

CHAPTER EIGHT

- 8.1 a.** $\hat{U}(T) = 25.96T + 0.02134T^2 \text{ J/mol}$
 $\underline{\underline{\hat{U}(0^\circ\text{C}) = 0 \text{ J/mol}}}$ $\underline{\underline{\hat{U}(100^\circ\text{C}) = 2809 \text{ J/mol}}}$ $\underline{\underline{T_{ref} = 0^\circ\text{C}}}$ (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.** $Q - W = \Delta U + \Delta E_k + \Delta E_p$
 $\Downarrow \Delta E_k = 0, \Delta E_p = 0, W = 0$
 $Q = \Delta U = (3.0 \text{ mol})[(2809 - 0) \text{ J/mol}] = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$
- d.** $C_v = \left(\frac{\partial \hat{U}}{\partial T} \right)_{\hat{V}} = \frac{d\hat{U}}{dT} = \underline{\underline{[25.96 + 0.04268T] \text{ J/(mol}\cdot^\circ\text{C)}}}$
 $\Delta \hat{U} = \int_{T_1}^{T_2} C_v(T) dT = \int_0^{100} (25.96 + 0.04268T) dT = \left(25.96T + 0.04268 \frac{T^2}{2} \right) \Big|_0^{100} \text{ J/mol}$
 $\Delta U = (3.0 \text{ mol}) \cdot \Delta \hat{U} \text{ (J/mol)}$
 $= (3.0 \text{ mol}) \cdot [25.96(100 - 0) + 0.02134(100^2 - 0)] \text{ (J/mol)} = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$
- 8.2 a.** $C_v = C_p - R \Rightarrow C_v = (35.3 + 0.0291T) [\text{J/(mol}\cdot^\circ\text{C})] - (8.314 [\text{J/(mol}\cdot\text{K})]) (1 \text{ K/}^\circ\text{C})$
 $\Rightarrow \underline{\underline{C_v = 27.0 + 0.0291T [\text{J/(mol}\cdot^\circ\text{C})]}}$
- b.** $\Delta \hat{H} = \int_{25}^{100} C_p dT = 35.3T \Big|_{25}^{100} + 0.0291 \frac{T^2}{2} \Big|_{25}^{100} = \underline{\underline{2784 \text{ J/mol}}}$
- 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.** $C_v [\text{kJ/(mol}\cdot^\circ\text{C})] = 0.0252 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2$
 $n = \frac{PV}{RT} = \frac{(2.00 \text{ atm})(3.00 \text{ L})}{(0.08206 [\text{atm}\cdot\text{L/(mol}\cdot\text{K})])(298 \text{ K})} = 0.245 \text{ mol}$
 $Q_1 = n\Delta \hat{U}_1 = (0.245 \text{ mol}) \cdot \int_{25}^{1000} 0.0252 dT \text{ (kJ/mol)} = \underline{\underline{6.02 \text{ kJ}}}$
 $Q_2 = n\Delta \hat{U}_2 = (0.245) \cdot \int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5} T] dT = \underline{\underline{7.91 \text{ kJ}}}$
 $Q_3 = n\Delta \hat{U}_3 = (0.245) \cdot \int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2] dT = \underline{\underline{7.67 \text{ kJ}}}$
 $\% \text{ error in } Q_1 = \frac{6.02 - 7.67}{7.67} \times 100\% = \underline{\underline{-21.5\%}}$
 $\% \text{ error in } Q_2 = \frac{7.91 - 7.67}{7.67} \times 100\% = \underline{\underline{3.13\%}}$

8.3 (cont'd)

b. $C_p = C_v + R$

$$C_p [\text{kJ} / (\text{mol} \cdot ^\circ \text{C})] = (0.0252 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2) + 0.008314$$

$$= \underline{\underline{0.0335 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2}}$$

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

$$= (0.245 \text{ mol}) \cdot \int_{25}^{1000} [0.0335 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2] dT [\text{kJ} / (\text{mol} \cdot ^\circ \text{C})] = \underline{\underline{9.65 \times 10^3 \text{ J}}}$$

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. $(C_p)_{\text{C}_6\text{H}_6(l)}(40^\circ \text{C}) = 0.1265 + 23.4 \times 10^{-5} (40) = \underline{\underline{0.1360 [\text{kJ}/(\text{mol} \cdot \text{K})]}}$

b. $(C_p)_{\text{C}_6\text{H}_6(v)}(40^\circ \text{C}) = 0.07406 + 32.95 \times 10^{-5} (40) - 25.20 \times 10^{-8} (40)^2 + 77.57 \times 10^{-12} (40)^3$

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

c. $(C_p)_{\text{C}(s)}(313 \text{ K}) = 0.01118 + 1.095 \times 10^{-5} (313) - 4.891 \times 10^{-2} (313)^{-2} = \underline{\underline{0.009615 [\text{kJ} / (\text{mol} \cdot \text{K})]}}$

d. $\Delta \hat{H}_{\text{C}_6\text{H}_6(v)} = 0.07406T + \frac{32.95 \times 10^{-5}}{2} T^2 - \frac{25.20 \times 10^{-8}}{3} T^3 + \frac{77.57 \times 10^{-12}}{4} T^4 \bigg]_{40}^{300} = \underline{\underline{31.71 \text{ kJ/mol}}}$

e. $\Delta \hat{H}_{\text{C}(s)} = 0.01118T + \frac{1.095 \times 10^{-5}}{2} T^2 + 4.891 \times 10^{-2} T^{-1} \bigg]_{313}^{573} = \underline{\underline{3.459 \text{ kJ/mol}}}$

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

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

b. $\hat{H} = \int_{100}^{350} [0.03346 + 0.6886 \times 10^{-5} T + 0.7604 \times 10^{-8} T^2 - 3.593 \times 10^{-12} T^3] dT$

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

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

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

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

c. $(C_p)_{\text{n-C}_6\text{H}_{14}(v)} [\text{kJ} / (\text{mol} \cdot ^\circ \text{C})] = 0.13744 + 40.85 \times 10^{-5} T - 23.92 \times 10^{-8} T^2 + 57.66 \times 10^{-12} T^3$

$$\Delta \hat{H} = \int_{500}^0 [0.13744 + 40.85 \times 10^{-5} T - 23.92 \times 10^{-8} T^2 + 57.66 \times 10^{-12} T^3] dT = \underline{\underline{-110.7 \text{ kJ/mol}}}$$

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

$$8.7 \quad T(^{\circ}\text{C}) = \frac{1}{1.8} [T'(^{\circ}\text{F}) - 32] = 0.5556T'(^{\circ}\text{F}) - 17.78$$

$$C_p (\text{cal/mol} \cdot ^{\circ}\text{C}) = 6.890 + 0.001436 [0.5556T'(^{\circ}\text{F}) - 17.78] = 6.864 + 0.0007978T'(^{\circ}\text{F})$$

$$C_p' (\text{Btu/lb} \cdot \text{mole} \cdot ^{\circ}\text{F}) \quad \underset{\substack{\Downarrow \\ \text{drop primes}}}{=} \quad C_p \frac{\text{cal}}{\text{mol} \cdot ^{\circ}\text{C}} \left| \frac{453.6 \text{ mol}}{1 \text{ lb} \cdot \text{mole}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| \left| \frac{1^{\circ}\text{C}}{1.8^{\circ}\text{F}} \right| = (1.00)C_p$$

$$\underline{\underline{C_p (\text{Btu/lb} \cdot \text{mole} \cdot ^{\circ}\text{F}) = 6.864 + 0.0007978T(^{\circ}\text{F})}}$$

$$8.8 \quad (C_p)_{\text{CH}_3\text{CH}_2\text{OH(l)}}(T) = 0.1031 + \frac{(0.1588 - 0.1031)}{100} T = 0.1031 + 0.000557T \text{ [kJ / (mol} \cdot ^{\circ}\text{C)]}$$

$$Q = \Delta H = \frac{55.0 \text{ L}}{\text{s}} \left| \frac{789 \text{ g}}{1 \text{ L}} \right| \left| \frac{1 \text{ mol}}{46.07 \text{ g}} \right| \underbrace{\left(0.1031T + \frac{0.000557}{2} T^2 \right)}_{\text{kJ/mol}} \bigg|_{20}^{78.5}$$

$$= 941.9 \times 7.636 \text{ kJ/s} = \underline{\underline{7193 \text{ kW}}}$$

$$8.9 \quad \text{a.} \quad \overbrace{\int_{100}^{200} [0.03360 + 1.367 \times 10^{-5} T - 1.607 \times 10^{-8} T^2 + 6.473 \times 10^{-12} T^3] dT}^{\text{kJ/mol}}$$

$$= \underline{\underline{17,650 \text{ kW}}}$$

$$\text{b.} \quad Q = \Delta U = \Delta H - \Delta PV = \Delta H - nR\Delta T = 17,650 \text{ kJ} - (5.0 \text{ kmol}) \cdot (8.314 \text{ [kJ / (kmol} \cdot \text{K)]}) \cdot (100 \text{ K})$$

$$= \underline{\underline{13,490 \text{ kJ}}}$$

The difference is the flow work done on the gas in the continuous system.

$$\text{c.} \quad Q_{\text{additional}} = \text{heat needed to raise temperature of vessel wall} + \text{heat that escapes from wall to surroundings.}$$

$$8.10 \quad \text{a.} \quad \underline{\underline{C_p \text{ is a constant, i.e. } C_p \text{ is independent of } T.}}$$

$$\text{b.} \quad Q = mC_p \Delta T \Rightarrow C_p = \frac{Q}{m\Delta T}$$

$$C_p = \frac{Q}{m\Delta T} = \frac{(16.73 - 6.14) \text{ kJ}}{(2.00 \text{ L})(3.10 \text{ K})} \left| \frac{1 \text{ L}}{659 \text{ g}} \right| \left| \frac{86.17 \text{ g}}{1 \text{ mol}} \right| \left| \frac{10^3 \text{ J}}{1 \text{ kJ}} \right| = \underline{\underline{0.223 \text{ kJ / (mol} \cdot \text{K)}}}$$

$$\text{Table B.2} \Rightarrow C_p = 0.216 \text{ kJ / (mol} \cdot ^{\circ}\text{C)} = 0.216 \text{ kJ / (mol} \cdot \text{K)}$$

$$8.11 \quad \hat{H} = \hat{U} + P\hat{V} \xrightarrow{P\hat{V}=RT} \hat{H} = \hat{U} + RT \xrightarrow{(\partial/\partial T)_p} \left(\frac{\partial \hat{H}}{\partial T} \right)_p = \left(\frac{\partial \hat{U}}{\partial T} \right)_p + R \Rightarrow C_p = \left(\frac{\partial \hat{U}}{\partial T} \right)_p + R$$

$$\text{But since } \hat{U} \text{ depends only on } T, \left(\frac{\partial \hat{U}}{\partial T} \right)_p = \frac{d\hat{U}}{dT} = \left(\frac{\partial \hat{U}}{\partial T} \right)_{\hat{V}} \equiv C_v \Rightarrow \underline{\underline{C_p = C_v + R}}$$

8.12 a. $(C_p)_{\text{H}_2\text{O(l)}} = 75.4 \text{ kJ} / (\text{kmol} \cdot ^\circ\text{C}) = 75.4 \text{ kJ}/(\text{kmol} \cdot ^\circ\text{C}) \quad V = 1230 \text{ L},$

$$n = \frac{V\rho}{M} = \frac{1230 \text{ L}}{1 \text{ L}} \left| \frac{1 \text{ kg}}{18 \text{ kg}} \right| \frac{1 \text{ kmol}}{18 \text{ kg}} = 68.3 \text{ kmol}$$

$$\dot{Q} = \frac{Q}{t} = \frac{n \cdot \int_T^{T_2} (C_p)_{\text{H}_2\text{O(l)}} dT}{t} = \frac{68.3 \text{ kmol}}{1 \text{ h}} \left| \frac{75.4 \text{ kJ}}{\text{kmol} \cdot ^\circ\text{C}} \right| \left| \frac{(40 - 29) ^\circ\text{C}}{8 \text{ h}} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| = \underline{\underline{1.967 \text{ kW}}}$$

b. $\dot{Q}_{\text{total}} = \dot{Q}_{\text{to the surroundings}} + \dot{Q}_{\text{to water}}, \quad \dot{Q}_{\text{to the surroundings}} = 1.967 \text{ kW}$

$$\dot{Q}_{\text{to water}} = \frac{Q_{\text{to water}}}{t} = \frac{n \cdot \int_{29}^{40} C_{p(\text{H}_2\text{O})} dT}{t} = \frac{68.3 \text{ kmol}}{3 \text{ h}} \left| \frac{75.4 \text{ kJ} / (\text{kmol} \cdot ^\circ\text{C})}{3600 \text{ s} / \text{h}} \right| \left| \frac{11 ^\circ\text{C}}{11 ^\circ\text{C}} \right| = 5.245 \text{ kW}$$

$$\dot{Q}_{\text{total}} = \underline{\underline{7.212 \text{ kW}}} \Rightarrow E_{\text{total}} = 7.212 \text{ kW} \times 3 \text{ h} = \underline{\underline{21.64 \text{ kW} \cdot \text{h}}}$$

c. $\text{Cost}_{\text{heating up from } 29 ^\circ\text{C to } 40 ^\circ\text{C}} = 21.64 \text{ kW} \cdot \text{h} \times \$0.10 / (\text{kW} \cdot \text{h}) = \underline{\underline{\$2.16}}$

$$\text{Cost}_{\text{keeping temperature constant for 13 h}} = 1.967 \text{ kW} \times 13 \text{ h} \times \$0.10 / (\text{kW} \cdot \text{h}) = \underline{\underline{\$2.56}}$$

$$\text{Cost}_{\text{total}} = \$2.16 + \$2.56 = \underline{\underline{\$4.72}}$$

d. If the lid is removed, more heat will be transferred into the surroundings and lost, resulting in higher cost.

