frac{1000\ \text{ml}}{\text{L}}\right|\frac{1.834\ \text{g}}{\text{ml}}\left|\frac{\text{mol}}{98.00\ \text{g}}\right|\frac{1\ \text{kmol}}{1000\ \text{mol}} = 0.3743\ \text{kmol / min}$$

$$\Downarrow$$

$$\underline{\frac{dn_p}{dt} = 0.3743}$$

$$\underline{\underline{t = 0,\ n_{p0} = 150 \times 0.05 = 7.5\ \text{kmol}}}$$

b. $\displaystyle\int_{7.5}^{n_p} dn_p = \int_0^t 0.3743\ dt \Rightarrow \underline{\underline{n_p = 7.5 + 0.3743t}}$ (kmol H_3PO_4 in tank)

$$\underline{\underline{x_p = \frac{n_p}{n} = \frac{n_p}{n_0 + n_p - n_{p0}} = \frac{7.5 + 0.3743t}{150 + 0.3743t}}}\quad \frac{\text{kmol } H_3PO_4}{\text{kmol}}$$

c. $0.15 = \dfrac{7.5 + 0.3743t}{150 + 0.3743t} \Rightarrow t = \underline{\underline{47.1\ \text{min}}}$

11-1

11.3 a. $\dot{m}_w = a + bt$ $(t = 0, \dot{m}_w = 750)$ & $(t = 5, \dot{m}_w = 1000) \Rightarrow \underline{\underline{\dot{m}_w(kg/h) = 750 + 50t(h)}}$

Balance on methanol: Accumulation = Input – Output
$M = kg\ CH_3OH$ in tank

$$\frac{dM}{dt} = \dot{m}_f - \dot{m}_w = 1200\ kg/h - (750 + 50t)\ kg/h$$

$$\Downarrow$$

$$\frac{dM}{dt} = 450 - 50t(kg/h)$$

$$\underline{\underline{t = 0,\ M = 750\ kg}}$$

b. $\displaystyle\int_{750}^{M} dM = \int_{0}^{t} (450 - 50t)dt$

$$\Downarrow$$

$$M - 750 = 450t - 25t^2$$

$$\Downarrow$$

$$\underline{\underline{M = 750 + 450t - 25t^2}}$$

Check the solution in two ways:
(1) $t = 0$, $M = 750\ kg \Rightarrow$ satisfies the initial condition;

(2) $\dfrac{dM}{dt} = 450 - 50t$ $\Rightarrow$ reproduces the mass balance.

c. $\dfrac{dM}{dt} = 0 \Rightarrow t = 450/50 = \underline{\underline{9\ h}} \Rightarrow M = 750 + 450(9) - 25(9)^2 = \underline{\underline{2775\ kg}}$ (maximum)

$$M = 0 = 750 + 450t - 25t^2$$

$$t = \frac{-450 \pm \sqrt{(450)^2 + 4(25)(750)}}{2(-25)} \Rightarrow t = \cancel{-1.54\ h},\ \underline{\underline{19.54\ h}}$$

d. $\dfrac{3.40\ m^3}{} \left| \dfrac{10^3\ liter}{1\ m^3} \right| \dfrac{0.792\ kg}{1\ liter} = 2693\ kg$ (capacity of tank)
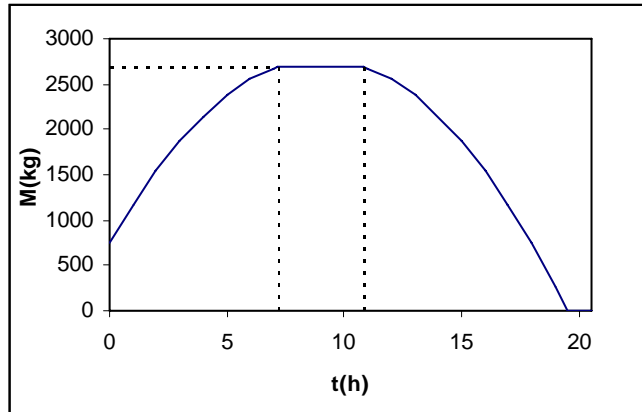
$$M = 2693 = 750 + 450t - 25t^2$$

$$t = \frac{-450 \pm \sqrt{(450)^2 + 4(25)(750 - 2693)}}{2(-25)} \Rightarrow t = 7.19\ h, 10.81\ h$$

Expressions for M(t) are:

$$M(t) = \begin{cases} 750 + 450t - 25t^2 & (0 \le t \le 7.19\ \text{and}\ 10.81 \le t \le 19.54) \text{ (tank is filling or draining)} \\ 2693 & (7.19 \le t \le 10.81) \qquad\qquad \text{(tank is overflowing)} \\ 0 & (19.54 \le t \le 20.54) \qquad\qquad \text{(tank is empty, draining} \end{cases}$$

as fast as methanol is fed to it)

11.3 (cont'd)

11.4 a. <u>Air initially in tank:</u> $N_0 = \dfrac{10.0 \text{ ft}^3 \;\Big|\; 492° \text{R} \;\Big|\; 1 \text{ lb - mole}}{\Big|\; 532° \text{R} \;\Big|\; 359 \text{ ft}^3 (\text{STP})} = 0.0258 \text{ lb - mole}$

<u>Air in tank after 15 s:</u>

$$\frac{P_f V}{P_0 V} = \frac{N_f RT}{N_0 RT} \Rightarrow N_f = N_0 \frac{P_f}{P_0} = \frac{0.0258 \text{ lb - mole} \;\Big|\; 114.7 \text{ psia}}{\Big|\; 14.7 \text{ psia}} = 0.2013 \text{ lb - mole}$$

<u>Rate of addition:</u> $\dot{n} = \dfrac{(0.2013 - 0.0258) \text{ lb - mole air}}{15 \text{ s}} = \underline{\underline{0.0117 \text{ lb - mole air/s}}}$

b. <u>Balance on air in tank:</u> Accumulation = input

$$\underline{\frac{dN}{dt} = 0.0117(\text{lb - moles/s})}; \quad t = 0, \; \underline{\underline{N = 0.0258 \text{ lb - mole}}}$$

c. <u>Integrate balance:</u> $\displaystyle\int_{0.0258}^{N} dN = \int_{0}^{t} \dot{n}\, dt \Rightarrow \underline{\underline{N = 0.0258 + 0.0117t}} \;(\text{lb - mole air})$

<u>Check the solution in two ways:</u>

(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. $t = 120 \text{ s} \Rightarrow N = 0.0258 + (0.0117)(120) = 1.43$ lb - moles air

$\underline{O_2 \text{ in tank}} = 0.21(1.43) = \underline{\underline{0.30 \text{ lb - mole } O_2}}$

11.5 **a.** Since the temperature and pressure of the gas are constant, a volume balance on the gas is equivalent to a mole balance (conversion factors cancel).

Accumulation = Input – Output

$$\frac{dV}{dt} = \frac{540 \text{ m}^3}{\text{h}} \left| \frac{1\text{ h}}{60 \text{ min}} \right. - \dot{V}_w \left(\text{m}^3/\text{min}\right)$$

$t = 0, V = 3.00 \times 10^3 \text{ m}^3 (t = 0 \text{ corresponds to 8:00 AM})$

$$\int_{3.00\times10^3}^{V} dV = \int_0^t (9.00 - \dot{V}_w) dt \Rightarrow \underline{\underline{V(\text{m}^3) = 3.00 \times 10^3 + 9.00t - \int_0^t \dot{V}_w dt}} \quad t \text{ in minutes}$$

b. Let $\dot{V}_{wi}$ = tabulated value of $\dot{V}_w$ at $t = 10(i-1)$ $\quad i = 1, 2, \ldots, 25$

$$\int_0^{240} \dot{V}_w dt \cong \frac{10}{3}\left[\dot{V}_{w1} + \dot{V}_{w25} + 4\sum_{i=2,4,\ldots}^{24}\dot{V}_{wi} + 2\sum_{i=3,5,\ldots}^{24}\dot{V}_{wi}\right] = \frac{10}{3}\left[11.4 + 9.8 + 4(124.6) + 2(113.4)\right]$$

$$= 2488 \text{ m}^3$$

$$V = 3.00 \times 10^3 + 9.00(240) - 2488 = \underline{\underline{2672 \text{ m}^3}}$$

c. Measure the height of the float roof (proportional to volume).
The feed rate decreased, or the withdrawal rate increased between data points, or the storage tank has a leak, or Simpson's rule introduced an error.

d.
```
        REAL VW(25), T, V, V0, H
        INTEGER I
        DATA V0, H/3.0E3, 10./
        READ (5, *) (VW(I), I = 1, 25)
        V= V0
        T=0.
        WRITE (6, 1)
        WRITE (6, 2) T, V
        DO 10 I = 2, 25
            T = H * (I – 1)
            V = V + 9.00 * H – 0.5 * H * (VW(I – 1) + VW(I))
            WRITE (6, 2) T, V
   10   CONTINUE
    1   FORMAT ('TIME (MIN)  VOLUME (CUBIC METERS)')
    2   FORMAT (F8.2, 7X, F6.0)
        END
$DATA
11.4   11.9    12.1    11.8    11.5    11.3
⋮
```

Results:

TIME (MIN)	VOLUME (CUBIC METERS)
0.00	3000.
10.00	2974.
20.00	2944.
⋮	⋮
230.00	2683.
240.00	2674.

$$V_{\text{trapezoid}} = 2674 \text{ m}^3 ; \quad V_{\text{Simpson}} = 2672 \text{ m}^3 ; \quad \frac{2674 - 2672}{2672} \times 100\% = \underline{\underline{0.07\%}}$$

Simpson's rule is more accurate.