8.13 a. $\Delta \hat{H}_{\text{N}_2(25^\circ\text{C}) \rightarrow \text{N}_2(700^\circ\text{C})} = \hat{H}_{\text{N}_2(700^\circ\text{C})} - \hat{H}_{\text{N}_2(25^\circ\text{C})} = (20.59 - 0) = \underline{\underline{20.59 \text{ kJ/mol}}}$

b. $\Delta \hat{H}_{\text{H}_2(800^\circ\text{F}) \rightarrow \text{H}_2(77^\circ\text{F})} = \hat{H}_{\text{H}_2(77^\circ\text{F})} - \hat{H}_{\text{H}_2(800^\circ\text{F})} = (0 - 5021) = \underline{\underline{-5021 \text{ Btu} / \text{lb} \cdot \text{mol}}}$

c. $\Delta \hat{H}_{\text{CO}_2(300^\circ\text{C}) \rightarrow \text{CO}_2(1250^\circ\text{C})} = \hat{H}_{\text{CO}_2(1250^\circ\text{C})} - \hat{H}_{\text{CO}_2(300^\circ\text{C})} = (63.06 - 11.58) = \underline{\underline{51.48 \text{ kJ/mol}}}$

d. $\Delta \hat{H}_{\text{O}_2(970^\circ\text{F}) \rightarrow \text{O}_2(0^\circ\text{F})} = \hat{H}_{\text{O}_2(0^\circ\text{F})} - \hat{H}_{\text{O}_2(970^\circ\text{F})} = (-539 - 6774) = \underline{\underline{-7313 \text{ Btu} / \text{lb} \cdot \text{mol}}}$

8.14 a. $\dot{m} = 300 \text{ kg} / \text{min} \quad \dot{n} = \frac{300 \text{ kg}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right| \left| \frac{1 \text{ mol}}{28.01 \text{ g}} \right| = 178.5 \text{ mol} / \text{s}$

$$\begin{aligned} \dot{Q} &= \dot{n} \cdot \Delta \hat{H} = \dot{n} \cdot \int_{T_1}^{T_2} C_p dT \\ &= (178.5 \text{ mol} / \text{s}) \cdot \int_{450}^{50} [0.02895 + 0.411 \times 10^{-5} T + 0.3548 \times 10^{-8} T^2 - 2.22 \times 10^{-12} T^3] dT [\text{kJ} / \text{mol}] \\ &= (178.5 \text{ mol} / \text{s}) (-12.076 [\text{kJ} / \text{mol}]) = \underline{\underline{-2,156 \text{ kW}}} \end{aligned}$$

b. $\dot{Q} = \dot{n} \cdot \Delta \hat{H} = \dot{n} \cdot [\hat{H}_{(50^\circ\text{C})} - \hat{H}_{(450^\circ\text{C})}] = (178.5 \text{ mol} / \text{s}) (0.73 - 12.815 [\text{kJ} / \text{mol}]) = \underline{\underline{-2,157 \text{ kW}}}$

8.15 a. $\dot{n} = 250 \text{ mol} / \text{h}$

i) $\dot{Q} = \dot{n} \Delta \hat{H} = \frac{250 \text{ mol}}{\text{h}} \left| \frac{(2676 - 3697) \text{ kJ}}{1 \text{ kg}} \right| \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \left| \frac{18.02 \text{ g}}{1 \text{ mol}} \right| = \underline{\underline{-1.278 \text{ kW}}}$

ii)
$$\begin{aligned} \dot{Q} &= \dot{n} \Delta \hat{H} = \dot{n} \cdot \int_{T_1}^{T_2} C_p dT \\ &= \frac{250 \text{ mol}}{\text{h}} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \int_{600}^{100} [0.03346 + 0.6880 \times 10^{-5} T + 0.7604 \times 10^{-8} T^2 - 3.593 \times 10^{-12} T^3] dT = \underline{\underline{-1.274 \text{ kW}}} \end{aligned}$$

8.15 (cont'd)

$$\text{iii) } \dot{Q} = \frac{250 \text{ mol}}{3600 \text{ s}} \cdot (2.54 - 20.91) [\text{kJ} / \text{mol}] = \underline{\underline{-1.276 \text{ kW}}}$$

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 $\Delta \hat{H}$.

$$\dot{n} = \frac{200 \text{ ft}^3}{\text{h}} \left| \frac{492^\circ \text{R}}{537^\circ \text{R}} \right| \left| \frac{1.2 \text{ atm}}{1 \text{ atm}} \right| \left| \frac{1 \text{ lb-mol}}{359 \text{ ft}^3 (\text{STP})} \right| = 0.6125 \text{ lb-mole} / \text{h}$$

$$\dot{Q} = \dot{n} \Delta \hat{H} = (0.6125 \frac{\text{lb-mole}}{\text{h}}) \cdot ((2993 - 0) [\text{Btu} / \text{lb-mole}]) = \underline{\underline{1833 \text{ Btu} / \text{h}}}$$

$$\text{8.17 a. } \frac{50 \text{ kg}}{1} \left| \frac{1.14 \text{ kJ}}{\text{kg} \cdot ^\circ \text{C}} \right| \left| \frac{(50 - 10)^\circ \text{C}}{1} \right| = \underline{\underline{2280 \text{ kJ}}}$$

b.

$$(C_p)_{\text{Na}_2\text{CO}_3} \approx 2(C_p)_{\text{Na}} + (C_p)_\text{C} + 3(C_p)_\text{O} = 2(0.026) + 0.0075 + 3(0.017) = 0.1105 \text{ kJ} / \text{mol} \cdot ^\circ \text{C}$$

$$\frac{50,000 \text{ g}}{1} \left| \frac{0.1105 \text{ kJ}}{\text{mol} \cdot ^\circ \text{C}} \right| \left| \frac{1 \text{ mol}}{105.99 \text{ g}} \right| \left| \frac{(50 - 10)^\circ \text{C}}{1} \right| = \underline{\underline{2085 \text{ kJ}}}$$

$$\% \text{ error} = \frac{2085 - 2280}{2280} \times 100\% = \underline{\underline{-8.6\% \text{ error}}}$$

$$\text{8.18 } (C_p)_{\text{C}_6\text{H}_{14}\text{O(l)}} = 6(0.012) + 14(0.018) + 1(0.025) = 0.349 \text{ kJ} / (\text{mol} \cdot ^\circ \text{C}) \quad (\text{Kopp's Rule})$$

$$(C_p)_{\text{CH}_3\text{COCH}_3(\text{l})} = 0.1230 + 18.6 \times 10^{-5} T \text{ kJ} / (\text{mol} \cdot ^\circ \text{C})$$

Assume $\Delta H_{\text{mix}} \cong 0$

$$C_{pm} = \frac{0.30(0.1230 + 18.6 \times 10^{-5} T) \text{ kJ}}{\text{mol} \cdot ^\circ \text{C}} \left| \frac{1 \text{ mol}}{58.08 \text{ g}} \right| + \frac{0.70(0.349) \text{ kJ}}{\text{mol} \cdot ^\circ \text{C}} \left| \frac{1 \text{ mol}}{102.17 \text{ g}} \right|$$

$$= [0.003026 + 9.607 \times 10^{-7} T] \text{ kJ} / (\text{g} \cdot ^\circ \text{C})$$

$$\Delta \hat{H} = \int_{45}^{20} [0.003026 + 9.607 \times 10^{-7} T] dT = \underline{\underline{-0.07643 \text{ kJ/g}}}$$

8.19 Assume ideal gas behavior, $\Delta H_{\text{mix}} \cong 0$

$$\bar{M}_w = \frac{1}{3}(16.04) + \frac{2}{3}(32.00) = 26.68 \frac{\text{g}}{\text{mol}}$$

$$\Delta \hat{H}_{\text{O}_2} = \int_{25}^{350} (C_p)_{\text{O}_2} dT = 10.08 \text{ kJ} / \text{mol}, \quad \Delta \hat{H}_{\text{CH}_4} = \int_{25}^{350} (C_p)_{\text{CH}_4} dT = 14.49 \text{ kJ} / \text{mol}$$

$$\hat{H} = \left[\frac{1}{3}(14.49 \text{ kJ} / \text{mol}) + \frac{2}{3}(10.08 \text{ kJ} / \text{mol}) \right] \left(\frac{1000 \text{ g}}{1 \text{ kg}} \right) \left(\frac{1 \text{ mol}}{26.68 \text{ g}} \right) = \underline{\underline{433 \text{ kJ/kg}}}$$

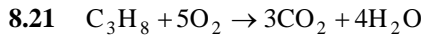
$$8.20 \quad n = \frac{1000 \text{ m}^3}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{273 \text{ K}}{303 \text{ K}} \left| \frac{1 \text{ kmol}}{22.4 \text{ m}^3 (\text{STP})} \right| = 0.6704 \text{ kmol/s} = 670.4 \text{ mol/s}$$

Energy balance on air:

$$Q = \Delta H = n\Delta\hat{H} \xrightarrow{\text{Table B.8 for } \Delta\hat{H}} Q = \frac{670.4 \text{ mol}}{\text{s}} \left| \frac{0.73 \text{ kJ}}{\text{mol}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = 489.4 \text{ kW}$$

$$\text{Solar energy required} = \frac{489.4 \text{ kW heating}}{0.3 \text{ kW heating}} \left| \frac{1 \text{ kW solar energy}}{1 \text{ kW}} \right| = 1631 \text{ kW}$$

$$\text{Area required} = \frac{1631 \text{ kW}}{1 \text{ kW}} \left| \frac{1000 \text{ W}}{900 \text{ W}} \right| \frac{1 \text{ m}^2}{1 \text{ m}^2} = \underline{\underline{1813 \text{ m}^2}}$$



$$\dot{n}_{\text{fuel}} = \frac{1.35 \times 10^5 \text{ SCFH}}{\text{h}} \left| \frac{1 \text{ lb-mol}}{359 \text{ ft}^3} \right| = 376 \frac{\text{lb-mol}}{\text{h}}$$

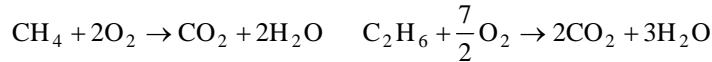
$$\dot{n}_{\text{air}} = \frac{376 \text{ lb-mol}}{\text{h}} \left| \frac{5 \text{ lb-mol O}_2}{1 \text{ lb-mol C}_3\text{H}_8} \right| \left| \frac{1 \text{ lb-mol air}}{0.21 \text{ lb-mol O}_2} \right| \frac{1.15}{1} = 1.03 \times 10^4 \frac{\text{lb-mol}}{\text{h}}$$

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

$$= \left(1.03 \times 10^4 \frac{\text{lb-mol}}{\text{h}} \right) \cdot \int_0^{302} [0.02894 + 0.4147 \times 10^{-5} T + 0.3191 \times 10^{-8} T^2 - 1.965 \times 10^{-12} T^3] dT$$

$$= \frac{1.03 \times 10^4 \text{ lb-mol}}{\text{h}} \left| \frac{8.954 \text{ kJ}}{\text{mol}} \right| \frac{453.593 \text{ mol}}{\text{lb-mol}} \left| \frac{9.486 \times 10^{-1} \text{ Btu}}{\text{kJ}} \right| = \underline{\underline{3.97 \times 10^7 \text{ Btu/h}}}$$

8.22 a. Basis: 100 mol feed (95 mol CH₄ and 5 mol C₂H₆)



$$n_{\text{O}_2} = 1.25 \cdot \left[\frac{95 \text{ mol CH}_4}{1 \text{ mol CH}_4} \left| \frac{2 \text{ mol O}_2}{1 \text{ mol CH}_4} \right| + \frac{5 \text{ mol C}_2\text{H}_6}{1 \text{ mol C}_2\text{H}_6} \left| \frac{3.5 \text{ mol O}_2}{1 \text{ mol C}_2\text{H}_6} \right| \right] = 259.4 \text{ mol O}_2$$

Product Gas:

$$\text{CO}_2: 95(1) + 5(2) = 105 \text{ mol CO}_2 \quad \text{H}_2\text{O}: 95(2) + 5(3) = 205 \text{ mol H}_2\text{O}$$

$$\text{O}_2: 259.4 - 95(2) - 5(3.5) = 51.9 \text{ mol O}_2 \quad \text{N}_2: 3.76(259.4) = 975 \text{ mol N}_2$$

Energy balance (enthalpies from Table B.8)

$$\Delta\hat{H}_{\text{CO}_2} = \hat{H}_{(\text{CO}_2, 450^\circ\text{C})} - \hat{H}_{(\text{CO}_2, 900^\circ\text{C})} = 18.845 - 42.94 = -24.09 \text{ kJ/mol}$$

$$\Delta\hat{H}_{\text{H}_2\text{O}} = \hat{H}_{(\text{H}_2\text{O}, 450^\circ\text{C})} - \hat{H}_{(\text{H}_2\text{O}, 900^\circ\text{C})} = 15.12 - 33.32 = -18.20 \text{ kJ/mol}$$

$$\Delta\hat{H}_{\text{O}_2} = \hat{H}_{(\text{O}_2, 450^\circ\text{C})} - \hat{H}_{(\text{O}_2, 900^\circ\text{C})} = 13.375 - 28.89 = -15.51 \text{ kJ/mol}$$

$$\Delta\hat{H}_{\text{N}_2} = \hat{H}_{(\text{N}_2, 450^\circ\text{C})} - \hat{H}_{(\text{N}_2, 900^\circ\text{C})} = 12.695 - 27.19 = -14.49 \text{ kJ/mol}$$

$$Q = \Delta H = [105(-24.09) + 205(-18.20) + 51.9(-15.51) + 975(-14.49)]$$

$$Q = 21,200 \text{ kJ / 100 mol feed}$$

b. From Table B.5: $\hat{H}_{\text{liq}}(40^\circ\text{C}) = 167.5 \text{ kJ/kg}$; $\hat{H}_{\text{vap}}(50 \text{ bars}) = 2794.2 \text{ kJ/kg}$;

$$Q = n \cdot \Delta\hat{H} = n(2794.2 - 167.5) = 21200 \Rightarrow n = \underline{\underline{8.07 \text{ kg / 100 mol feed}}}$$

8.22 (cont'd)

- c. From part (b), 8.07 kg steam is produced per 100 mol feed

$$\dot{n}_{feed} = \frac{1250 \text{ kg steam}}{\text{h}} \left| \frac{0.1 \text{ kmol feed}}{8.07 \text{ kg steam}} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| = 4.30 \times 10^{-3} \text{ kmol/s}$$

$$\dot{V}_{product \text{ gas}} = \frac{4.30 \text{ mol feed}}{\text{s}} \left| \frac{1336.9 \text{ mol product gas}}{100 \text{ mol feed}} \right| \left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \left| \frac{723 \text{ K}}{1.01325 \times 10^5 \text{ Pa}} \right| = 3.41 \text{ m}^3/\text{s}$$

- 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

$$\text{Assume } \Delta H_{mix} \cong 0 \Rightarrow \Delta H = \Delta H_{C_{10}H_{12}O_2} + \Delta H_{C_6H_6}$$

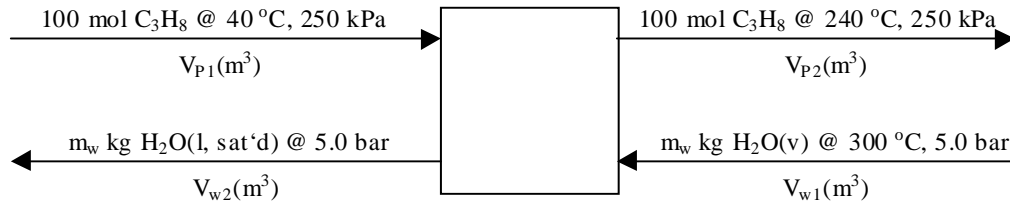
$$\text{Kopp's rule: } (C_p)_{C_{10}H_{12}O_2} = 10(12) + 12(18) + 2(25) = 386 \text{ J/(mol} \cdot ^\circ\text{C)} = 2.35 \text{ J/(g} \cdot ^\circ\text{C)}$$

$$\Delta H_{C_{10}H_{12}O_2} = \frac{20.0 \text{ L}}{\text{L}} \left| \frac{1021 \text{ g}}{10^3 \text{ J}} \right| \left| \frac{1 \text{ kJ}}{\text{g} \cdot ^\circ\text{C}} \right| \left| \frac{2.35 \text{ J}}{\text{g} \cdot ^\circ\text{C}} \right| (71 - 25) ^\circ\text{C} = 2207 \text{ kJ}$$

$$\Delta H_{C_6H_6} = \frac{15.0 \text{ L}}{\text{L}} \left| \frac{879 \text{ g}}{78.11 \text{ g}} \right| \left| \frac{1 \text{ mol}}{78.11 \text{ g}} \right| \cdot \left[\int_{298}^{348} [0.06255 + 23.4 \times 10^{-5} T] dT \right] = 1166 \text{ kJ}$$

$$\Delta H = 2207 + 1166 = 3373 \text{ kJ}$$

8.24 a.



- b. References: H_2O (l, 0.01 °C), C_3H_8 (gas, 40 °C)

$$C_3H_8: \hat{H}_{in} = 0 \text{ kJ/mol}; \hat{H}_{out} = \int_{40}^{240} C_{p,C_3H_8} dT = 19.36 \text{ kJ/mol} \quad (C_p \text{ from Table B.2})$$

$$H_2O: \hat{H}_{in} = 3065 \text{ kJ/kg} \quad (\text{Table B.7}); \hat{H}_{out} = 640.1 \text{ kJ/kg} \quad (\text{Table B.6})$$

- c. $\Delta \hat{H}_{C_3H_8} = 19.36 \text{ kJ/mol}$, $\Delta \hat{H}_w = (640.1 - 3065) \text{ kJ/kg} = -2425 \text{ kJ/kg}$

$$Q = \Delta H = 100 \Delta \hat{H}_{C_3H_8} + m_w \Delta \hat{H}_w = 0 \Rightarrow m_w = 0.798 \text{ kg}$$

$$\text{From Table B.7: } \hat{V}_{steam}(5.0 \text{ bar}, 300^\circ\text{C}) = 0.522 \text{ m}^3/\text{kg}$$

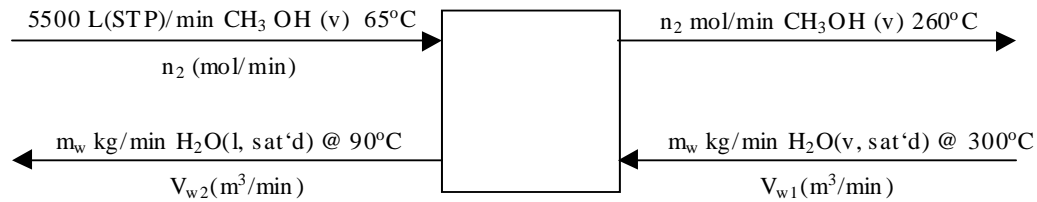
$$\hat{V}_{C_3H_8}(40^\circ\text{C}, 250 \text{ kPa}) = \frac{0.008314 \text{ m}^3 \cdot \text{kPa}/(\text{mol} \cdot \text{K})}{250 \text{ kPa}} \left| \frac{313 \text{ K}}{1} \right| = 0.0104 \text{ m}^3/\text{mol } C_3H_8$$

$$\frac{0.798 \text{ kg steam}}{100 \text{ mol } C_3H_8} \left| \frac{0.522 \text{ m}^3 \text{ steam}}{1 \text{ kg steam}} \right| \left| \frac{1 \text{ mol } C_3H_8}{0.0104 \text{ m}^3 C_3H_8} \right| = 0.400 \text{ m}^3 \text{ steam}/\text{m}^3 C_3H_8$$

- d. $Q = m_w \Delta \hat{H}_w = \frac{0.798 \text{ kg steam}}{100 \text{ mol } C_3H_8} \left| \frac{2425 \text{ kJ}}{\text{kg steam}} \right| \left| \frac{1 \text{ mol } C_3H_8}{0.0104 \text{ m}^3 C_3H_8} \right| = 1860 \frac{\text{kJ}}{\text{m}^3 C_3H_8 \text{ fed}}$

- e. A lower outlet temperature for propane and a higher outlet temperature for steam.

8.25 a.



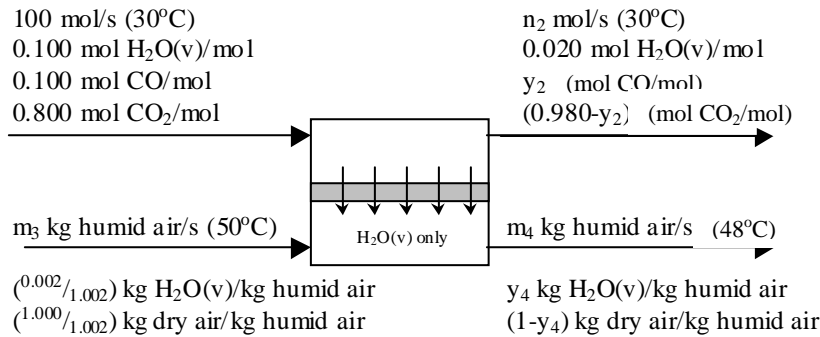
$$n_2 = \frac{5500 \text{ L(STP)}}{\text{min}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| = 245.5 \text{ mol CH}_3\text{OH(v)/min}$$

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 H₂O/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.



Basis: 100 mol gas mixture/s

5 unknowns: n_2, m_3, m_4, y_2, y_4

– 4 independent material balances, H₂O(v), CO, CO₂, dry air

– 1 energy balance equation

0 degrees of freedom (all unknowns may be determined)

b.

$$\left. \begin{array}{l} (1) \text{ CO balance: } (100)(0.100) = \dot{n}_2 y_2 \\ (2) \text{ CO}_2 \text{ balance: } (100)(0.800) = \dot{n}_2 (1 - y_2) \end{array} \right\} \Rightarrow \dot{n}_2 = 91.84 \text{ mol/s}, \quad x_2 = 0.1089 \text{ mol CO/mol}$$

$$(3) \text{ Dry air balance: } m_3 \frac{1.000}{1.002} = m_4 (1 - y_4)$$

$$(4) \text{ H}_2\text{O balance: } \frac{(100)(0.100)(18)}{1000} + \dot{m}_3 \frac{0.002}{1.002} = 91.84 \frac{(0.020)(18)}{1000} + \dot{m}_4 y_4$$

References: CO, CO₂, H₂O(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)	$m_3 \left(\frac{0.002}{1.002} \right) \left(\frac{1000}{18} \right)$	0.847	$m_4 y_4 \left(\frac{1000}{18} \right)$	0.779
dry air	$m_3 \left(\frac{1.000}{1.002} \right) \left(\frac{1000}{29} \right)$	0.727	$m_4 (1 - y_4) \left(\frac{1000}{29} \right)$	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 $\Rightarrow m_3 = 2.55 \text{ kg/s}$, $m_4 = 2.70 \text{ kg/s}$, $y_4 = 0.0564 \text{ kg H}_2\text{O/kg}$

$$\frac{2.55 \text{ kg humid air / s}}{100 \text{ mol gas / s}} = 0.0255 \frac{\text{kg humid air}}{\text{mol gas}}$$

$$\text{Mole fraction of water: } \frac{0.0564 \text{ kg H}_2\text{O}}{(1 - 0.0564) \text{ kg dry air}} \left| \frac{29 \text{ kg DA}}{\text{kmol DA}} \right| \frac{1 \text{ kmol H}_2\text{O}}{18 \text{ kg H}_2\text{O}} = 0.0963 \frac{\text{kmol H}_2\text{O}}{\text{kmol DA}}$$

$$\Rightarrow \frac{0.0963 \text{ kmol H}_2\text{O}}{(1 + 0.0963) \text{ kmol humid air}} = 0.0878 \frac{\text{kmol H}_2\text{O}}{\text{kmol humid air}}$$

$$\text{Relative humidity: } \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*(48^\circ \text{C})} = \frac{(0.0878)(760 \text{ mm Hg})}{83.71 \text{ mm Hg}} \times 100\% = \underline{\underline{79.7\%}}$$

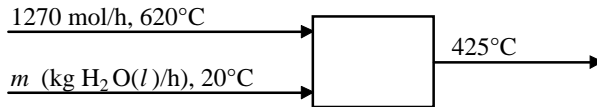
- c. The membrane must be permeable to water, impermeable to CO, CO₂, O₂, and N₂, and both durable and leakproof at temperatures up to 50°C.

8.27 a. $y_{\text{H}_2\text{O}} = \frac{p^*(57^\circ \text{C})}{P} = \frac{129.82 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.171 \text{ mol H}_2\text{O/mol}$

↓

$$\frac{28.5 \text{ m}^3(\text{STP})}{\text{h}} \left| \frac{1 \text{ mol}}{0.0224 \text{ m}^3(\text{STP})} \right| = 1270 \text{ mol/h} \Rightarrow 217.2 \text{ mol H}_2\text{O/h} \quad (3.91 \text{ kg H}_2\text{O/h})$$

$$1270 - 217.2 = 1053 \frac{\text{mol dry gas}}{\text{h}} \xrightarrow[\text{percentages}]{\text{given}} \begin{cases} 89.5 \text{ mol CO/h} \\ 110.5 \text{ mol CO}_2/\text{h} \\ 5.3 \text{ mol O}_2/\text{h} \\ 847.6 \text{ mol N}_2/\text{h} \end{cases}$$



References for enthalpy calculations:

CO, CO₂, O₂, N₂ at 25°C (Table B.8); H₂O(l, 0.01°C) (steam tables)

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
CO	89.5	18.22	89.5	12.03	} n in mol/h \hat{H} in kJ/mol
CO ₂	110.6	27.60	110.6	17.60	
O ₂	5.3	19.10	5.3	12.54	
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 \hat{H} in kJ/kg
H ₂ O(l)	m	83.9	--	--	

8.27 (cont'd)

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -8504 + 3246m = 0 \Rightarrow \underline{\underline{m = 2.62 \text{ kg/h}}}$$

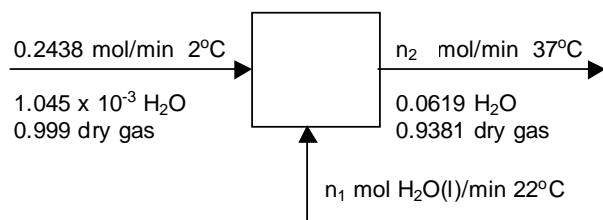
- b. When cold water contacts hot gas, heat is transferred from the hot gas to the cold water lowering the temperature of the gas (the object of the process) and raising the temperature of the water.

8.28 2°C , 15% rel. humidity $\Rightarrow p_{\text{H}_2\text{O}} = (0.15)(5.294 \text{ mm Hg}) = 0.7941 \text{ mm Hg}$

$$(y_{\text{H}_2\text{O}})_{\text{inhaled}} = (0.7941)/(760) = 1.045 \times 10^{-3} \text{ mol H}_2\text{O/mol inhaled air}$$

$$\dot{n}_{\text{inhaled}} = \frac{5500 \text{ ml}}{\text{min}} \left| \frac{273 \text{ K}}{275 \text{ K}} \right| \left| \frac{1 \text{ liter}}{10^3 \text{ ml}} \right| \left| \frac{1 \text{ mol}}{22.4 \text{ liters(STP)}} \right| = 0.2438 \text{ mol air inhaled/min}$$

Saturation at 37°C $\Rightarrow y_{\text{H}_2\text{O}} = \frac{p^*(37^\circ\text{C})}{760 \text{ mm Hg}} = \frac{47.067}{760} = 0.0619 \text{ mol H}_2\text{O/mol exhaled dry gas}$



Mass of dry gas inhaled (and exhaled) $= \frac{(0.2438)(0.999) \text{ mol dry gas}}{\text{min}} \left| \frac{29.0 \text{ g}}{\text{mol}} \right| = 7.063 \text{ g/min}$

Dry gas balance: $(0.999)(0.2438) = 0.9381 \dot{n}_2 \Rightarrow \dot{n}_2 = 0.2596 \text{ mols exhaled/min}$

H₂O balance: $(0.2438)(1.045 \times 10^{-3}) + \dot{n}_1 = (0.2596)(0.0619) \Rightarrow \dot{n}_1 = 0.0158 \text{ mol H}_2\text{O/min}$

References for enthalpy calculations: H₂O(l) at triple point, dry gas at 2°C

substance	\dot{m}_{in}	\hat{H}_{in}	\dot{m}_{out}	\hat{H}_{out}
Dry gas	7.063	0	7.063	36.75
H ₂ O(v)	0.00459	2505	0.290	2569
H ₂ O(l)	0.285	92.2	—	—