11.6 **a.** $\dot{v}_{out}(\text{L/min}) = kV(\text{L}) \underset{\substack{V=300 \\ \dot{v}_{out}=60}}{\Longrightarrow} \dot{v}_{out} = 0.200V$ $\dot{v}_{out} = 20.0 \ \text{L/min} \Rightarrow \underline{\underline{V_s = 100 \ \text{L}}}$

b. Balance on water: Accumulation = input – output (L/min).
(Balance volume directly since density is constant)

$$\frac{dV}{dt} = 20.0 - 0.200V$$
$$\overline{\overline{t = 0, V = 300}}$$

c. $\dfrac{dV}{dt} = 0 = 200 - 0.200V_s \Rightarrow \underline{\underline{V_s = 100 \ \text{L}}}$

The plot of V vs. t begins at (t=0, V=300). When t=0, the slope (dV/dt) is
$20.0 - 0.200(300) = -40.0$. As t increases, V decreases. $\Rightarrow dV/dt = 20.0 - 0.200V$
becomes less negative, approaches zero as $t \rightarrow \infty$. The curve is therefore <u>concave up.</u>
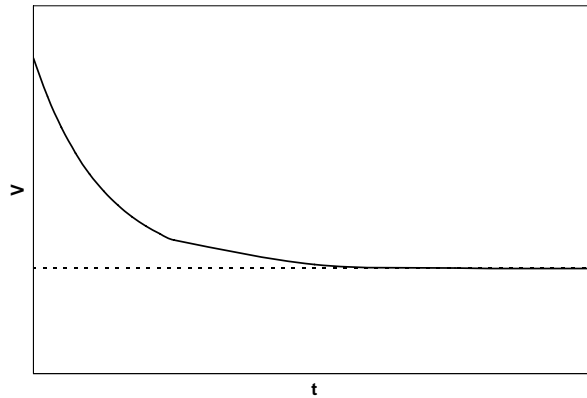
d. $\displaystyle\int_{300}^{V} \frac{dV}{20.0 - 0.200V} = \int_0^t dt$

$$\Rightarrow -\frac{1}{0.200}\ln\left(\frac{20.0 - 0.200V}{-40.0}\right) = t$$

$$\Rightarrow -0.5 + 0.005V = \exp(-0.200t) \Rightarrow \underline{\underline{V = 100.0 + 200.0\exp(-0.200t)}}$$

$$V = 1.01(100) = 101 \ \text{L} \ (1\% \text{ from steady state}) \Rightarrow$$

$$101 = 100 + 200\exp(-0.200t) \Rightarrow t = \frac{\ln(1/200)}{-0.200} = \underline{\underline{26.5 \ \text{min}}}$$

11.7 **a.** A plot of D (log scale) vs. t (rectangular scale) yields a straight line through the points ($t = 1$ week, $D = 2385$ kg/week) and ($t = 6$ weeks, $D = 755$ kg/week).

$$\ln D = bt + \ln a \Leftrightarrow D = ae^{bt}$$

$$b = \frac{\ln D_2/D_1}{t_2 - t_1} = \frac{\ln(755/2385)}{6-1} = -0.230$$

$$\ln a = \ln D_1 - bt_1 = \ln(2385) + (0.230)(1) = 8.007 \Rightarrow a = e^{8.007} = 3000$$

$$\Downarrow$$

$$\underline{\underline{D = 3000e^{-0.230t}}}$$

b. <u>Inventory balance:</u> Accumulation = –output

$$\frac{dI}{dt} = -3000e^{-0.230t} \; \text{(kg/week)}$$

$$\underline{\underline{t = 0, I = 18,000 \text{ kg}}}$$

$$\int_{18,000}^{I} dI = \int_0^t -3000e^{-0.230t} \, dt \Rightarrow I - 18,000 = \frac{3000}{0.230} e^{-0.230t} \bigg]_0^t \Rightarrow \underline{\underline{I = 4957 + 13,043e^{-0.230t}}}$$

c. $t = \infty \Rightarrow \underline{\underline{I = 4957 \text{ kg}}}$

11.8 **a.** <u>Total moles in room:</u> $N = \dfrac{1100 \text{ m}^3}{} \bigg| \dfrac{273 \text{ K}}{295 \text{ K}} \bigg| \dfrac{10^3 \text{ mol}}{22.4 \text{ m}^3 (\text{STP})} = 45,440$ mol

<u>Molar throughput rate:</u> $\dot{n} = \dfrac{700 \text{ m}^3}{\text{min}} \bigg| \dfrac{273 \text{ K}}{295 \text{ K}} \bigg| \dfrac{10^3 \text{ mol}}{22.4 \text{ m}^3 (\text{STP})} = 28,920$ mol/min

<u>SO_2 balance</u> ($t = 0$ is the instant after the SO_2 is released into the room):

$$N(\text{mol})x(\text{mol } SO_2/\text{mol}) = \text{mol } SO_2 \text{ in room}$$
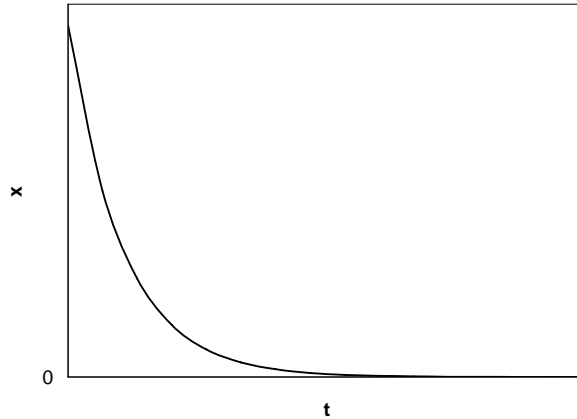
Accumulation = –output.

$$\frac{d}{dt}(Nx) = -\dot{n}x \underset{\substack{N=45,440 \\ \dot{n}=28,920}}{\Rightarrow} \frac{dx}{dt} = -0.6364x$$

$$\underline{\underline{t = 0, \; x = \frac{1.5 \text{ mol } SO_2}{45,440 \text{ mol}} = 3.30 \times 10^{-5} \; \text{mol } SO_2/\text{mol}}}$$

b. The plot of x vs. t begins at (t=0, x=3.30×10⁻⁵). When t=0, the slope (dx/dt) is $-0.6364 \times 3.30 \times 10^{-5} = -2.10 \times 10^{-5}$. As t increases, x decreases.$\Rightarrow$ $dx/dt = -0.6364x$ becomes less negative, approaches zero as $t \to \infty$. The curve is therefore <u>concave up.</u>

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 $\Rightarrow$ satisfies the initial condition;

(2) $\dfrac{dx}{dt} = -0.6364\times3.30\times10^{-5}e^{-0.6364t} = -0.6364x \Rightarrow$ reproduces the mass balance.

d. $C_{SO_2} = \dfrac{45,440 \text{ moles}}{1100 \text{ m}^3}\left|\dfrac{x \text{ mol } SO_2}{\text{mol}}\right|\dfrac{1 \text{ m}^3}{10^3 \text{ L}} = 4.131\times10^{-2}x = \underline{\underline{1.3632\times10^{-6}e^{-0.6364t}}}$ mol SO_2 / L

i) $t = 2$ min $\Rightarrow C_{SO_2} = \underline{\underline{3.82\times10^{-7}\dfrac{\text{mol } SO_2}{\text{liter}}}}$

ii) $x = 10^{-6} \Rightarrow t = \dfrac{\ln\left(10^{-6}/3.30\times10^{-5}\right)}{-0.6364} = \underline{\underline{5.5 \text{ min}}}$

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.

11.9 **a.** Balance on CO: Accumulation=-output

N (mol) x (mol CO / mol) $=$ total moles of CO in the laboratory

Molar flow rate of entering and leaving gas: $\dot{n}\ (\dfrac{\text{kmol}}{\text{h}}) = \dfrac{P\dot{V}_p}{RT}$

Rate at which CO leaves: $\dot{n}\ (\dfrac{\text{kmol}}{\text{h}})\ x\!\left(\dfrac{\text{kmol CO}}{\text{kmol}}\right) = \dfrac{P\dot{V}_p}{RT}x$

CO balance: Accumulation = -output

$$\dfrac{d(Nx)}{dt} = -\dfrac{P\dot{V}_p}{RT}x \Rightarrow \dfrac{dx}{dt} = -\left(\dfrac{P}{NRT}\right)\dot{V}_p x$$

$$\Downarrow PV = NRT$$

$$\dfrac{dx}{dt} = -\dfrac{\dot{V}_p}{V}x$$

$t = 0,\ x = 0.01\ \dfrac{\text{kmol CO}}{\text{kmol}}$

b. $\displaystyle\int_{0.01}^{x}\dfrac{dx}{x} = -\dfrac{\dot{V}_p}{V}\int_{0}^{t_r}dt \Rightarrow t_r = -\dfrac{V}{\dot{V}_p}\ln(100x)$

c. $V = 350\ \text{m}^3$

$t_r = -\dfrac{350}{700}\ln\!\left(100 \times 35 \times 10^{-6}\right) = \underline{\underline{2.83\ \text{hrs}}}$

d. The room air composition may not be uniform, so the actual concentration of CO in parts of the room may still be higher than the safe level. Also, "safe" is on the average; someone could be particularly sensitive to CO.

Precautionary steps:
Purge the laboratory longer than the calculated purge time. Use a CO detector

to measure the real concentration of CO in the laboratory and make sure it is

lower than the safe level everywhere in the laboratory.