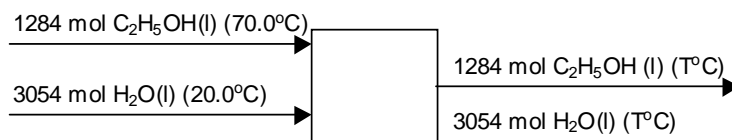
$$\begin{aligned} \dot{m} \text{ in g/min} \quad \dot{m}_{\text{H}_2\text{O}} &= 18.02 \dot{n}_{\text{H}_2\text{O}} \\ \hat{H} \text{ in J/g} \quad \hat{H}_{\text{H}_2\text{O}} &\text{ from Table 8.4} \\ \hat{H}_{\text{dry gas}} &= 1.05(T - 2) \end{aligned}$$

$$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \frac{966.8 \text{ J}}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| \left| \frac{24 \text{ hr}}{1 \text{ day}} \right| = \underline{\underline{1.39 \times 10^6 \text{ J/day}}}$$

8.29 a. $\frac{75 \text{ liters C}_2\text{H}_5\text{OH}(l)}{\text{liter}} \left| \frac{789 \text{ g}}{46.07 \text{ g}} \right| \frac{1 \text{ mol}}{1} = 1284 \text{ mol C}_2\text{H}_5\text{OH}(l)$

$(C_p)_{\text{CH}_3\text{OH}} = 0.1031 + 0.557 \times 10^{-3} T \text{ (kJ / (mol} \cdot ^\circ\text{C))}$ (fitting the two values in Table B.2)

$\frac{55 \text{ L H}_2\text{O}(l)}{\text{liter}} \left| \frac{1000 \text{ g}}{18.01 \text{ g}} \right| \frac{1 \text{ mol}}{1} = 3054 \text{ mol H}_2\text{O}(l) \quad (C_p)_{\text{H}_2\text{O}} = 0.0754 \text{ (kJ/mol} \cdot ^\circ\text{C)}$



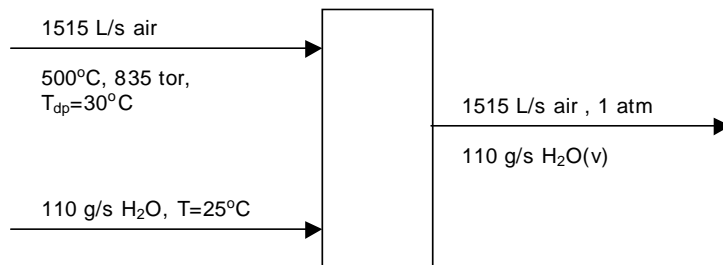
$$0 = 1284 \int_{70}^T (0.1031 + 0.557 \times 10^{-3} T) dT + 3054 \int_{25}^T (0.0754) dT$$

$$\left. \begin{array}{l} Q = \Delta U \cong \Delta H (\text{liquids}) \\ Q = 0 (\text{adiabatic}) \end{array} \right\} \Rightarrow \Downarrow \text{Integrate, solve quadratic equation}$$

$$\underline{\underline{T = 44.3^\circ\text{C}}}$$

- 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.



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 H_2O in the air stream.

$$\dot{n}_1 + \dot{n}_2 = \frac{1515 \text{ L}}{\text{s}} \left| \frac{835 \text{ mm Hg}}{773 \text{ K}} \right| \frac{\text{mol} \cdot \text{K}}{62.36 \text{ L} \cdot \text{mm Hg}} = 26.2 \text{ mol/s}$$

$$\frac{\dot{n}_2}{\dot{n}_1 + \dot{n}_2} = y = \frac{p^*(30^\circ\text{C})}{P_{\text{total}}} = \frac{31.824 \text{ mmHg}}{835 \text{ mmHg}} = 0.0381 \text{ mol H}_2\text{O} / \text{mol air}$$

$$\Rightarrow \dot{n}_1 = 25.2 \text{ mol dry air / s; } \dot{n}_2 = 1.0 \text{ mol H}_2\text{O / s}$$

8.30 (cont'd)

References: H₂O (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	$\int_{25}^T (C_p)_{air} dT$
H ₂ O(v)	1.0	$\int_{25}^{100} (C_p)_{H_2O(l)} dT + \hat{H}_{vap}$ $\int_{100}^{500} (C_p)_{H_2O(v)} dT$	7.1	$\int_{25}^{100} (C_p)_{H_2O(l)} dT + \hat{H}_{vap}$ $\int_{100}^T (C_p)_{H_2O(v)} dT$
H ₂ O(l)	6.1	0	--	--

$$\Delta H = 0 = \dot{n}_{out} \cdot \hat{H}_{out} - \dot{n}_{in} \cdot \hat{H}_{in}$$

$$(25.2) \left(\int_{25}^T (C_p)_{air} dT \right) + (7.1) \left(\int_{25}^{100} (C_p)_{H_2O(l)} dT + \hat{H}_{vap} + \int_{100}^T (C_p)_{H_2O(v)} dT \right) \\ - (25.2)(14.37) - (1.00) \left(\int_{25}^{100} (C_p)_{H_2O(l)} dT + \hat{H}_{vap} + \int_{100}^{500} (C_p)_{H_2O(v)} dT \right) = 0$$

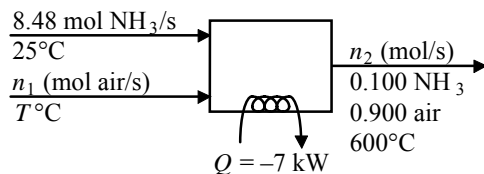
Integrate, solve : T = 139°C

b. $\dot{Q} = -(25.2) \int_{500}^{139} (C_p)_{air} dT - (1.00) \int_{500}^{139} (C_p)_{H_2O(v)} dT = \underline{\underline{-290 \text{ kW}}}$

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: $\frac{520 \text{ kg NH}_3}{\text{h}} \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \left| \frac{1 \text{ mol}}{17.03 \text{ g}} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| = 8.48 \text{ mol NH}_3/\text{s}$



NH₃ balance: $8.48 = 0.100n_2 \Rightarrow n_2 = 84.8 \text{ mol/s}$

Air balance: $n_1 = (0.900)(84.8) = 76.3 \text{ mol air/s}$

References for enthalpy calculations: NH₃(g), air at 25°C

NH₃ $\hat{H}_{\text{in}} = 0.0$

$$\hat{H}_{\text{out}} = \int_{25}^{600} (C_p)_{\text{NH}_3} dT \xRightarrow{\text{Table B.2}} \hat{H}_{\text{out}} = 25.62 \text{ kJ/mol}$$

Air: $C_p \text{ (J/mol} \cdot \text{°C)} = 0.02894 + 0.4147 \times 10^{-5} T + 0.3191 \times 10^{-8} T^2 - 1.965 \times 10^{-12} T^3$

$$\begin{aligned} \hat{H}_{\text{in}} &= \int_{25}^T C_p dT \\ &= (-0.4913 \times 10^{-12} T^4 + 0.1064 \times 10^{-8} T^3 + 0.20735 \times 10^{-5} T^2 + 0.02894 T - 0.7248) (\text{kJ/mol}) \end{aligned}$$

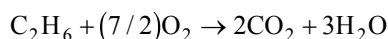
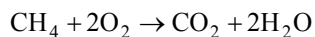
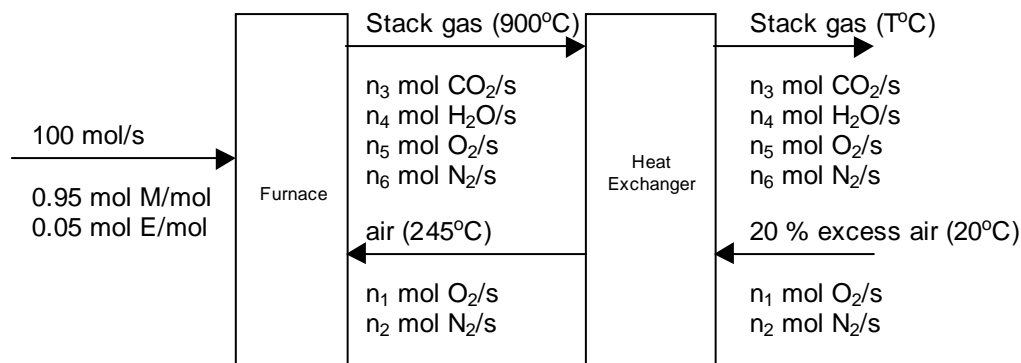
$$\hat{H}_{\text{out}} = \int_{25}^{600} C_p dT = 17.55 \text{ kJ/mol}$$

Energy balance: $Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$

$$\begin{aligned} -7 \text{ kJ/s} &= (8.48 \text{ mols NH}_3/\text{s})(25.62 \text{ kJ/mol}) + (76.3 \text{ mols air/s})(17.55 \text{ kJ/mol}) - (8.48)(0.0) \\ &\quad - (76.3)(-0.4913 \times 10^{-12} T^4 + 0.1064 \times 10^{-8} T^3 + 0.20735 \times 10^{-5} T^2 + 0.02894 T - 0.7248) \end{aligned}$$

Solve for T by trial-and-error, E-Z Solve, or Excel/Goal Seek $\Rightarrow T = \underline{\underline{691^\circ\text{C}}}$

8.32 a. Basis: 100 mol/s of natural gas. Let M represent methane, and E for ethane



8.32 (cont'd)

$$\dot{n}_{air} = 1.2 \left[\frac{95 \text{ mol M}}{\text{s}} \left| \frac{2 \text{ mol O}_2}{1 \text{ mol M}} \right| \frac{4.76 \text{ mol air}}{\text{mol O}_2} + \frac{5 \text{ mol E}}{\text{s}} \left| \frac{3.5 \text{ mol O}_2}{1 \text{ mol E}} \right| \frac{4.76 \text{ mol air}}{\text{mol O}_2} \right]$$

$$\dot{n}_{air} = \underline{1185 \text{ mol air/s}}$$

$$\dot{n}_1 = 0.21 \times 1185 = 249 \text{ mol O}_2/\text{s}, \dot{n}_2 = 0.79 \times 1185 = 936 \text{ mol N}_2/\text{s}$$

$$\dot{n}_3 = \frac{95 \text{ mol M}}{\text{s}} \left| \frac{1 \text{ mol CO}_2}{1 \text{ mol M}} \right| + \frac{5 \text{ mol E}}{\text{s}} \left| \frac{2 \text{ mol CO}_2}{1 \text{ mol E}} \right| = \underline{105 \text{ mol CO}_2/\text{s}}$$

$$\dot{n}_4 = \frac{95 \text{ mol M}}{\text{s}} \left| \frac{2 \text{ mol H}_2\text{O}}{1 \text{ mol M}} \right| + \frac{5 \text{ mol E}}{\text{s}} \left| \frac{3 \text{ mol H}_2\text{O}}{1 \text{ mol E}} \right| = \underline{205 \text{ mol H}_2\text{O/s}}$$

$$\dot{n}_5 = 249 - \frac{95 \text{ mol M}}{\text{s}} \left| \frac{2 \text{ mol O}_2}{1 \text{ mol M}} \right| + \frac{5 \text{ mol E}}{\text{s}} \left| \frac{3.5 \text{ mol O}_2}{1 \text{ mol E}} \right| = \underline{41.5 \text{ mol O}_2/\text{s}}$$

$$\dot{n}_6 = \dot{n}_2 = \underline{936 \text{ mol N}_2/\text{s}}$$

Energy balance on air:

$$\dot{Q} = \dot{n}_{air} \int_{20}^{245} (C_p)_{air} dT = \left(1185 \frac{\text{mol air}}{\text{s}} \right) \left(6.649 \frac{\text{kJ}}{\text{mol air}} \right) = 7879 \frac{\text{kJ}}{\text{s}} (= 7879 \text{ kW})$$

Energy balance on stack gas:

$$\dot{Q} = -\Delta H = -\sum_{i=3}^6 \left(\dot{n}_i \int_{900}^T (C_p)_i dT \right)$$

$$-7879 = \dot{n}_3 \int_{900}^T (C_p)_{\text{CO}_2} dT + \dot{n}_4 \int_{900}^T (C_p)_{\text{H}_2\text{O(v)}} dT + \dot{n}_5 \int_{900}^T (C_p)_{\text{O}_2} dT + \dot{n}_6 \int_{900}^T (C_p)_{\text{N}_2} dT$$

Substitute for the heat capacities (Table B.2), integrate, solve for T using E-Z Solve $\Rightarrow \underline{T = 732^\circ\text{C}}$

b.
$$\frac{350 \text{ m}^3 (\text{STP})}{\text{h}} \left| \frac{\text{mol}}{22.4 \text{ L (STP)}} \right| \left| \frac{1000 \text{ L}}{\text{m}^3} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| = 4.34 \text{ mol/s}$$

$$\text{Scale factor} = \frac{4.34 \text{ mol/s}}{100 \text{ mol/s}} = 0.0434$$

$$\dot{Q}' = 0.0434(7851) = \underline{341 \text{ kW}}$$

8.33 a.
$$\Delta \hat{H} = \int_0^{600} C_p dT = \frac{100}{3} [33.5 + 4(35.1 + 38.4 + 42.0) + 2(36.7 + 40.2)43.9] = 23100 \text{ J/mol}$$

$$\dot{Q} = \Delta H = n \Delta \hat{H} = \frac{150 \text{ mol}}{\text{s}} \left| \frac{23100 \text{ J}}{\text{mol}} \right| \left| \frac{1 \text{ kW}}{1000 \text{ J/s}} \right| = \underline{3465 \text{ kW}}$$

b. The method of least squares (Equations A1-4 and A1-5) yields (for $X = T$, $y = C_p$)

$$\underline{C_p = 0.0334 + 1.732 \times 10^{-5} T (^\circ\text{C}) [\text{kJ}/(\text{mol} \cdot ^\circ\text{C})]} \Rightarrow \underline{Q = 150 \int_0^{600} [0.0334 + 1.732 \times 10^{-5} T] dT = 3474 \text{ kW}}$$

The estimates are exactly identical; in general, (a) would be more reliable, since a linear fit is forced in (b).