11.10 a. Total mass balance: Accumulation = input – output

$$\dfrac{dM}{dt} = \dot{m} - \dot{m}\left(\text{kg/min}\right) = 0 \Rightarrow \therefore\ \underline{\underline{M \text{ is a constant} = 200\ \text{kg}}}$$

b. Sodium nitrate balance: Accumulation = - output
x = mass fraction of $NaNO_3$

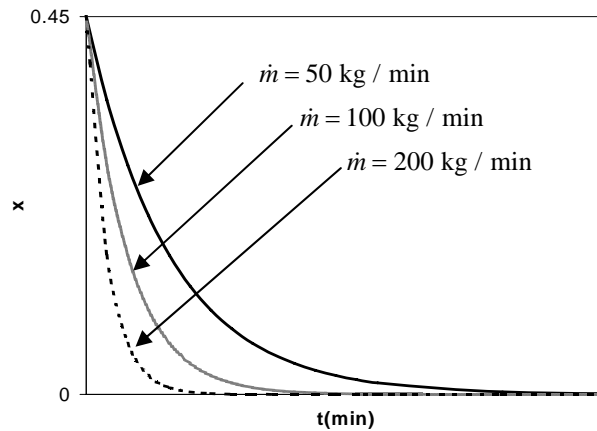$$\dfrac{d(xM)}{dt} = -x\dot{m}\left(\text{kg/min}\right)$$

$$\Downarrow$$

$$\dfrac{dx}{dt} = -\dfrac{\dot{m}}{M}x = -\dfrac{\dot{m}}{200}x$$

$$\underline{\underline{t = 0,\ x = 90/200 = 0.45}}$$

11.10 (cont'd)

c.

$$\frac{dx}{dt} = -\frac{\dot{m}}{200}x < 0 \text{ , x decreases when t increases}$$

$\dfrac{dx}{dt}$ becomes less negative until x reaches 0;

Each curve is concave up and approaches x = 0 as t → ∞;

$\dot{m}$ increases ⇒ $\dfrac{dx}{dt}$ becomes more negative ⇒ x decreases faster.

d. $\displaystyle\int_{0.45}^{x}\frac{dx}{x} = -\int_{0}^{t}\frac{\dot{m}}{M}dt \Rightarrow \ln\frac{x}{0.45} = -\frac{\dot{m}}{200}t \Rightarrow \underline{\underline{x = 0.45\exp\left(-\frac{\dot{m}t}{200}\right)}}$

Check the solution:

(1) t = 0, x = 0.45 ⇒ satisfies the initial condition;

(2) $\dfrac{dx}{dt} = -0.45 \times \dfrac{\dot{m}}{200}\exp(-\dfrac{\dot{m}t}{200}) = -\dfrac{\dot{m}}{200}x \Rightarrow$ satisfies the mass balance.
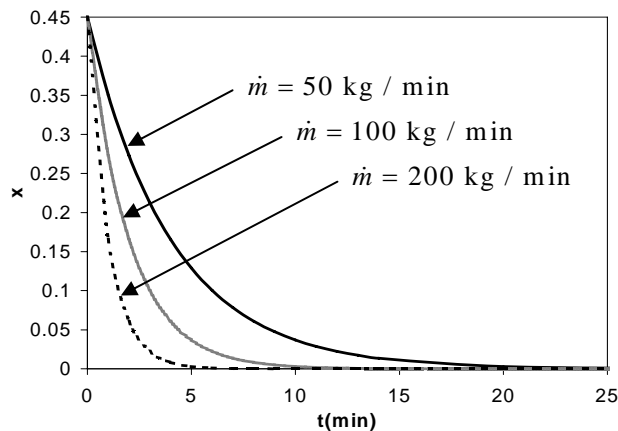
e. $\dot{m} = 100 \text{ kg/min} \Rightarrow t = -2\ln\left(x_f / 0.45\right)$

90% ⇒ $x_f = 0.045 \Rightarrow \underline{\underline{t = 4.6 \text{ min}}}$

99% ⇒ $x_f = 0.0045 \Rightarrow \underline{\underline{t = 9.2 \text{ min}}}$

99.9% ⇒ $x_f = 0.00045 \Rightarrow \underline{\underline{t = 13.8 \text{ min}}}$

11.11 a. <u>Mass of tracer in tank:</u> $V\left(m^3\right)C\left(kg/m^3\right)$

<u>Tracer balance:</u> Accumulation = –output. If perfectly mixed, $C_{out} = C_{tank} = C$

$$\frac{d(VC)}{dt} = -\dot{v}C \ (kg/min) \xrightarrow{\text{V is constant}} \begin{array}{l} \dfrac{dC}{dt} = -\dfrac{\dot{v}}{V}C \\[2mm] t = 0, C = \dfrac{m_0}{V} \end{array}$$

b. $\displaystyle\int_{m_0/V}^{C} \frac{dC}{C} = -\int_0^t \frac{\dot{v}}{V}dt \Rightarrow \ln\left(\frac{C}{m_0/V}\right) = -\frac{\dot{v}t}{V} \Rightarrow C = \frac{m_0}{V}\exp\left(-\frac{\dot{v}t}{V}\right)$

c. Plot C (log scale) vs t (rect. scale) on semilog paper: Data lie on straight line (verifying assumption of perfect mixing) through $\left(t = 1, C = 0.223 \times 10^{-3}\right)$ & $\left(t = 2, C = 0.050 \times 10^{-3}\right)$.

$$-\frac{\dot{v}}{V} = \frac{\ln(0.050/0.223)}{2-1} = -1.495 \ \text{min}^{-1}$$

$$\Downarrow$$

$$V = \left(30 \ m^3/min\right)\Big/\left(1.495 \ \text{min}^{-1}\right) = \underline{\underline{20.1 \ m^3}}$$

11.12 a. In tent at any time, P=14.7 psia, V=40.0 ft³, T=68°F=528°R

$$\Rightarrow N = \frac{PV}{RT} = \text{m(liquid)} = \frac{14.7 \ \text{psia} \quad \Big| \quad 40.0 \ \text{ft}^3}{10.73 \ \dfrac{\text{ft}^3 \cdot \text{psia}}{\text{lb - mole} \cdot^o \ \text{R}} \quad \Big| \quad 528 \ ^o\text{R}} = \underline{\underline{0.1038 \ \text{lb - mole}}}$$

b. <u>Molar throughout rate:</u>

$$\dot{n}_{in} = \dot{n}_{out} = \dot{n} = \frac{60 \ \text{ft}^3}{\text{min}} \Bigg| \frac{492^\circ \text{R}}{528^\circ \text{R}} \Bigg| \frac{16.0 \ \text{psia}}{14.7 \ \text{psia}} \Bigg| \frac{1 \ \text{lb - mole}}{359 \ \text{ft}^3 \ (\text{STP})} = 0.1695 \ \text{lb - mole/min}$$

<u>Moles of O$_2$ in tank</u>$= N\,(\text{lb - mole}) \times \left(\dfrac{\text{lb - mole O}_2}{\text{lb - mole}}\right)$

<u>Balance on O$_2$:</u> Accumulation = input – output

$$\frac{d(Nx)}{dt} = 0.35\dot{n} - x\dot{n} \Rightarrow 0.1038\frac{dx}{dt} = 0.1695(0.35 - x) \Rightarrow \begin{array}{l} \dfrac{dx}{dt} = 1.63(0.35 - x) \\[2mm] t = 0, \ x = 0.21 \end{array}$$

c. $\displaystyle\int_{0.21}^{x} \frac{dx}{0.35 - x} = \int_0^t 1.63dt \Rightarrow -\ln\frac{(0.35 - x)}{(0.35 - 0.21)} = 1.63t$

$$\Rightarrow \frac{0.35 - x}{0.14} = e^{-1.63t} \Rightarrow \underline{\underline{x = 0.35 - 0.14e^{-1.63t}}}$$

$$x = 0.27 \Rightarrow t = \frac{1}{1.63}\left[-\ln\left(\frac{0.35 - 0.27}{0.35 - 0.21}\right)\right] = \underline{\underline{0.343 \ \text{min}}} \ (\text{or} \ \underline{\underline{20.6 \ \text{s}}})$$

11.13 a. <u>Mass of isotope at any time</u> $= V(\text{liters})C(\text{mg isotope}/\text{liter})$

<u>Balance on isotope:</u> Accumulation = –consumption

$$\frac{d}{dt}(VC) = -kC\left(\frac{\text{mg}}{\text{L}\cdot\text{s}}\right)V(\text{L}) \xrightarrow{\text{Cancel V}} \quad \frac{dC}{dt} = -kC$$

$$t = 0, C = C_0$$

<u>Separate variables and integrate</u>

$$\int_{C_0}^{C}\frac{dC}{C} = \int_0^t -k\,dt \Rightarrow \ln\left(\frac{C}{C_0}\right) = -kt \Rightarrow t = \frac{-\ln(C/C_0)}{k}$$

$$C = 0.5C_0 \Rightarrow t_{1/2} = \frac{-\ln(0.5)}{k} \Rightarrow t_{1/2} = \frac{\ln 2}{k}$$

b. $t_{1/2} = 2.6\ \text{hr} \Rightarrow k = \dfrac{\ln 2}{2.6\ \text{hr}} = 0.267\ \text{hr}^{-1}$

$$C = 0.01C_0 \xrightarrow[t=-\ln(C/C_0)/k]{} t = \frac{-\ln(0.01)}{0.267} = \underline{\underline{17.2\ \text{hr}}}$$