8.34 a.
$$\ln C_p = bT^{1/2} + \ln a \Rightarrow C_p = a \exp(bT^{1/2}), \sqrt{T_1} = 7.1, C_{p1} = 0.329, \sqrt{T_2} = 17.3, C_{p2} = 0.533$$

$$\left. \begin{aligned} b &= \frac{\ln C_{p2}/C_{p1}}{\sqrt{T_2} - \sqrt{T_1}} = 0.0473 \\ \ln a &= \ln C_{p1} - b\sqrt{T_1} = -1.4475 \Rightarrow a = e^{-1.4475} = 0.235 \end{aligned} \right\} \Rightarrow \underline{C_p = 0.235 \exp(0.0473 T^{1/2})}$$

8.34 (cont'd)

$$\text{b. } \int_{1800}^{150} 0.235 \exp(0.0473T^{1/2}) dT = \frac{(0.235)(2)}{0.0473} \left\{ \exp(0.473T^{1/2}) \left[T^{1/2} - \frac{1}{.0473} \right] \right\}_{1800}^{150} = -1730 \text{ cal/g}$$

```

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
     SUM1 = 0.0
     DO 30 J = 2, NM1, 2
30  SUM1 = SUM1 + 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, 5X13, 'POINT INTEGRATION', DELTA(H) = ', E11.4, 'CAL/G')
200 CONTINUE
    STOP
    END

```

Solution: $N = 11 \Rightarrow \Delta \hat{H} = -1731 \text{ cal/g}$

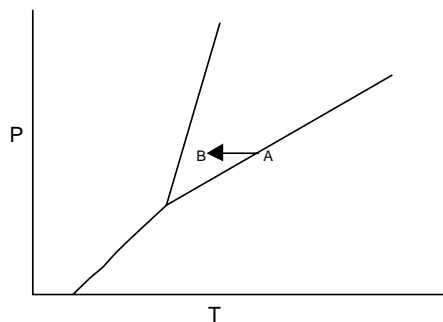
$N = 101 \Rightarrow \Delta \hat{H} = -1731 \text{ cal/g}$

Simpson's rule with $N = 11$ thus provides an excellent approximation

$$\text{8.35 a. } \left. \begin{array}{l} \dot{m} = 175 \text{ kg / min} \\ M.W. = 62.07 \text{ g / mol} \\ \Delta \hat{H}_v = 56.9 \text{ kJ / mol} \end{array} \right\} \Rightarrow \dot{Q} = \Delta H = \frac{175 \text{ kg}}{\text{min}} \left| \frac{1000 \text{ g}}{\text{kg}} \right| \left| \frac{1 \text{ mol}}{62.07 \text{ g}} \right| \left| \frac{56.9 \text{ kJ}}{\text{mol}} \right| \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = \underline{\underline{2670 \text{ kW}}}$$

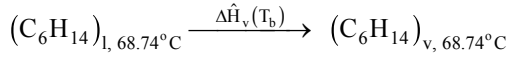
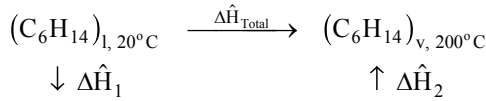
b. The product stream will be a mixture of vapor and liquid.

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 $\Rightarrow T_b = 68.74^\circ\text{C}$, $\Delta\hat{H}_v(T_b) = 28.85 \text{ kJ/mol}$

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



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

$$\Delta\hat{H}_2 = \int_{68.74}^{200} [0.13744 + 40.85 \times 10^{-5}T - 23.92 \times 10^{-8}T^2 + 57.66 \times 10^{-9}T^3] \, dT$$

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

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

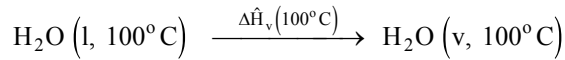
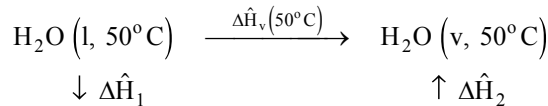
b. $\Delta\hat{H} = \underline{\underline{-64.05 \text{ kJ/mol}}}$

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

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

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

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



$$\Delta\hat{H}_1 = \int_{25}^{100} C_{p\text{H}_2\text{O}(l)} \, dT = 3.77 \text{ kJ/mol}$$

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

$$\Delta\hat{H}_v(50^\circ\text{C}) = 3.77 + 40.656 - 1.69 = \underline{\underline{42.7 \text{ kJ/mol}}}$$

Steam table: $\frac{(2547.3 - 104.8) \text{ kJ}}{\text{kg}} \left| \frac{18.01 \text{ g}}{1 \text{ mol}} \right| \frac{1 \text{ kg}}{1000 \text{ g}} = 44.0 \text{ kJ/mol}$

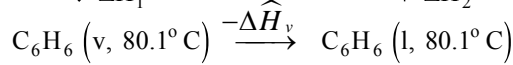
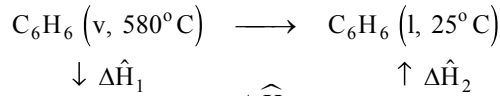
The first value uses physical properties of water at 1 atm (Tables B.1, B.2, and B.8), while the heat of vaporization at 50°C in Table B.5 is for a pressure of 0.1234 bar (0.12 atm). The difference is ΔH for liquid water going from 50°C and 0.1234 bar to 50°C and 1 atm plus ΔH for water vapor going from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

8.38

$$\frac{1.75 \text{ m}^3}{2.0 \text{ min}} \left| \frac{879 \text{ kg}}{\text{m}^3} \right| \left| \frac{1 \text{ kmol}}{78.11 \text{ kg}} \right| \left| \frac{1000 \text{ mol}}{1 \text{ kmol}} \right| \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = 164.1 \text{ mol/s}$$

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

8.38 (cont'd)



$$\Delta \hat{H}_1 = \int_{580}^{80.1} C_{p\text{C}_6\text{H}_6(\text{v})} dT = -77.23 \text{ kJ/mol}$$

$$\Delta \hat{H}_2 = \int_{353.1}^{298} C_{p\text{C}_6\text{H}_6(\text{l})} dT = -7.699 \text{ kJ/mol}$$

$$\Delta \hat{H} = \Delta \hat{H}_1 - \Delta \hat{H}_v(80.1^\circ\text{C}) + \Delta \hat{H}_2 = -115.7 \text{ kJ/mol}$$

$$Q = \Delta H = n\Delta \hat{H} = (164.1 \text{ mol/s})(-115.7 \text{ kJ/mol}) = \underline{\underline{-1.90 \times 10^{-4} \text{ kW}}}$$

8.39 35°C $15\% \text{ relative saturation}$ $\left\{ \Rightarrow y_{\text{CCl}_4} = 0.15 \frac{P_V^*(25^\circ\text{C})}{1 \text{ atm}} = 0.15 \frac{176.0 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0347 \text{ mol CCl}_4/\text{mol} \right.$

$$(\Delta \hat{H}_v)_{\text{CCl}_4} \xrightarrow{\text{Table B.1}} 30.0 \frac{\text{kJ}}{\text{mol}} \Rightarrow Q = \Delta H = \frac{10 \text{ mol}}{\text{min}} \left| \frac{0.0347 \text{ mol CCl}_4}{\text{mol}} \right| \left| \frac{30.0 \text{ kJ}}{\text{mol CCl}_4} \right| = \underline{\underline{10.4 \text{ kJ/min}}}$$

Time to Saturation

6 kg carbon	0.40 g CCl ₄	1 mol CCl ₄	1 mol gas	1 min	= <u><u>45.0 min</u></u>
	g carbon	153.84 g CCl ₄	0.0347 mol CCl ₄	10 mol gas	

8.40 a. $\text{CO}_2(\text{g}, 20^\circ\text{C}) \rightarrow \text{CO}_2(\text{s}, -78.4^\circ\text{C}): \Delta \hat{H} = \int_{20}^{-78.4} (C_p)_{\text{CO}_2(\text{g})} dT - \Delta \hat{H}_{\text{sub}}(-78.4^\circ\text{C})$

In the absence of better heat capacity data; we use the formula given in Table B.2 (which is strictly applicable only above 0°C).

$$\Delta \hat{H} \approx \int_{20}^{-78.4} \left[0.3611 + 4.233 \times 10^{-5} T - 2.887 \times 10^{-8} T^2 + 7.464 \times 10^{-12} T^3 \right] dT \left(\frac{\text{kJ}}{\text{mol}} \right)$$

$$-6030 \frac{\text{cal}}{\text{mol}} \left| \frac{4.184 \times 10^{-3} \text{ kJ}}{1 \text{ cal}} \right| = -28.66 \text{ kJ/mol}$$

$$Q = \Delta H = n\Delta \hat{H} = \frac{300 \text{ kg CO}_2}{\text{h}} \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \left| \frac{1 \text{ mol}}{44.01 \text{ g}} \right| \left| \frac{28.66 \text{ kJ removed}}{\text{mol CO}_2} \right| = \underline{\underline{1.95 \times 10^5 \text{ kJ/h}}}$$

(or $6.23 \times 10^7 \text{ cal/hr}$ or 72.4 kW)

b. According to Figure 6.1-1b, $T_{\text{fusion}} = -56^\circ\text{C}$

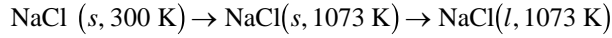
$$\dot{Q} = \Delta H = \dot{n}\Delta \hat{H}$$

$$\text{where, } \Delta \hat{H} = \int_{20}^{-56} (C_p)_{\text{CO}_2(\text{v})} dT + \Delta \hat{H}_v(-56^\circ\text{C}) + \int_{-56}^{-78.4} (C_p)_{\text{CO}_2(\text{l})} dT$$

$$\underline{\underline{\dot{Q} = \dot{n} \left[\int_{20}^{-56} (C_p)_{\text{CO}_2(\text{v})} dT + \Delta \hat{H}_v(-56^\circ\text{C}) + \int_{-56}^{-78.4} (C_p)_{\text{CO}_2(\text{l})} dT \right]}}$$

8.41 a. $C_p = a + bT$

$$\left. \begin{aligned} b &= \frac{53.94 - 50.41}{500 - 300} = 0.01765 \\ a &= 53.94 - (0.01765)(500) = 45.12 \end{aligned} \right\} \Rightarrow C_p (\text{J/mol} \cdot \text{K}) = \underline{\underline{45.12 + 0.01765T(\text{K})}}$$



$$\begin{aligned} \Delta \hat{H} &= \int_{300}^{1073} C_{ps} dT + \Delta \hat{H}_m(1073 \text{ K}) = \left[\int_{300}^{1073} (45.12 + 0.01765T) dT \right] \frac{\text{J}}{\text{mol}} + \frac{30.21 \text{ kJ}}{\text{mol}} \left| \frac{10^3 \text{ J}}{1 \text{ kJ}} \right. \\ &= \underline{\underline{7.44 \times 10^4 \text{ J/mol}}} \end{aligned}$$

b. $Q = \Delta U = n \int_{300}^{1073} C_v dT + \Delta \hat{U}_m(1073 \text{ K})$

$$\begin{aligned} &\Downarrow \begin{array}{l} C_v \approx C_p \\ \Delta U_m \approx \Delta H_m \end{array} \\ Q \approx \Delta H = n \Delta \hat{H} &= \frac{200 \text{ kg}}{1 \text{ kg}} \left| \frac{10^3 \text{ g}}{58.44 \text{ g}} \right| \left| \frac{1 \text{ mol}}{74450 \text{ J}} \right| = \underline{\underline{2.55 \times 10^8 \text{ J}}} \end{aligned}$$

c. $t = \frac{2.55 \times 10^8 \text{ J}}{0.85 \times 3000 \text{ kJ}} \left| \frac{\text{s}}{10^3 \text{ J}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right| = \underline{\underline{100 \text{ s}}}$

8.42 $\Delta \hat{H}_v = 35.98 \text{ kJ/mol}$, $T_b = 136.2^\circ \text{C} = 409.4 \text{ K}$, $P_c = 37.0 \text{ atm}$, $T_c = 619.7 \text{ K}$ (from Table B.1)

Trouton's rule: $\Delta \hat{H}_v \approx 0.088 T_b = (0.088)(409.4 \text{ K}) = \underline{\underline{36.0 \text{ kJ/mol}}}$ (0.1% error)

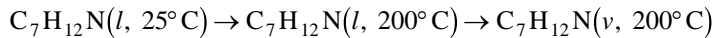
Chen's rule:

$$\Delta \hat{H}_v \approx \frac{T_b \left[0.0331 \left(\frac{T_b}{T_c} \right) - 0.0327 + 0.0297 \log_{10} P_c \right]}{1.07 - \left(\frac{T_b}{T_c} \right)} = \underline{\underline{35.7 \text{ kJ/mol}}} \text{ (-0.7% error)}$$

Watson's correlation: $\Delta \hat{H}_v(100^\circ \text{C}) \approx 35.98 \left(\frac{619.7 - 373.2}{619.7 - 409.4} \right)^{0.38} = \underline{\underline{38.2 \text{ kJ/mol}}}$

8.43 $\text{C}_7\text{H}_{12}\text{N}$: Kopp's Rule $\Rightarrow C_p \approx 7(0.012) + 12(0.018) + 0.033 = 0.333 \text{ kJ}/(\text{mol} \cdot ^\circ \text{C})$

Trouton's Rule $\Rightarrow \Delta \hat{H}_v(200^\circ \text{C}) = 0.088(200 + 273.2) = 41.6 \text{ kJ/mol}$



$$\Delta \hat{H} = \int_{25}^{200} C_p dT + \Delta \hat{H}_v(200^\circ \text{C}) \approx 0.333(200 - 25) \frac{\text{kJ}}{\text{mol}} + 41.6 \frac{\text{kJ}}{\text{mol}} = \underline{\underline{100 \text{ kJ/mol}}}$$

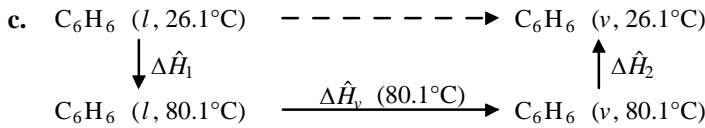
8.44 a. Antoine equation: $T_b(^{\circ}\text{C}) = \frac{1211.033}{6.90565 - \log(100)} - 220.790 = 26.1^{\circ}\text{C}$

Watson Correction: $\Delta\hat{H}_v(26.1^{\circ}\text{C}) = 30.765 \left(\frac{562.6 - 299.3}{562.6 - 353.1} \right)^{0.38} = \underline{\underline{33.6 \text{ kJ/mol}}}$

b. Antoine equation: $T_b(50 \text{ mm Hg}) = 11.8^{\circ}\text{C}$; $T_b(150 \text{ mm Hg}) = 35.2^{\circ}\text{C}$

Clausius-Clapeyron: $\ln p = -\frac{\Delta\hat{H}_v}{RT} + C \Rightarrow \Delta\hat{H}_v = -R \frac{\ln(p_2/p_1)}{1/T_2 - 1/T_1}$

$\Delta\hat{H}_v = -0.008314 \frac{\text{kJ}}{\text{mol} \cdot \text{K}} \left\{ \frac{\ln(150/50)}{1/308.4 \text{ K} - 1/285.0 \text{ K}} \right\} = \underline{\underline{34.3 \text{ kJ/mol}}}$



$\Delta\hat{H}_1 = \int_{26.1}^{80.1} (C_p)_l dT = 7.50 \text{ kJ/mol}$

$\Delta\hat{H}_2 = \int_{80.1}^{26.1} (C_p)_v dT = -4.90 \text{ kJ/mol}$

$\Delta\hat{H}_v(26.1^{\circ}\text{C}) = 7.50 + 30.765 - 4.90 = \underline{\underline{33.4 \text{ kJ/mol}}}$

8.45 a. $T_{\text{out}} \equiv 49.3^{\circ}\text{C}$. 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

$\dot{n}_f = \frac{1550 \text{ L}}{\text{s}} \left| \frac{273 \text{ K}}{423 \text{ K}} \right| \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| = 44.66 \text{ mol C}_5\text{H}_{10}(\text{v})/\text{s}$

55% condensation: $\dot{n}_l = 0.550(44.66 \text{ mol/s}) = 24.56 \text{ mol C}_5\text{H}_{10}(\text{l})/\text{s}$

Cyclopentane balance $\Rightarrow \dot{n}_v = (44.66 - 24.56) \text{ mol C}_5\text{H}_{10}/\text{s} = 20.10 \text{ mol C}_5\text{H}_{10}(\text{v})/\text{s}$

Reference: $\text{C}_5\text{H}_{10}(\text{l})$ at 49.3°C

Substance	\dot{n}_{in} (mol/s)	\hat{H}_{in} (kJ/mol)	\dot{n}_{out} (mol/s)	\hat{H}_{out} (kJ/mol)
$\text{C}_5\text{H}_{10}(\text{l})$	—	—	24.56	0
$\text{C}_5\text{H}_{10}(\text{v})$	44.66	\hat{H}_f	20.10	\hat{H}_v

$H_i = \Delta\hat{H}_v + \int_{49.3^{\circ}\text{C}}^{T_i} C_p dT$

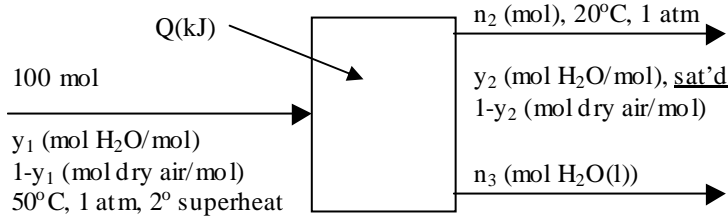
8.45 (cont'd)

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: $\dot{Q} = \sum n_{\text{out}} \hat{H}_{\text{out}} - \sum n_{\text{in}} \hat{H}_{\text{in}} = -1.16 \times 10^3 \text{ kJ/s} = \underline{\underline{-1.16 \times 10^3 \text{ kW}}}$

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. $\underline{\underline{2^\circ\text{C superheat}}} \Rightarrow \underline{\underline{y_1}} = \frac{p^*(48^\circ\text{C})}{p}$

saturation at outlet $\Rightarrow \underline{\underline{y_2}} = \frac{p^*(20^\circ\text{C})}{p}$

dry air balance: $(100)(1 - y_1) = \underline{\underline{n_2}}(1 - y_2)$

H₂O balance: $(100)(y_1) = (n_2)(y_2) + \underline{\underline{n_3}}$

c. References: Air (25°C), H₂O(l , 20°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
H ₂ O(v)	$100 \cdot y_1$	\hat{H}_2	$n_2 \cdot y_2$	\hat{H}_4	\hat{H} in kJ/mol
H ₂ O(l)	—	—	n_3	0	

$$\hat{H}_1 = \int_{25}^{50} (C_p)_{\text{air}} dT = \int_{25}^{50} [0.02894 + 0.4147 \times 10^{-5} T + 0.3191 \times 10^{-8} T^2 - 1.965 \times 10^{-12} T^3] dT$$

$$\hat{H}_2 = \int_{20}^{100} (C_p)_{\text{H}_2\text{O}(l)} dT + \Delta\hat{H}_v(100^\circ\text{C}) + \int_{100}^{50} (C_p)_{\text{H}_2\text{O}(v)} dT$$

$$= \int_{20}^{100} [0.0754] dT + 40.656 +$$

$$\int_{100}^{50} [0.03346 + 0.688 \times 10^{-5} T + 0.7604 \times 10^{-8} T^2 - 3.593 \times 10^{-12} T^3] dT$$

$$\hat{H}_3 = \int_{25}^{20} (C_p)_{\text{air}} dT$$

$$\hat{H}_4 = \int_{20}^{100} (C_p)_{\text{H}_2\text{O}(l)} dT + \Delta\hat{H}_v(100^\circ\text{C}) + \int_{100}^{20} (C_p)_{\text{H}_2\text{O}(v)} dT$$

8.46 (cont'd)

c.
$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i \quad V_{air} = \frac{100 \text{ mol}}{\left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \frac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}}}$$

$$\Rightarrow \frac{Q}{V_{air}} = \frac{\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i}{\frac{100 \text{ mol}}{\left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \frac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}}}}$$

d.
$$\underline{2^\circ\text{C superheat}} \Rightarrow y_1 = \frac{p^*(48^\circ\text{C})}{p} = \frac{83.71 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.110 \text{ mol H}_2\text{O/mol}$$

$$\underline{\text{saturation at outlet}} \Rightarrow y_2 = \frac{p^*(20^\circ\text{C})}{p} = \frac{17.535 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.023 \text{ mol H}_2\text{O/mol}$$

$$\underline{\text{dry air balance:}} \quad (100)(1 - 0.110) = n_2(1 - 0.023) \Rightarrow n_2 = 91.10 \text{ mol}$$

$$\underline{\text{H}_2\text{O balance:}} \quad (100)(0.110) = (91.10)(0.023) + n_3 \Rightarrow n_3 = \frac{8.90 \text{ mol H}_2\text{O}}{1 \text{ mol}} = 0.018 \text{ kg}$$

$= 0.160 \text{ kg H}_2\text{O condensed}$

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = -480.5 \text{ kJ}$$

$$V_{air} = \frac{100 \text{ mol}}{\left| \frac{8.314 \text{ Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right| \frac{323 \text{ K}}{1.01325 \times 10^5 \text{ Pa}}} = 2.65 \text{ m}^3$$

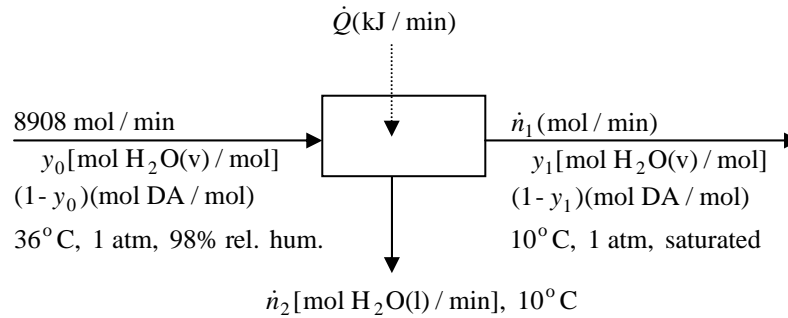
$$\Rightarrow \frac{0.160 \text{ kg H}_2\text{O condensed}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{0.0604 \text{ kg H}_2\text{O condensed / m}^3 \text{ air fed}}}$$

$$\Rightarrow \frac{-480.5 \text{ kJ}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{-181 \text{ kJ / m}^3 \text{ air fed}}}$$

e. Solve equations with E-Z Solve.

f.
$$Q = \frac{-181 \text{ kJ}}{\text{m}^3 \text{ air fed}} \left| \frac{250 \text{ m}^3 \text{ air fed}}{\text{h}} \right| \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ / s}} \right| = \underline{\underline{-12.6 \text{ kW}}}$$

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



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

b. Inlet air: $y_0 P = 0.98 p_w^* (36^\circ \text{C}) \Rightarrow y_0 = \frac{0.98(44.563 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.0575 \text{ mol H}_2\text{O(v)}/\text{mol}$

Outlet air: $y_1 = p^*(10^\circ \text{C}) / P = (9.209 \text{ mm Hg}) / (760 \text{ mm Hg}) = 0.0121 \text{ mol H}_2\text{O(v)}/\text{mol}$

Air balance: $(1 - 0.0575)(8908 \text{ mol/min}) = (1 - 0.0121)n_1 \Rightarrow n_1 = 8499 \text{ mol/min}$

H₂O balance: $0.0575 \left(8908 \frac{\text{mol}}{\text{min}} \right) = 0.0121 (8499 \frac{\text{mol}}{\text{min}}) + n_2 \Rightarrow n_2 = \underline{\underline{409 \text{ mol H}_2\text{O(l)}/\text{min}}}$

References: H₂O(l, triple point), air (77°F)

Substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{out}	
Air	8396	0.3198	8396	-0.4352	\dot{n} in mol/min
H ₂ O(v)	512	46.2	103	45.3	\hat{H} in kJ/mol
H ₂ O(l)	—	—	409	0.741	

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

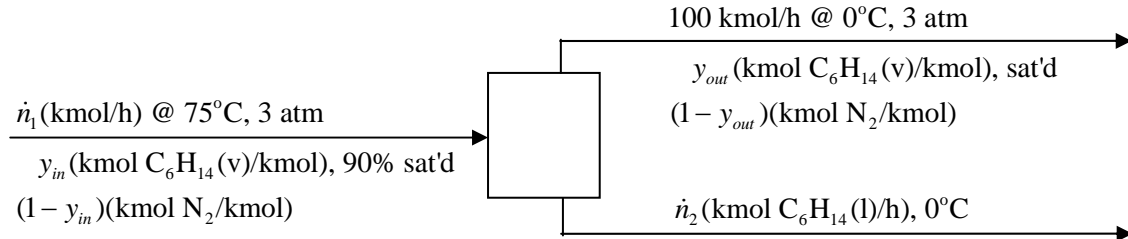
H₂O: \hat{H} (kJ/kg) from Table B.5 \times (0.018 kg/mol)

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \frac{-2.50 \times 10^4 \text{ kJ}}{\text{min}} \bigg| \frac{60 \text{ min}}{1 \text{ h}} \bigg| \frac{9.486 \times 10^{-4} \text{ Btu}}{0.001 \text{ kJ}} \bigg| \frac{1 \text{ ton}}{-12000 \text{ Btu/h}} = \underline{\underline{119 \text{ tons}}}$$

8.48

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

Antoine:

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

$$y_{\text{out}} = \frac{p_v^*(0^\circ\text{C})}{P} = \frac{45.24}{3(760)} = 0.0198 \text{ kmol C}_6\text{H}_{14}/\text{kmol},$$

$$y_{\text{in}} = \frac{0.90 p_v^*(75^\circ\text{C})}{P} = \frac{(0.90)(920.44)}{3(760)} = 0.363 \frac{\text{kmol C}_6\text{H}_{14}}{\text{kmol}}$$

N₂ balance: $\dot{n}_1(1 - 0.363) = 100(1 - 0.0198) \Rightarrow \dot{n}_1 = 153.9 \text{ kmol/h}$

C₆H₁₄ balance: $(153.9)(0.363) = (100)(0.0198) + \dot{n}_2 \Rightarrow \dot{n}_2 = 53.89 \text{ kmol C}_6\text{H}_{14}(l)/\text{h}$

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: N₂(25°C), n-C₆H₁₄(l, 0°C)

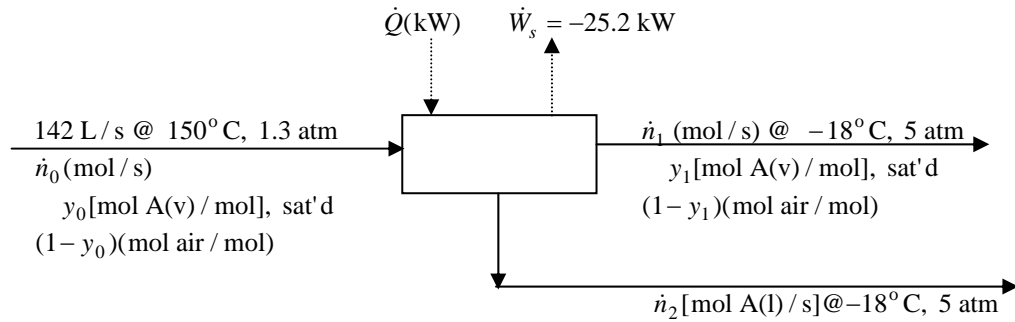
Substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
N ₂	98000	1.46	98000	-0.726	\dot{n} in mol/h
n-C ₆ H ₁₄ (r)	55800	44.75	2000	33.33	\hat{H} in kJ/mol
n-C ₆ H ₁₄ (l)	—	—	53800	0.0	

N₂: $\hat{H} = \bar{C}_p(T - 25), \quad \underline{n - \text{C}_6\text{H}_{14}(\text{v})}: \hat{H} = \int_0^{68.7} C_{p\ell} dT + \Delta \hat{H}_v(68.7) + \int_{68.7}^T C_{pv} dT$

Energy balance: $Q = \Delta H = (-2.64 \times 10^6 \text{ kJ/h})(1 \text{ h} / 3600 \text{ s}) \Rightarrow \underline{\underline{-733 \text{ kW}}}$

$$\sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

8.49 Let A denote acetone.



- a. Degree of freedom analysis: 6 unknowns (\dot{n}_0 , \dot{n}_1 , \dot{n}_2 , y_0 , y_1 , \dot{Q})
 -2 material balances
 -1 equation of state for feed gas
 -1 sampling result for feed gas
 -1 saturation condition at outlet
 -1 energy balance
 0 degrees of freedom