11.14 $A \rightarrow$ products

a. <u>Mole balance on A:</u> Accumulation = –consumption

$$\frac{d(C_A V)}{dt} = -kC_A V \qquad (V \text{ constant; cancels})$$

$$t = 0, C_A = C_{A0}$$

$$\Rightarrow \int_{C_{A0}}^{C_A}\frac{dC_A}{C_A} = \int_0^t -k\,dt \Rightarrow \ln\left(\frac{C_A}{C_{A0}}\right) = -kt \Rightarrow \underline{\underline{C_A = C_{A0}\exp(-kt)}}$$

b. Plot C_A (log scale) vs. t (rect. scale) on semilog paper. The data fall on a straight line (verifies assumption of first-order) through $(t = 21.3,\ C_A = 0.0262)$ & $(t = 120.0,\ C_A = 0.0185)$.

$$\ln C_A = -kt + \ln C_{A0}$$

$$-k = \frac{\ln(0.0185/0.0262)}{120.0 - 21.3} = -3.53\times 10^{-3}\ \text{min}^{-1} \Rightarrow \underline{\underline{k = 3.5\times 10^{-3}\ \text{min}^{-1}}}$$

11.15 $2A \rightarrow 2B + C$

a. <u>Mole balance on A:</u> Accumulation = –consumption

$$\frac{d(C_A V)}{dt} = -kC_A^2 V \qquad (V \text{ constant; cancels})$$

$$t = 0, C_A = C_{A0}$$

$$\Rightarrow \int_{C_{A0}}^{C_A}\frac{dC_A}{C_A^2} = \int_0^t -k\,dt \Rightarrow -\frac{1}{C_A} + \frac{1}{C_{A0}} = -kt \Rightarrow \underline{\underline{C_A = \left[\frac{1}{C_{A0}} + kt\right]^{-1}}}$$

11.15 (cont'd)

b. $C_A = 0.5C_{A0} \Rightarrow -\dfrac{1}{0.5C_{A0}} + \dfrac{1}{C_{A0}} = -kt_{1/2} \Rightarrow t_{1/2} = \dfrac{1}{kC_{A0}}$; but $C_{A0} = \dfrac{n_{A0}}{V} = \dfrac{P_0}{RT} \Rightarrow t_{1/2} = \dfrac{RT}{kP_0}$

$n_A = 0.5n_{A0}$

$n_B = (0.5n_{A0}$ mol A react.$)(2$ mol $B/2$ mol A react.$) = 0.5n_{A0}$

$n_C = (0.5n_{A0}$ mol A react.$)(1$ mol $C/2$ mol A react.$) = 0.25n_{A0}$

total moles $= 1.25n_{A0} \Rightarrow P_{1/2} = 1.25\dfrac{n_{A0}RT}{V} = 1.25P_0$

c. Plot $t_{1/2}$ vs. $1/P_0$ on rectangular paper. Data fall on straight line (verifying 2nd order decomposition) through $(t_{1/2} = 1060, 1/P_0 = 1/0.135)$ & $(t_{1/2} = 209, 1/P_0 = 1/0.683)$

Slope: $\dfrac{RT}{k} = \dfrac{1060 - 209}{1/0.135 - 1/0.683} = 143.2$ s·atm

$\Rightarrow k = \dfrac{(1015 \text{ K})(0.08206 \text{ L·atm/mol·K})}{143.2 \text{ s·atm}} = 0.582$ L/mol·s

d. $t_{1/2} = \dfrac{RT}{k_0 P_0} \exp\left(\dfrac{E}{RT}\right) \Rightarrow \ln\left(\dfrac{t_{1/2}P_0}{RT}\right) = \ln\dfrac{1}{k_0} + \dfrac{E}{R}\dfrac{1}{T}$

Plot $t_{1/2}P_0/RT$ (log scale) vs. $1/T$ (rect. scale) on semilog paper.

$\left[t_{1/2}(\text{s}), P_0 = 1 \text{ atm}, R = 0.08206 \text{ L·atm}/(\text{mol·K}), \text{T(K)}\right]$

Data fall on straight line through $(t_{1/2}P_0/RT = 74.0, 1/T = 1/900)$ &

$(t_{1/2}P_0/RT = 0.6383, 1/T = 1/1050)$

$\dfrac{E}{R} = \dfrac{\ln(0.6383/74.0)}{1/1050 - 1/900} = 29{,}940$ K $\xrightarrow{\text{R=8.314 J/ (mol ·K)}}$ $E = 2.49 \times 10^5$ J/mol

$\ln\dfrac{1}{k_0} = \ln(0.6383) - \dfrac{29{,}940}{1050} = -28.96 \Rightarrow k_0 = 3.79 \times 10^{12}$ L/(mol·s)

e. $T = 980 \text{ K} \Rightarrow k = k_0 \exp\left(-\dfrac{E}{RT}\right) = 0.204$ L/(mol·s)

$C_{A0} = \dfrac{0.70(1.20 \text{ atm})}{(0.08206 \text{ L·atm/mol·K})(980 \text{ K})} = 1.045 \times 10^{-2}$ mol/L

$\downarrow$90% conversion

$C_A = 0.10C_{A0} \Rightarrow t = \dfrac{1}{k}\left[\dfrac{1}{C_A} - \dfrac{1}{C_{A0}}\right] = \dfrac{1}{0.204}\left[\dfrac{1}{1.045 \times 10^{-3}} - \dfrac{1}{1.045 \times 10^{-2}}\right]$

$= 4222$ s $= 70.4$ min

11.16 $A \to B$

    a.   <u>Mole balance on A:</u> Accumulation = –consumption(V constant)

$$\frac{dC_A}{dt} = -\frac{k_1 C_A}{1 + k_2 C_A}$$

$$t = 0, C_A = C_{A0}$$

$$\int_{C_{A0}}^{C_A} \frac{1 + k_2 C_A}{k_1 C_A} dC_A = \int_0^t -dt \Rightarrow \frac{1}{k_1} \ln \frac{C_A}{C_{A0}} + \frac{k_2}{k_1}(C_A - C_{A0}) = -t \Rightarrow \underline{\underline{t = \frac{k_2}{k_1}(C_{A0} - C_A) - \frac{1}{k_1} \ln \frac{C_A}{C_{A0}}}}$$

    b.   Plot $t/(C_A - C_{A0})$ vs. $\ln(C_A / C_{A0})/(C_{A0} - C_A)$ on rectangular paper:

$$\overbrace{\frac{t}{(C_{A0} - C_A)}}^{y} = \underbrace{-\frac{1}{k_1}}_{\text{slope}} \overbrace{\frac{\ln(C_A/C_{A0})}{C_{A0} - C_A}}^{x} + \underbrace{\frac{k_2}{k_1}}_{\text{intercept}}$$

        Data fall on straight line through $\left(\overset{y_1}{116.28}, \overset{x_1}{-0.2111} \right)$ & $\left(\overset{y_2}{130.01}, \overset{x_2}{-0.2496} \right)$

$$-\frac{1}{k_1} = \frac{130.01 - 116.28}{-0.2496 - (-0.2111)} = -356.62 \Rightarrow \underline{\underline{k_1 = 2.80 \times 10^{-3} \ \text{L/(mol·s)}}}$$

$$\frac{k_2}{k_1} = 130.01 + 356.62(-0.2496) = 41.00 \Rightarrow \underline{\underline{k_2 = 0.115 \ \text{L/mol}}}$$

11.17 $CO + Cl_2 \Rightarrow COCl_2$

    a. $\dfrac{3.00 \ \text{L} \ | \ 273 \ \text{K} \ | \ 1 \ \text{mol}}{\ \ | \ 303.8 \ \text{K} \ | \ 22.4 \ \text{L(STP)}} = 0.12035$ mol gas

$$\left. \begin{array}{l} (C_{CO})_i = 0.60(0.12035 \ \text{mol})/3.00 \ \text{L} = \underline{\underline{0.02407}} \ \text{mol/L CO} \\ (C_{Cl_2})_i = 0.40(0.12035 \ \text{mol})/3.00 \ \text{L} = \underline{\underline{0.01605}} \ \text{mol/L Cl}_2 \end{array} \right\} \text{initial concentrations}$$

$$\left. \begin{array}{l} C_{CO}(t) = 0.02407 - C_p(t) \\ \overline{\underline{C_{Cl_2}(t) = 0.01605 - C_p(t)}} \end{array} \right\} \text{Since 1 mol } COCl_2 \text{ formed requires 1 mol of each reactant}$$

    b.   Mole balance on Phosgene: Accumulation = generation

$$\frac{d(VC_p)}{dt} = \frac{8.75 C_{CO} C_{Cl_2}}{\left(1 + 58.6 C_{Cl_2} + 34.3 C_p\right)^2} \xrightarrow{V=3.00 \ \text{L}} \begin{array}{l} \dfrac{dC_p}{dt} = \dfrac{2.92(0.02407 - C_p)(0.01605 - C_p)}{\left(1.941 - 24.3 C_p\right)^2} \\ \\ \underline{\underline{t = 0, C_p = 0}} \end{array}$$

    c. Cl_2 limiting; 75% conversion $\Rightarrow C_p = 0.75(0.01605) = 0.01204$ mol/L

$$\underline{\underline{t = \frac{1}{2.92} \int_0^{0.01204} \frac{\left(1.941 - 24.3 C_p\right)^2}{(0.02407 - C_p)(0.01605 - C_p)} dC_p}}$$