- b. Ideal gas equation of state Raoult's law

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

Feed stream analysis

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

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

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

Substance	\dot{n}_{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}

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

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

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

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

8.49 (cont'd)

c.

$$(1) \Rightarrow \dot{n}_0 = \underline{5.32 \text{ mol feed gas/s}} \quad (2) \Rightarrow y_1 = \underline{6.58 \times 10^{-3} \text{ mol A(v)/mol outlet gas}}$$

$$(3) \Rightarrow y_0 = \underline{0.147 \text{ mol A(v)/mol feed gas}}$$

$$(4) \Rightarrow \dot{n}_1 = 4.57 \text{ mol outlet gas/s} \quad (5) \Rightarrow \dot{n}_2 = 0.75 \text{ mol A(l)/s}$$

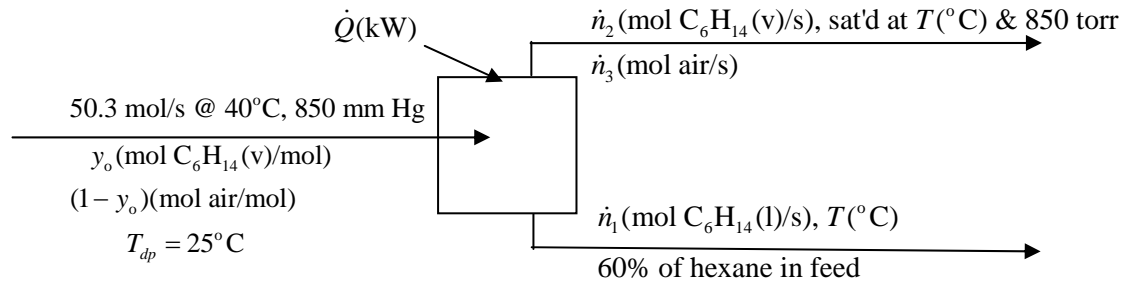
$$(6) \Rightarrow \hat{H}_{A0} = 48.1 \text{ kJ/mol}, \hat{H}_{A1} = 34.0 \text{ kJ/mol}$$

$$(7) \Rightarrow \hat{H}_{a0} = 3.666 \text{ kJ/mol}, \hat{H}_{a1} = -1.245 \text{ kJ/mol}$$

$$(8) \Rightarrow \underline{\underline{\dot{Q} = -84.1 \text{ kW}}}$$

8.50 a. Feed: $\frac{3 \text{ m}}{\text{s}} \left| \frac{\pi(35)^2 \text{ cm}^2}{10^4 \text{ cm}^2} \right| \frac{1 \text{ m}^2}{(273+40)\text{K}} \left| \frac{273 \text{ K}}{760 \text{ torr}} \right| \frac{1 \text{ kmol}}{22.4 \text{ m}^3 \text{ (STP)}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| = 50.3 \frac{\text{mol}}{\text{s}}$

Assume outlet gas is at 850 mm Hg.



Degree-of-freedom analysis

- 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 $H = C_6H_{14}$

Antoine equation, Table B.4

$$(T_{dp})_{feed} = 25^\circ\text{C} \Rightarrow y_0 = \frac{p_H^*(25^\circ\text{C})}{P} = \frac{151 \text{ mm Hg}}{850 \text{ mm Hg}} = 0.178 \text{ mol H/mol}$$

$$\underline{60\% \text{ recovery}} \Rightarrow \dot{n}_1 = \frac{0.600}{1} \left| \frac{(50.3)(0.178) \text{ mols H feed}}{\text{s}} \right| = 5.37 \text{ mol H(l)/s}$$

$$\underline{\text{Hexane balance:}} (0.178)(50.3) = 5.37 + \dot{n}_2 \Rightarrow \dot{n}_2 = 3.58 \text{ mol H(v)/s}$$

8.50 (cont'd)

Air balance: $\dot{n}_3 = (50.3)(1 - 0.178) = 41.3 \text{ mol air/s}$

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: $p_H^*(T) = p_H(T) = 67.8 \text{ mm Hg} \xrightarrow{\text{Table B.4}} \underline{\underline{T = 7.8^\circ\text{C}}}$

Reference states: $\text{C}_6\text{H}_{14}(l, 7.8^\circ\text{C})$, air (25°C)

Substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{out}	
$\text{C}_6\text{H}_{14}(v)$	8.95	37.5	3.58	32.7	\dot{n} in mol/s
$\text{C}_6\text{H}_{14}(l)$	—	—	5.37	0	\hat{H} in kJ/mol
Air	41.3	0.435	41.3	-0.499	

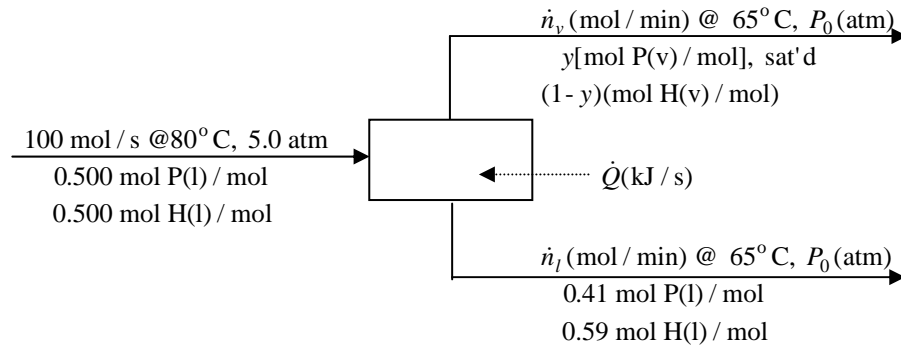
$$\text{C}_6\text{H}_{14}(v): \hat{H} = \int_{7.8}^{68.74} C_{p,l} dT + \Delta\hat{H}_v(68.74^\circ\text{C}) + \int_{68.74}^T C_{p,v} dT, \quad \begin{matrix} C_p \text{ from Table B.2} \\ \Delta\hat{H}_v \text{ from Table B.1} \end{matrix}$$

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

$$\text{Energy balance: } Q = \Delta H = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \frac{-257 \text{ kJ/s}}{-1 \text{ kJ/s}} \bigg| \frac{1 \text{ kW cooling}}{-1 \text{ kJ/s}} = \underline{\underline{257 \text{ kW}}}$$

c. $u \cdot A = u' \cdot A'; \quad A = \frac{\pi \cdot D^2}{4}; \quad D' = \frac{1}{2} D \quad \left\} \Rightarrow u' = 4 \cdot u = \underline{\underline{12.0 \text{ m/s}}}$

8.51

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) $\Rightarrow p_P^*(65^\circ\text{C}) = 1851\text{ mm Hg}$, $p_H^*(65^\circ\text{C}) = 675\text{ mm Hg}$

Raoult's law for pentane and hexane

$$\begin{aligned} 0.410 p_P^*(65^\circ\text{C}) &= y P_0 \\ 0.590 p_H^*(65^\circ\text{C}) &= (1 - y) P_0 \end{aligned} \quad \Rightarrow \quad \begin{aligned} y &= 0.656 \text{ mol P(v) / mol} \\ P_0 &= 1157 \text{ mm Hg (1.52 atm)} \end{aligned}$$

Total mole balance: $100 \text{ mol} = \dot{n}_v + \dot{n}_l \quad \Rightarrow \quad \dot{n}_v = 36.6 \text{ mol vapor / s}$

Pentane balance: $50 \text{ mole P} = 0.656 \dot{n}_v + 0.410 \dot{n}_l \quad \Rightarrow \quad \dot{n}_l = 63.4 \text{ mol liquid / s}$

Ideal gas equation of state: $V_v = \frac{n_v RT}{P_0} = \frac{36.6 \text{ mol}}{\text{s}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \frac{(65 + 273)\text{K}}{1.52 \text{ atm}} = \underline{\underline{667 \text{ L / s}}}$

Fractional vaporization of propane: $f = \frac{(0.656 \times 36.6) \text{ mol P(v) / s}}{50.0 \text{ mol P(l) fed / s}} = \underline{\underline{0.480 \frac{\text{mol P vaporized}}{\text{mol fed}}}}$

References: P(l), H(l) at 65°C

Substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{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	

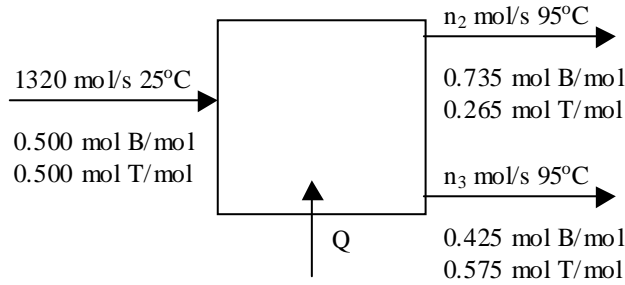
$$\text{Vapor: } \hat{H}(T) = \int_{65^\circ\text{C}}^{T_b} C_{pl} dT + \Delta \hat{H}_v(T_b) + \int_{T_b}^T C_{pv} dT$$

$$\text{Liquid: } \hat{H}(T) = \int_{65^\circ\text{C}}^T C_{pl} dT$$

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



$$\left. \begin{array}{l} \text{Total mole balance: } 1320 = n_2 + n_3 \\ \text{Benzene balance: } 1320(0.500) = n_2(0.735) + n_3(0.425) \end{array} \right\} \Rightarrow \begin{cases} n_2 = 319 \text{ mol/s} \\ n_3 = 1001 \text{ mol/s} \end{cases}$$

References: 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) $\Rightarrow p_B^*(95^\circ\text{C}) = 1176 \text{ torr}$, $p_T^*(95^\circ\text{C}) = 476.9 \text{ torr}$

Raoult's law

$$\left. \begin{array}{l} \text{Benzene: } (0.425)(1176) = (0.735)P \Rightarrow P = 680 \text{ torr} \\ \text{Toluene: } (0.575)(476.9) = (0.265)P' \Rightarrow P' = 1035 \text{ torr} \end{array} \right\} \Rightarrow P \neq P'$$

\Rightarrow Analyses are inconsistent.

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 Kopp's rule (Table B.10): $\text{C}_5\text{H}_{12}\text{O}(s) \rightarrow C_p = (5)(7.5) + (12)(9.6) + 17 = 170 \text{ J/mol}$

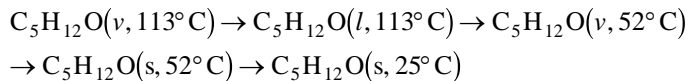
$$\text{C}_5\text{H}_{12}\text{O}(l) \rightarrow C_p = (5)(12) + (12)(18) + 25 = 301 \text{ J/mol}$$

Trouton's rule — Eq. (8.4-3): $\Delta H_v = (0.109)(113 + 273) = 42.1 \text{ kJ/mol}$

$$\text{Eq. (8.4-5)} \Rightarrow \Delta \hat{H}_m = (0.050)(52 + 273) = 16.25 \text{ kJ/mol}$$

$$\text{Basis: } \frac{235 \text{ m}^3}{\text{h}} \left| \frac{273 \text{ K}}{389 \text{ K}} \right| \frac{1 \text{ kmol}}{22.4 \text{ m}^3(\text{STP})} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{1 \text{ h}}{3600 \text{ s}} = 2.05 \text{ mol/s}$$

Neglect enthalpy change for the vapor transition from 116°C to 113°C.



8.53 (cont'd)

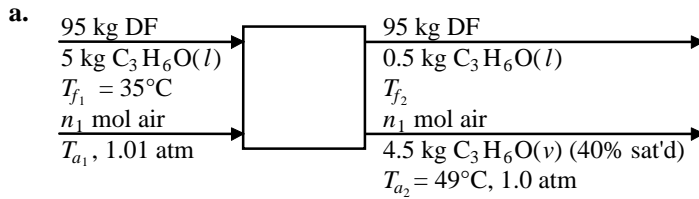
$$\Delta \hat{H} = -\Delta \hat{H}_v + C_{pl}(52 - 113) - \Delta \hat{H}_m + C_{ps}(25 - 52)$$

$$= -42.1 \frac{\text{kJ}}{\text{mol}} - 16.2 \frac{\text{kJ}}{\text{mol}} - [(301)(61) + (170)(27)] \frac{\text{J}}{\text{mol}} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} = -81.3 \text{ kJ/mol}$$

Required heat transfer: $Q = \Delta H = n\Delta \hat{H} = \frac{2.05 \text{ mol}}{\text{s}} \left| \frac{-81.3 \text{ kJ}}{\text{mol}} \right| \frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-167 \text{ kW}}}$

8.54

Basis: 100 kg wet film \Rightarrow $\left. \begin{array}{l} 95 \text{ kg dry film} \\ 5 \text{ kg acetone} \end{array} \right\} \xrightarrow{90\% \text{ A evaporation}} \left. \begin{array}{l} 0.5 \text{ kg acetone remain in film} \\ 4.5 \text{ kg acetone exit in gas phase} \end{array} \right\}$



Antoine equation (Table B.4) $\Rightarrow p_{\text{C}_3\text{H}_6\text{O}}^* = 591.18 \text{ mm Hg}$

$$\frac{4.5 \text{ kg C}_3\text{H}_6\text{O}}{58.08 \text{ kg}} \left| \frac{1 \text{ kmol}}{\text{kmol}} \right| \frac{10^3 \text{ mol}}{\text{kmol}} = 77.5 \text{ mol C}_3\text{H}_6\text{O}(v) \text{ in exit gas}$$

$$\Rightarrow y = \frac{77.5}{77.5 + n_1} = \frac{0.40(591.18 \text{ mm Hg})}{760 \text{ mm Hg}} \Rightarrow n_1 = \frac{171.6 \text{ mol}}{\text{mol}} \left| \frac{22.4 \text{ L(STP)}}{95 \text{ kg DF}} \right| = 40.5 \frac{\text{L(STP)}}{\text{kg DF}}$$

b. References: Air(25°C), C₃H₆O(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 ₆ H ₁₄ O(l)	86.1	0	8.6	$0.129(T_{f2} - 35)$	n in mol \hat{H} in kJ/mol
C ₆ H ₁₄ O(v)	—	—	77.5	32.3	
Air	171.6	$\int_{25}^{T_{a1}} (C_p)_{\text{air}} dT$	171.6	0.70	

$$\hat{H}_{\text{A(v)}} = \int_{35}^{86} (C_p)_l dT + \Delta \hat{H}_v + \int_{86}^{49} (C_p)_v dT, \quad \hat{H}_{\text{DF}} = C_p(T - 35)$$

Energy balance

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 126.4(T_{f2} - 35) + 1.11(T_{f2} - 35) + 2623.4 - 171.6 \int_{25}^{T_{a1}} (C_p)_{\text{air}} dT = 0$$

$$\Rightarrow \int_{25}^{T_{a1}} (C_p)_{\text{air}} dT = \frac{127.5(T_{f2} - 35) + 2623.4}{171.6}$$

c. $T_{a1} = 120^\circ \text{C} \Rightarrow \int_{25}^{T_{a1}} (C_p)_{\text{air}} dT = 2.78 \text{ kJ/mol} \Rightarrow (T_{f2} - 35)^\circ \text{C} = \underline{\underline{-16.8^\circ \text{C}}}$

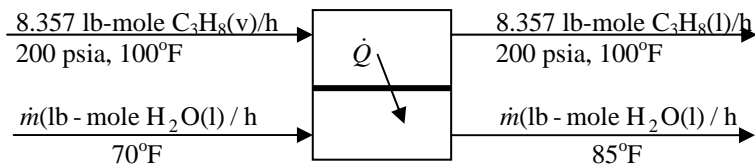
8.54 (cont'd)

d. $T_{f2} = 34^\circ\text{C} \xRightarrow{\text{T\&E}} T_{a1} = 506^\circ\text{C}$, $T_{f2} = 36^\circ\text{C} \xRightarrow{\text{T\&E}} T_{a1} = 552^\circ\text{C}$

- 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 $T_{\text{set}}(p = 200 \text{ psia}) \approx 100^\circ\text{F}$ (Cox chart – Fig. 6.1-4)

a. Basis: $\frac{3.00 \times 10^3 \text{ SCF}}{\text{h}} \left| \frac{1 \text{ lb-mole}}{359 \text{ SCF}} \right| = 8.357 \text{ lb-mole/h C}_3\text{H}_8$



The outlet water temperature is 85°F . It must be less 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.