11.17 (cont'd)

d.
```
        REAL F(51), SUM1, SUM2, SIMP
        INTEGER I, J, NPD(3), N, NM1, NM2
        DATA NPD/5, 21, 51/
        FN(C) = (1.441 – 24.3 * C) ** 2/(0.02407 – C)/(0.01605 – C)
        DO 10 I = 1, 3
            N = NPD(I)
            NM1 = N – 1
            NM2 = N – 2
            DO 20 J = 1, N
                C = 0.01204 * FLOAT(J – 1)/FLOAT(NM1)
                F(J) = FN(C)
  20        CONTINUE
            SUM1 = 0.
            DO 30 J = 2, NM1, 2
                SUM = SUM1 + F(S)
  30        CONTINUE
            SUM2 = 0.
            DO 40 J = 3, NM2, 2
                SUM2 = SUM2 + F(J)
  40        CONTINUE
            SIMP = 0.01204/FLOAT(NM1)/3.0 * (F(1) + F(N) + 4.0 * SUM1 + 2.0 * SUM2)
            T = SIMP/2.92
            WRITE (6, 1) N, T
  10    CONTINUE
   1    FORMAT (I4, 'POINTS —', 2X, F7.1, 'MINUTES')
        END
       RESULTS
       5 POINTS —   91.0 MINUTES
       21 POINTS — 90.4 MINUTES
       51 POINTS — 90.4 MINUTES
       t = 90.4 minutes
```

11.18 a. Moles of CO_2 in liquid phase at any time $= V\left(cm^3\right)C_A\left(mols/cm^3\right)$

Balance on CO_2 in liquid phase: Accumulation = input

$$\frac{d}{dt}\left(VC_A\right) = kS\left(C_A^* - C_A\right)\left(\frac{mols}{s}\right) \underset{\div V}{\Rightarrow} \begin{array}{l} \dfrac{dC_A}{dt} = \dfrac{kS}{V}\left(C_A^* - C_A\right) \\ \underline{\underline{t = 0, C_A = 0}} \end{array}$$

Separate variables and integrate. Since $p_A = y_A P$ is constant, $C_A^* = p_A/H$ is also a constant.

$$\int_0^{C_A} \frac{dC_A}{C_A^* - C_A} = \int_0^t \frac{kS}{V}\,dt \Rightarrow -\ln\left(C_A^* - C_A\right)\Big]_{C_A=0}^{C_A} = \frac{kS}{V}\,t$$

$$\Rightarrow \ln\left[\underbrace{\frac{C_A^* - C_A}{C_A^*}}_{1-C_A/C_A^*}\right] = -\frac{kS}{V}\,t \overset{\exp(\ )}{\Rightarrow} 1 - \frac{C_A}{C_A^*} = e^{-kSt/V} \Rightarrow \underline{\underline{C_A = C_A^*\left(1 - e^{-kSt/V}\right)}}$$

11.18 (cont'd)

b. $t = -\dfrac{V}{kS}\ln\left[1 - \dfrac{C_A}{C_A^*}\right]$

$V = 5\,\text{L} = 5000\,\text{cm}^3,\ k = 0.020\ \text{cm/s},\ S = 78.5\ \text{cm}^2,\ C_A = 0.62 \times 10^{-3}\ \text{mol / cm}^3$

$C_A^* = y_A P/H = (0.30)(20\ \text{atm})/\left(9230\ \text{atm}\cdot\text{cm}^3/\text{mol}\right) = 0.65 \times 10^{-3}\ \text{mol/cm}^3$

$t = -\dfrac{\left(5000\ \text{cm}^3\right)}{(0.02\ \text{cm/s})\left(78.5\ \text{cm}^2\right)}\ln\left(1 - \dfrac{0.62 \times 10^{-3}}{0.65 \times 10^{-3}}\right) = 9800\ \text{s} \Rightarrow \underline{\underline{2.7\ \text{hr}}}$

(We assume, in the absence of more information, that the gas-liquid interfacial surface area equals the cross sectional area of the tank. If the liquid is well agitated, S may in fact be much greater than this value, leading to a significantly lower t than that to be calculated)

11.19 $A \rightarrow B$

a. <u>Total Mass Balance:</u> Accumulation = input

$$\frac{dM}{dt} = \frac{d(\rho V)}{dt} = \rho\dot{v}$$

$$\Downarrow$$

$$\underline{\underline{\frac{dV}{dt} = \dot{v}}}$$

$$\underline{\underline{t = 0,\ V = 0}}$$

<u>A Balance:</u> Accumulation = input – consumption

$$\frac{dN_A}{dt} = C_{A0}\dot{v} - (kC_A)V \xrightarrow{C_A=N_A/V} \qquad \underline{\underline{\frac{dN_A}{dt} = C_{Ao}\dot{v} - kN_A}}$$

$$\underline{\underline{t = 0,\ N_A = 0}}$$

b. Steady State: $\dfrac{dN_A}{dt} = 0 \Rightarrow \underline{\underline{N_A = \dfrac{C_{A0}\dot{v}}{k}}}$

c. $\displaystyle\int_0^V dV = \int_0^t \dot{v}\,dt \Rightarrow \underline{\underline{V = \dot{v}t}}$

$$\int_0^{N_A} \frac{dN_A}{C_{A0}\dot{v} - kN_A} = \int_0^t dt$$

$$\Rightarrow -\frac{1}{k}\ln\left(\frac{C_{A0}\dot{v} - kN_A}{C_{A0}\dot{v}}\right) = t \Rightarrow \frac{C_{A0}\dot{v} - kN_A}{C_{A0}\dot{v}} = e^{-kt}$$

$$\Rightarrow \underline{\underline{N_A = \frac{C_{A0}\dot{v}}{k}\left[1 - \exp(-kt)\right]}} \quad t \to \infty \Rightarrow \underline{\underline{N_A = \frac{C_{A0}\dot{v}}{k}}}$$

$$\underline{\underline{C_A = \frac{N_A}{V} = \frac{C_{A0}[1 - \exp(-kt)]}{kt}}}$$

11.19 (cont'd)

When the feed rate of A equals the rate at which A reacts, N_A reaches a steady value.
N_A would never reach the steady value in a real reactor. The reasons are:
(1) In our calculation, $V = \dot{v}t \Rightarrow t \to \infty$, $V \to \infty$.

But in a real reactor, the volume is limited by the reactor volume;

(2) The steady value can only be reached at $t \to \infty$. In a real reactor, the reaction time is finite.

d. $\lim_{t \to \infty} C_A = \lim_{t \to \infty} \dfrac{C_{A0}[1 - \exp(-kt)]}{kt} = \lim_{t \to \infty} \dfrac{C_{A0}}{kt} = \underline{\underline{0}}$

From part c, $t \to \infty$, $N_A \to$ a finite number, $V \to \infty \Rightarrow C_A = \dfrac{N_A}{V} \to 0$

11.20 a. $MC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$\left\| \begin{array}{l} M = (3.00 \text{ L})(1.00 \text{ kg / L}) = 3.00 \text{ kg} \\ C_v = C_p = (0.0754 \text{ kJ / mol} \cdot^\circ \text{C})(1 \text{ mol} / 0.018 \text{ kg}) = 4.184 \text{ kJ / kg} \cdot^\circ \text{C} \\ \dot{W} = 0 \end{array} \right.$

$\dfrac{dT}{dt} = 0.0797\dot{Q} \text{ (kJ / s)}$

$\underline{\underline{t = 0, \ T = 18^\circ \text{C}}}$

b. $\int_{18^\circ C}^{100^\circ C} dT = \int_0^{240 \text{ s}} 0.0797\dot{Q} \, dt \Rightarrow \dot{Q} = \dfrac{100 - 18}{240 \times 0.0797} = 4.287 \ \dfrac{\text{kJ}}{\text{s}} = \underline{\underline{4.29 \text{ kW}}}$

c. Stove output is much greater.
Only a small fraction of energy goes to heat the water.
Some energy heats the kettle.
Some energy is lost to the surroundings (air).

11.21 a. <u>Energy balance:</u> $MC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$\left\| \begin{array}{l} M = 20.0 \text{ kg} \\ C_v \approx C_p = (0.0754 \text{ kJ / mol} \cdot^\circ \text{C})(1 \text{ mol} / 0.0180 \text{ kg}) = 4.184 \text{ kJ / (kg} \cdot^\circ \text{C)} \\ \dot{Q} = (0.97)(2.50) = 2.425 \ \text{kJ/s} \\ \dot{W} = 0 \end{array} \right.$

$\dfrac{dT}{dt} = 0.0290 \left(^\circ \text{C/s}\right), \quad \underline{\underline{t = 0, \ T = 25^\circ \text{C}}}$

The other 3% of the energy is used to heat the vessel or is lost to the surroundings.

b. $\int_{25^\circ C}^{T} dT = \int_0^t 0.0290 dt \Rightarrow \underline{\underline{T = 25^\circ \text{C} + 0.0290t(s)}}$

c. $T = 100^\circ \text{C} \Rightarrow t = (100 - 25)/0.0290 = 2585 \text{ s} \Rightarrow \underline{\underline{43.1 \text{ min}}}$

No, since the vessel is closed, the pressure will be greater than 1 atm (the pressure at the normal boiling point).
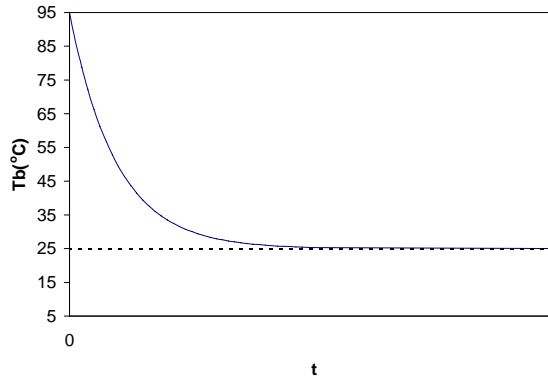
11.22 a. Energy balance on the bar

$$MC_v \frac{dT_b}{dt} = \dot{Q} - \dot{W} = -UA(T_b - T_w)$$

Table B.1
↓

$M = (60 \text{ cm}^3)(7.7 \text{ g/cm}^3) = 462 \text{ g}$
$C_v = 0.46 \text{ kJ/(kg·°C)}, \ T_w = 25°\text{C}$
$U = 0.050 \text{ J/(min·cm}^2\text{·°C)}$
$A = 2[(2)(3) + (2)(10) + (3)(10)]\text{cm}^2 = 112 \text{ cm}^2$

$$\underline{\frac{dT_b}{dt} = -0.02635(T_b - 25) \ (°\text{C/min})}$$

$$\underline{\underline{t = 0, \ T_b = 95°\text{C}}}$$

b. $\dfrac{dT_b}{dt} = 0 = -0.02635(T_{bf} - 25) \Rightarrow \underline{\underline{T_{bf} = 25°\text{C}}}$

c. $\displaystyle\int_{95}^{T_b} \frac{dT_b}{T_b - 25} = \int_0^t -0.02635\,dt$

$$\Rightarrow \ln\left(\frac{T_b - 25}{95 - 25}\right) = -0.02635t$$

$$\Rightarrow \underline{\underline{T_b(t) = 25 + 70\exp(-0.02635t)}}$$

Check the solution in three ways:

(1) t = 0, $T_b = 25 + 70 = 95°C \Rightarrow$ satisfies the initial condition;

(2) $\dfrac{dT_b}{dt} = -70 \times 0.02635e^{-0.02635t} = -0.02635(T_b - 25) \Rightarrow$ reproduces the mass balance;

(3) t → ∞, $T_b = 25°C \Rightarrow$ confirms the steady state condition.

$T_b = 30°C \Rightarrow \underline{\underline{t = 100 \text{ min}}}$

11.23

$\quad$ 12.0 kg/min $\qquad$ 12.0 kg/min
$\quad$ 25°C $\qquad\qquad$ T (°C)
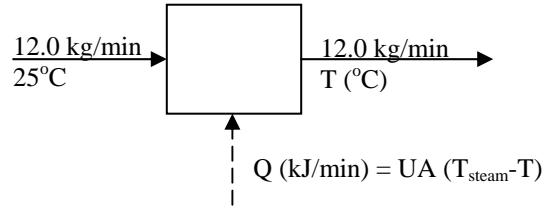
$\vdots$ Q (kJ/min) = UA (T_{steam}-T)

a. <u>Energy Balance:</u> $MC_v \dfrac{dT}{dt} = \dot{m}C_p(25-T) + UA(T_{steam}-T)$

$\quad M = 760$ kg

$\quad \dot{m} = 12.0 \ \text{kg/min}$

$\qquad\qquad\qquad\qquad\Longrightarrow \quad$ $\underline{\underline{dT/dt = 1.50 - 0.0224T}}$ (°C/min), $\ t = 0, \ T = 25°C$

$\quad C_v \approx C_p = 2.30 \ \text{kJ/(min·°C)}$

$\quad UA = 11.5 \ \text{kJ/(min·°C)}$

$\quad T_{steam}(\text{sat'd; 7.5bars}) = 167.8°C$

b. <u>Steady State:</u> $\dfrac{dT}{dt} = 0 = 1.50 - 0.0224T_s \Rightarrow \underline{\underline{T_s = 67°C}}$
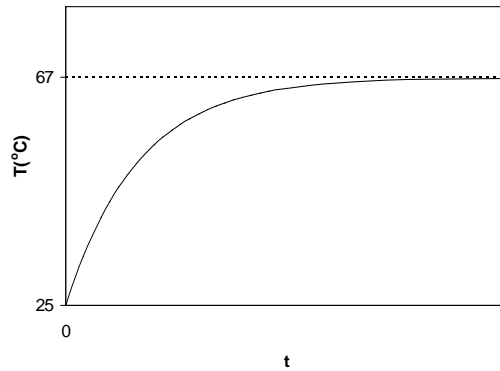
c. $\displaystyle\int_{25}^{T_f} \dfrac{dT}{1.50 - 0.0224T} = \int_0^t dt \Rightarrow \underline{\underline{t = -\dfrac{1}{0.0224}\ln\left(\dfrac{1.50-0.0224T}{0.94}\right)}} \Rightarrow T = \dfrac{1.50 - 0.94\exp(-0.0224t)}{0.0224}$

$t = 40$ min. $\Rightarrow \underline{\underline{T = 49.8°C}}$

d. U changed. Let $x = (UA)_{new}$. The differential equation becomes:

$\dfrac{dT}{dt} = 0.3947 + 0.096x - (0.01579 + 5.721x)T$

$\displaystyle\int_{25}^{55} \dfrac{dT}{0.3947 + 0.096x - (0.01579 + 5.721\times 10^{-4}x)T} = \int_0^{40} dt$

$\Rightarrow \quad -\dfrac{1}{0.01579 + 5.721\times 10^{-4}x}\ln\left[\dfrac{0.3947 + 0.096x - \left(0.01579 + 5.721\times 10^{-4}x\right)\times 55}{0.3947 + 0.096x - \left(0.01579 + 5.721\times 10^{-4}x\right)\times 25}\right] = 40$

$\Rightarrow x = 14.27 \ \text{kJ / (min·°C)}$

$\dfrac{\Delta U}{U_{initial}} = \dfrac{\Delta(UA)}{(UA)_{initial}} = \dfrac{14.27 - 11.5}{11.5}\times 100\% = \underline{\underline{24.1\%}}$

11.24 a. <u>Energy balance:</u> $MC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$$\Big\Downarrow \begin{array}{l} \dot{W} = 0, \ C_v = 1.77 \ \text{J/g} \cdot ^\circ\text{C} \\ M = 350 \ \text{g}, \ \dot{Q} = 40.2W = 40.2 \ \text{J/s} \end{array}$$

$$\left.\begin{array}{l} \dfrac{dT}{dt} = 0.0649 \ (^\circ\text{C/s}) \\ t = 0, \ T = 20^\circ\text{C} \end{array}\right\} \Rightarrow \begin{array}{l} T = 20 + 0.0649t(\text{s}) \\ T = 40^\circ\text{C} \Rightarrow t = 308 \ \text{s} \Rightarrow \underline{5.1 \ \text{min}} \end{array}$$

b. The benzene temperature will continue to rise until it reaches $T_b = 80.1^\circ\text{C}$; thereafter the heat input will serve to vaporize benzene isothermally.

<u>Time to reach T_b</u> (neglect evaporation): $t = \dfrac{80.1 - 20}{0.0649} = 926 \ \text{s}$

<u>Time remaining:</u> 40 minutes $(60 \ \text{s/min}) - 926 \ \text{s} = 1474 \ \text{s}$

<u>Evaporation:</u> $\Delta\hat{H}_v = (30.765 \ \text{kJ/mol})(1 \ \text{mol}/78.11 \ \text{g})(1000 \ \text{J/kJ}) = 393 \ \text{J/g}$

<u>Evaporation rate</u> $= (40.2 \ \text{J/s}) / (393 \ \text{J/g}) = 0.102 \ \text{g/s}$

<u>Benzene remaining</u> $= 350 \ \text{g} - (0.102 \ \text{g/s})(1474 \ \text{s}) = \underline{\underline{200 \ \text{g}}}$

c. 1. Used a dirty flask. Chemicals remaining in the flask could react with benzene. Use a clean flask.
2. Put an open flask on the burner. Benzene vaporizes $\Rightarrow$ toxicity, fire hazard.
   Use a covered container or work under a hood.
3. Left the burner unattended.
4. Looked down into the flask with the boiling chemicals. Damage eyes. Wear goggles.
5. Rubbed his eyes with his hand. Wash with water.
6. Picked up flask with bare hands. Use lab gloves.
7. Put hot flask on partner's homework. Fire hazard.

11.25 a. <u>Moles of air in room:</u> $n = \dfrac{60 \ \text{m}^3}{} \left| \dfrac{273 \ \text{K}}{283 \ \text{K}} \right| \dfrac{1 \ \text{kg - mole}}{22.4 \ \text{m}^3 (\text{STP})} = 2.58 \ \text{kg - moles}$

<u>Energy balance on room air:</u> $nC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$$\Big\Downarrow \begin{array}{l} \dot{Q} = \dot{m}_s \Delta\hat{H}_v (\text{H}_2\text{O, 3bars, sat'd}) - 30.0(T - T_0) \\ \dot{W} = 0 \end{array}$$

$$nC_v \dfrac{dT}{dt} = \dot{m}_s \Delta\hat{H}_v - 30.0(T - T_0)$$

$$\Big\Downarrow \begin{array}{l} N = 2.58 \ \text{kg - moles} \\ C_v = 20.8 \ \text{kJ/(kg - mole} \cdot ^\circ\text{C)} \\ \Delta\hat{H}_v = 2163 \ \text{kJ/kg} \ (\text{from Table B.6}) \\ T_0 = 0^\circ\text{C} \end{array}$$

$$\underline{\underline{\dfrac{dT}{dt} = 40.3\dot{m}_s - 0.559T \ (^\circ\text{C/hr})}}$$

$$\underline{\underline{t = 0, \ T = 10^\circ\text{C}}}$$

(Note: a real process of this type would involve air escaping from the room and a constant pressure being maintained. We simplify the analysis by assuming *n* is constant.)

11.25 (cont'd)

b. At steady-state, $dT/dt = 0 \Rightarrow 40.3\dot{m}_s - 0.559T = 0 \Rightarrow \dot{m}_s = \dfrac{0.559T}{40.3}$

$T = 24°C \Rightarrow \underline{\underline{\dot{m}_s = 0.333 \text{ kg/hr}}}$

c. Separate variables and integrate the balance equation:

$$\int_{10}^{T_f} \frac{dT}{40.3\dot{m}_s - 0.559T} = \int_0^t dt \quad \xrightarrow[\substack{\dot{m}_s = 0.333 \\ T_f = 23°C}]{} \quad \int_{10}^{23} \frac{dT}{13.4 - 0.559T} = t$$

$$\Downarrow$$

$$t = -\frac{1}{0.559}\ln\left[\frac{13.4 - 0.559(23)}{13.4 - 0.559(10)}\right] = \underline{\underline{4.8 \text{ hr}}}$$

11.26 a. Integral energy balance $(t = 0 \text{ to } t = 20 \text{ min})$

$$Q = \Delta U = MC_v\Delta T = \frac{250 \text{ kg}}{} \left|\frac{4.00 \text{ kJ}}{\text{kg·°C}}\right| \frac{(60 - 20)°C}{} = 4.00 \times 10^4 \text{ kJ}$$

Required power input: $\dot{Q} = \dfrac{4.00 \times 10^4 \text{ kJ}}{20 \text{ min}} \left|\dfrac{1 \text{ min}}{60 \text{ s}}\right| \dfrac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{33.3 \text{ kW}}}$

b. Differential energy balance: $MC_v\dfrac{dT}{dt} = \dot{Q} \quad \xrightarrow[\substack{M = 250 \text{ kg} \\ C_v = 4.00 \text{ kJ/kg·°C}}]{} \quad \dfrac{dT}{dt} = 0.001\dot{Q}(t)$

$$\underline{\underline{t = 0, \ T = 20°C}}$$

Integrate: $\displaystyle\int_{20°C}^{T} dT = \int_0^t 0.001\,\dot{Q}\,dT \Rightarrow T = 20°C + \int_0^t \dot{Q}dt$

Evaluate the integral by Simpson's Rule (Appendix A.3)

$$\int_0^{600 \text{ s}} \dot{Q}dt = \frac{30}{3}\Big[33 + 4(33 + 35 + 39 + 44 + 50 + 58 + 66 + 75 + 85 + 95)$$

$$+ 2(34 + 37 + 41 + 47 + 54 + 62 + 70 + 80 + 90) + 100\Big] = 34830 \text{ kJ}$$

$$\Rightarrow T(600 \text{ s}) = 20°C + (0.001 \text{ °C/kJ})(34830 \text{ kJ}) = \underline{\underline{54.8°C}}$$

c. Past 600 s, $\dot{Q} = 100 + \dfrac{10 \text{ kW}}{60 \text{ s}}(t - 600 \text{ s}) = t/6$

$$T = 20 + 0.001\int_0^t \dot{Q}dt = 20 + 0.001\left[\underbrace{\int_0^{600} \dot{Q}dt}_{34830} + \int_{600}^t \frac{t}{6}dt\right]$$

$$\Rightarrow T = 54.8 + \frac{0.001}{6}\left(\frac{t^2}{6} - \frac{600^2}{2}\right) \Rightarrow t(s) = \sqrt{12000(T - 24.8)}$$

$T = 85°C \Rightarrow t = 850 \text{ s} = 14 \text{ min, } 10 \text{ s} \Rightarrow \underline{\underline{\text{explosion at } 10:14 + 10 \text{ s}}}$

11.27 a. Total Mass Balance:

Accumulation=Input– Output

$$\Downarrow$$

$$\frac{dM_{tot}}{dt} = \dot{m}_i - \dot{m}_o \Rightarrow \frac{d(\rho V)}{dt} = 8.00\rho - 4.00\rho \xrightarrow{\rho=constant} \frac{dV}{dt} = 4.00 \text{ L}/\text{s}$$
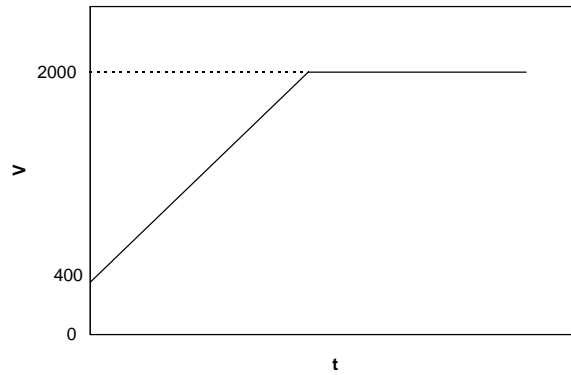
$$t = 0, \ V_0 = 400 \text{ L}$$

KCl Balance:

$$\text{Accumulation=Input-Output} \Rightarrow \frac{dM_{KCl}}{dt} = \dot{m}_{i,KCl} - \dot{m}_{o,KCl} \Rightarrow \frac{d(CV)}{dt} = 1.00 \times 8.00 - 4.00C$$

$$\Rightarrow V\frac{dC}{dt} + C\frac{dV}{dt} = 8 - 4C \xrightarrow{dV/dt = 4} \frac{dC}{dt} = \frac{8 - 8C}{V}$$

$$t = 0, \ C_0 = 0 \text{ g}/\text{L}$$

b. (i)The plot of V vs. t begins at (t=0, V=400). The slope (=dV/dt) is 4 (a positive constant). V increases linearly with increasing t until V reaches 2000. Then the tank begins to overflow and V stays constant at 2000.

(ii) The plot of C vs. t begins at (t=0, C=0). When t=0, the slope (=dC/dt) is (8-0)/400=0.02. As t increases, C increases and V increases (or stays constant)⟹ dC/dt=(8-8C)/V becomes less positive, approaches zero as t→ ∞. The curve is therefore <u>concave down.</u>
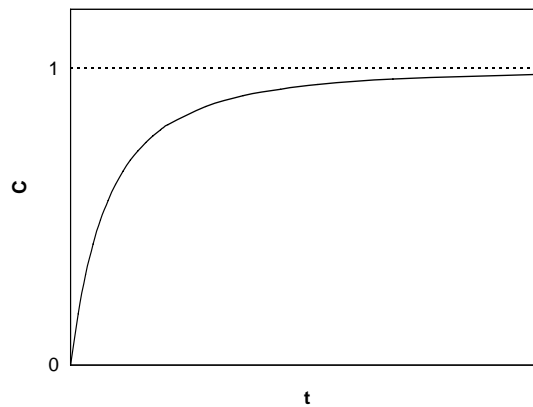
c. $$\frac{dV}{dt} = 4 \Rightarrow \int_{400}^{V} dV = 4\int_0^t dt \Rightarrow \underline{\underline{V = 400 + 4t}}$$

11.27 (cont'd)

$$\frac{dC}{dt} = \frac{8 - 8C}{V} \xrightarrow{V=400+4t} \frac{dC}{dt} = \frac{1 - C}{50 + 0.5t}$$

$$\int_0^C \frac{dC}{1 - C} = \int_0^t \frac{dt}{50 + 0.5t} \Rightarrow -\ln(1 - C)\big]_0^C = 2\ln(50 + 0.5t)\big]_0^t$$

$$\Rightarrow \ln(1 - C)^{-1} = 2\ln\frac{50 + 0.5t}{50} = \ln(1 + 0.01t)^2$$

$$\Rightarrow \frac{1}{1 - C} = (1 + 0.01t)^2 \Rightarrow \underline{\underline{C = 1 - \frac{1}{(1 + 0.01t)^2}}}$$

When the tank overflows, $V = 400 + 4t = 2000 \Rightarrow t = 400$ s

$$C = 1 - \frac{1}{(1 + 0.01 \times 400)^2} = \underline{\underline{0.96 \text{ g}/\text{L}}}$$

11.28 a. <u>Salt Balance on the 1st tank:</u>
Accumulation=-Output
$$\Downarrow$$

$$\frac{d(C_{S1}V_1)}{dt} = -C_{S1}\dot{v} \Rightarrow \frac{dC_{S1}}{dt} = -C_{S1}\frac{\dot{v}}{V_1} = -0.08C_{S1}$$

$$\underline{\underline{C_{S1}(0) = 1500/500 = 3 \text{ g}/\text{L}}}$$
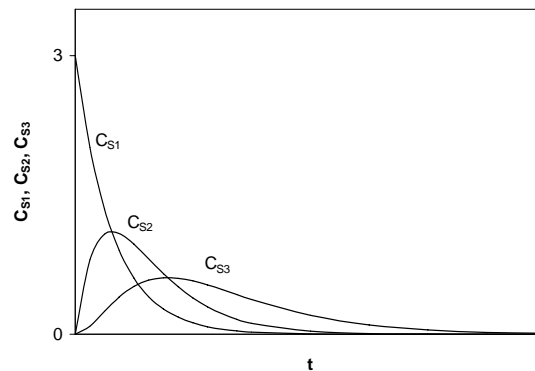
<u>Salt Balance on the 2nd tank:</u>
Accumulation=Input-Output
$$\Downarrow$$

$$\frac{d(C_{S2}V_2)}{dt} = C_{S1}\dot{v} - C_{S2}\dot{v} \Rightarrow \frac{dC_{S2}}{dt} = (C_{S1} - C_{S2})\frac{\dot{v}}{V_2} = 0.08(C_{S1} - C_{S2})$$

$$\underline{\underline{C_{S2}(0) = 0 \text{ g}/\text{L}}}$$

<u>Salt Balance on the 3rd tank:</u>
Accumulation=Input-Output
$$\Downarrow$$

$$\frac{d(C_{S3}V_3)}{dt} = C_{S2}\dot{v} - C_{S3}\dot{v} \Rightarrow \frac{dC_{S3}}{dt} = (C_{S2} - C_{S3})\frac{\dot{v}}{V_3} = 0.04(C_{S2} - C_{S3})$$

$$\underline{\underline{C_{S3}(0) = 0 \text{ g}/\text{L}}}$$

b.

The plot of C_{S1} vs. t begins at (t=0, C_{S1}=3). When t=0, the slope (=dC_{S1}/dt) is $-0.08 \times 3 = -0.24$. As t increases, C_{S1} decreases $\Rightarrow dC_{S1}/dt$=-0.08C_{S1} becomes less negative, approaches zero as t$\rightarrow \infty$. The curve is therefore <u>concave up.</u>

The plot of C_{S2} vs. t begins at (t=0, C_{S2}=0). When t=0, the slope (=dC_{S2}/dt) is $0.08(3-0) = 0.24$. As t increases, C_{S2} increases, C_{S1} decreases ($C_{S2} < C_{S1}$)$\Rightarrow dC_{S2}/dt$ =0.08(C_{S1}-C_{S2}) becomes less positive until dC_{S2}/dt changes to negative ($C_{S2} > C_{S1}$). Then C_{S2} decreases with increasing t as well as C_{S1}. Finally dC_{S2}/dt approaches zero as t$\rightarrow\infty$. Therefore, C_{S2} increases until it reaches a maximum value, then it decreases.

The plot of C_{S3} vs. t begins at (t=0, C_{S3}=0). When t=0, the slope (=dC_{S3}/dt) is $0.04(0-0) = 0$. As t increases, C_{S2} increases ($C_{S3} < C_{S2}$)$\Rightarrow dC_{S3}/dt$ =0.04(C_{S2}-C_{S3}) becomes positive $\Rightarrow C_{S2}$ increases with increasing t until dC_{S3}/dt changes to negative ($C_{S3} > C_{S1}$). Finally dC_{S3}/dt approaches zero as t$\rightarrow\infty$. Therefore, C_{S3} increases until it reaches a maximum value then it decreases.

c.
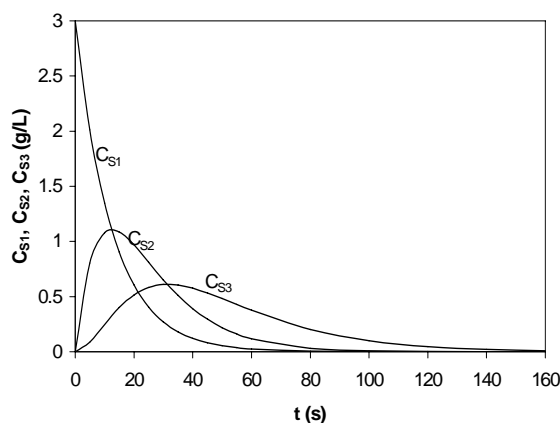
11.29 a. (i) <u>Rate of generation of B in the 1st reaction:</u> $r_{B1} = 2r_1 = \underline{\underline{0.2C_A}}$

(ii) <u>Rate of consumption of B in the 2nd reaction:</u> $-r_{B2} = r_2 = \underline{\underline{0.2C_B^2}}$

b. <u>Mole Balance on A:</u>
Accumulation=-Consumption
$\Downarrow$

$$\frac{d(C_A V)}{dt} = -0.1C_A V \Rightarrow \frac{dC_A}{dt} = -0.1C_A$$

$$t = 0, \ C_{A0} = \underline{\underline{1.00 \text{ mol} / \text{L}}}$$
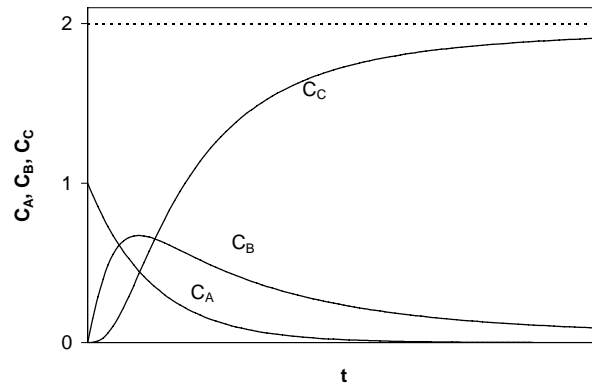
<u>Mole Balance on B:</u>
Accumulation= Generation-Consumption
$\Downarrow$

$$\frac{d(C_B V)}{dt} = 0.2C_A V - 0.2C_B^2 V \Rightarrow \frac{dC_B}{dt} = 0.2C_A - 0.2C_B^2$$

$$t = 0, \ C_{B0} = \underline{\underline{0 \text{ mol} / \text{L}}}$$

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 $\Rightarrow$ 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 ($C_B^2 < C_A$)$\Rightarrow$ 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 $\Rightarrow$ dC_C/dt =0.2 C_B^2 becomes positive also increases with increasing t
$\Rightarrow$ C_C increases faster until C_B decreases with increasing t $\Rightarrow$ 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.
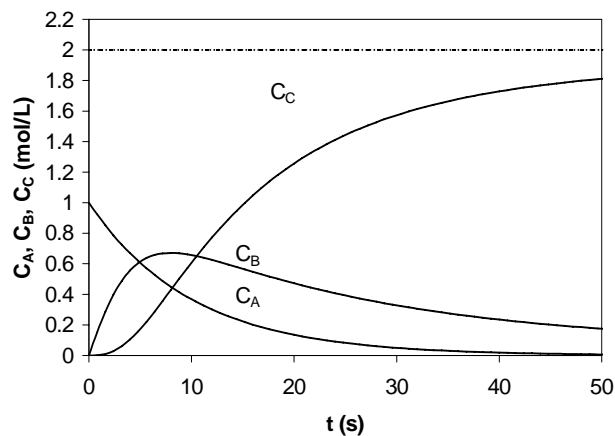
11.30 a. When $x = 1$, $\underline{\underline{y = 1}}$.

$$y = \frac{ax}{x+b} \overset{x=1, y=1}{\Rightarrow} 1 = \frac{a}{1+b} \Rightarrow \underline{\underline{a = 1+b}}$$

b. Raoult's Law: $\quad p_{C_5H_{12}} = yP = xp*_{C_5H_{12}}(46^oC) \Rightarrow y = \dfrac{xp*_{C_5H_{12}}(46^oC)}{P}$

Antoine Equation: $\quad p*_{C_5H_{12}}(46^oC) = 10^{(6.84471 - \frac{1060.793}{46+231.541})} = 1053$ mm Hg

$$\Rightarrow y = \frac{xp*_{C_5H_{12}}(46^oC)}{P} = \frac{0.7 \times 1053}{760} = \underline{\underline{0.970}}$$

$$\begin{cases} y = \dfrac{ax}{x+b} \overset{x=0.70,\ y=0.970}{\Longrightarrow} 0.970 = \dfrac{0.70a}{0.70+b} \cdots\cdots(1) \\ \text{From part (a), } a = 1+b \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(2) \end{cases} \Rightarrow \begin{cases} \underline{\underline{a = 1.078}} \\ \underline{\underline{b = 0.078}} \end{cases}$$

c. Mole Balance on Residual Liquid:
Accumulation=-Output
$$\Downarrow$$

$$\frac{dN_L}{dt} = -\dot{n}_V$$

$$\underline{\underline{t = 0,\ N_L = 100 \text{ mol}}}$$

Balance on Pentane:
Accumulation=-Output
$$\Downarrow$$

$$\frac{d(N_L x)}{dt} = -\dot{n}_V y \Rightarrow x\frac{dN_L}{dt} + N_L \frac{dx}{dt} = -\dot{n}_V \frac{ax}{x+b}$$

$$\Downarrow dN_L / dt = -\dot{n}_V$$

$$\frac{dx}{dt} = -\frac{\dot{n}_V}{N_L}\left(\frac{ax}{x+b} - x\right)$$

$$\underline{\underline{t = 0,\ x = 0.70}}$$

d. Energy Balance: Consumption=Input
$$\Downarrow$$

$$\dot{n}_V \Delta \hat{H}_{vap} = \dot{Q} \xrightarrow{\Delta \hat{H}_{vap} = 27.0 \text{ kJ/mol}} \dot{n}_V = \frac{\dot{Q}}{(27.0 \text{ kJ/mol})}$$

From part (c), $\dfrac{dN_L}{dt} = -\dot{n}_V \xrightarrow{t=0,\ N_L = 100 \text{ mol}} N_L = 100 - \dot{n}_V t = 100 - \dfrac{\dot{Q}t}{27.0}$

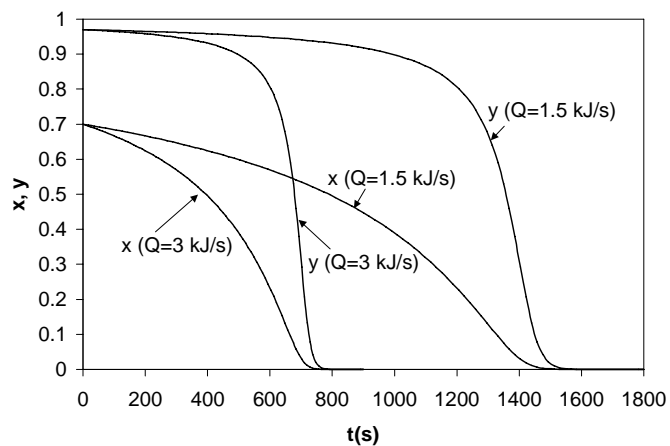$$\frac{\dot{n}_V}{N_L} = \frac{\dot{Q}/27.0}{100 - \dfrac{\dot{Q}t}{27.0}}$$

Substitute this expression into the equation for dx/dt from part (c):

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.