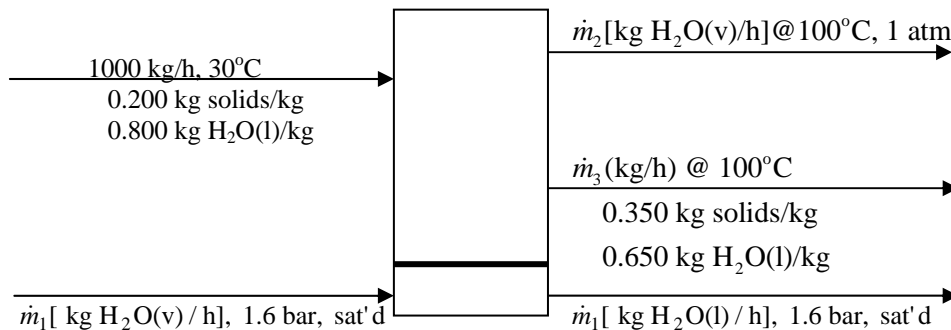
- b. Energy balance on propane:

$$\dot{Q} = \Delta \dot{H} = -\dot{n} \Delta \hat{H}_v = \frac{8.357 \text{ lb-moles}}{\text{h}} \left| \begin{array}{c} \text{Table B.1} \\ \downarrow \\ -18.77 \text{ kJ} \\ \text{mol} \end{array} \right| \left| \frac{0.9486 \text{ Btu}}{\text{kJ}} \right| \left| \frac{453.593 \text{ mol}}{1 \text{ lb-mole}} \right| = -6.75 \times 10^4 \frac{\text{Btu}}{\text{h}}$$

Energy balance on cooling water: Assume no heat loss to surroundings.

$$\dot{Q} = \Delta \dot{H} = \dot{m} C_p \Delta T \Rightarrow \dot{m} = \frac{6.75 \times 10^4 \text{ Btu}}{\text{h}} \left| \frac{\text{lb}_m \cdot ^\circ\text{F}}{1.0 \text{ Btu}} \right| \left| \frac{15^\circ\text{F}}{15^\circ\text{F}} \right| = 4500 \frac{\text{lb}_m \text{ cooling water}}{\text{h}}$$

8.56



- a. Solids balance: $200 = 0.35m_3 \Rightarrow m_3 = 571.4 \text{ kg/h slurry}$
H₂O balance: $800 = m_2 + 0.65(571.4) \Rightarrow m_2 = 428.6 \text{ kg/h H}_2\text{O}(v)$

8.56 (cont'd)

References: Solids (0.01°C), H₂O (l, 0.01°C)

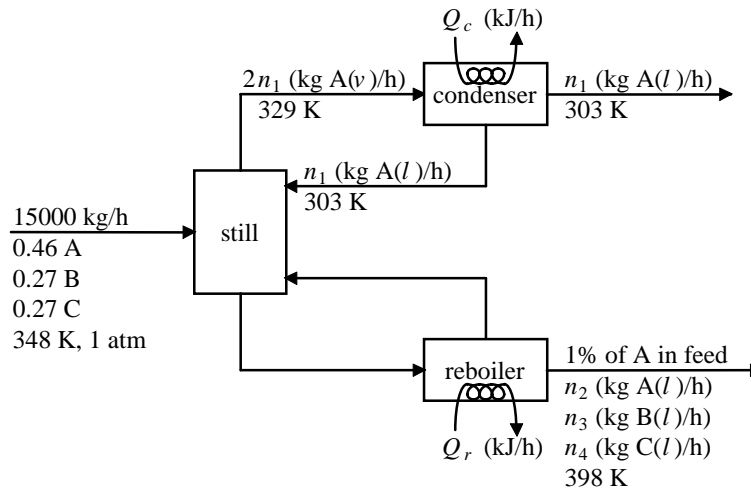
Substance	\dot{m}_{in}	\hat{H}_{in}	\dot{m}_{out}	\hat{H}_{out}	
Solids	200	62.85	200	209.6	\dot{m} (kg/h) \hat{H} (kJ/kg) \hat{H}_{H_2O} from steam tables
H ₂ O(l)	800	125.7	571.4	419.1	
H ₂ O(v)	—	—	428.6	2676	
H ₂ O, 1.6 bar	\dot{m}_1	2696.2	\dot{m}_1	475.4	

$$\text{E.B. } Q = \Delta H = \sum_{out} \dot{m}_i \hat{H}_i - \sum_{in} \dot{m}_i \hat{H}_i = 0 \Rightarrow 1.315 \times 10^6 - 2221 \dot{m}_1 = 0 \Rightarrow \dot{m}_1 = \underline{\underline{592 \text{ kg steam/h}}}$$

b. $(592.0 - 428.6) = \underline{\underline{163 \text{ kg/h additional steam}}}$

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. $\dot{n}_2 = (0.01)(0.46)(15,000 \text{ kg/h}) = 69 \text{ kg A/h}$

Acetic acid balance: $\dot{n}_3 = (0.27)(15,000) = 4050 \text{ kg B/h}$

Acetic anhydride balance: $\dot{n}_4 = (0.27)(15,000) = 4050 \text{ kg/h}$

Acetone balance: $(0.46)(15,000) = n_1 + 69 \Rightarrow n_1 = 6831 \text{ kg/h}$

↓

Distillate product: 6831 kg acetone/h

8169 kg/h

Bottoms product: $(69 + 4050 + 4050) \text{ kg/h} = 8169 \text{ kg/h}$

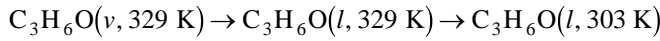
0.8% acetone

49.6% acetic acid

49.6% acetic anhydride

b. Energy balance on condenser

8.57 (cont'd)



$$\Delta \hat{H} = -\Delta \hat{H}_v(329 \text{ K}) + \int_{329}^{303} C_{p,l} dT = -520.6 + (2.3)(-26) = -580.4 \text{ kJ/kg}$$

$$\dot{Q}_c = \Delta \dot{H} = \dot{n} \Delta \hat{H} = \frac{(2 \times 6831) \text{ kg}}{\text{h}} \left| \frac{-580.4 \text{ kJ}}{\text{kg}} \right| = \underline{\underline{-7.93 \times 10^6 \text{ kJ/h}}}$$

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 \hat{H} in kJ/kg
A (l, 398 K)	—	0	69	115.0	
B (l, 398 K)	—	0	4050	109.0	
C (l, 398 K)	—	0	4050	113	

Acetic anhydride (l): $C_p \approx [(4 \times 12) + (6 \times 18) + (3 \times 25)] \frac{\text{J}}{\text{mol} \cdot ^\circ\text{C}} \left| \frac{1 \text{ mol}}{102.1 \text{ g}} \right| \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right|$
 $= 2.3 \text{ kJ/kg} \cdot ^\circ\text{C}$

$$\hat{H}(T) = C_p (T - 348) \text{ (all substances)}$$

$$\dot{Q} = \Delta \dot{H} \Rightarrow \dot{Q}_c + \dot{Q}_r = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i \Rightarrow \dot{Q}_r = -\dot{Q}_c + \sum_{\text{out}} \dot{n}_i \hat{H}_i = (7.93 \times 10^6 + 2.00 \times 10^5) \text{ kJ/h}$$

$$\uparrow = 0 \qquad \qquad \qquad = \underline{\underline{8.13 \times 10^6 \text{ kJ/h}}}$$

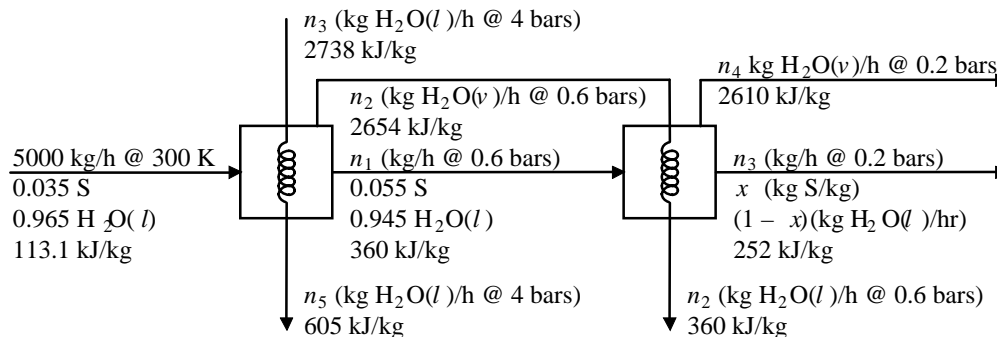
(We have neglected heat losses from the still.)

d. H₂O (saturated at ≈ 11 bars): $\Delta \hat{H}_v = 1999 \text{ kJ/kg}$ (Table 8.6)

$$\dot{Q}_r = \dot{n}_{\text{H}_2\text{O}} \Delta \hat{H}_v \Rightarrow \dot{n}_{\text{H}_2\text{O}} = \frac{8.13 \times 10^6 \text{ kJ/h}}{1999 \text{ kJ/kg}} = \underline{\underline{4070 \text{ kg steam/h}}}$$

8.58 Basis: 5000 kg seawater/h

a. S = Salt



b. S balance on 1st effect: $(0.035)(5000) = 0.055 \dot{n}_1 \Rightarrow \dot{n}_1 = 3182 \text{ kg/h}$

Mass balance on 1st effect: $5000 = 3182 + \dot{n}_2 \Rightarrow \dot{n}_2 = 1818 \text{ kg/h}$

8.58 (cont'd)

Energy balance on 1st effect:

$$\Delta \dot{H} = 0 \Rightarrow (\dot{n}_2)(2654) + (\dot{n}_1)(360) + (\dot{n}_5)(605 - 2738) - (5000)(113.1) = 0$$

$$\xrightarrow[\substack{\dot{n}_1 = 3182 \\ \dot{n}_2 = 1818}]{\dot{n}_5 = 2534 \text{ kg H}_2\text{O}(v)/\text{h}}$$

c. Mass balance on 2nd effect: $3182 = \dot{n}_3 + \dot{n}_4$ (1)

Energy balance on 2nd effect: ($\Delta H = 0$)

$$(\dot{n}_4)(2610) + (\dot{n}_3)(252) + (\dot{n}_2)(360 - 2654) - (\dot{n}_1)(360) = 0$$

$$\Downarrow \dot{n}_1 = 3182, \dot{n}_2 = 1818$$

$$5.316 \times 10^6 = 252\dot{n}_3 + 2610\dot{n}_4 \quad (2)$$

Solve (1) and (2) simultaneously:

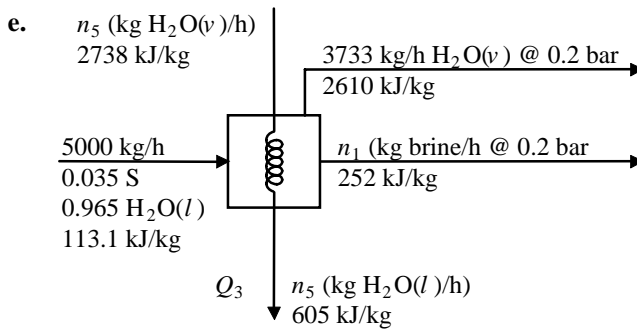
$$\dot{n}_3 = 1267 \text{ kg/h brine solution}$$

$$\dot{n}_4 = 1915 \text{ kg/h H}_2\text{O}(v)$$

Production rate of fresh water $= \dot{n}_2 + \dot{n}_4 = (1818 + 1915) = \underline{\underline{3733 \text{ kg/h fresh water}}}$

Overall S balance: $(0.035)(5000) = 1267x \Rightarrow \underline{\underline{x = 0.138 \text{ kg salt/kg}}}$

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.



Mass balance: $5000 = 3733 + \dot{n}_1 \Rightarrow \dot{n}_1 = 1267 \text{ kg/h}$

Energy balance: ($\Delta \dot{H} = 0$)

$$(3733)(2610) + (1267)(252) + \dot{n}_5(605 - 2738) - (5000)(113.1) = 0$$

$$\Rightarrow \underline{\underline{\dot{n}_5 = 4452 \text{ kg H}_2\text{O}(v)/\text{h}}}$$

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: $x_{L7}\dot{n}_{L7} = x_{L1}\dot{n}_{L1} \Rightarrow \dot{n}_{L1} = \frac{(0.035)(5000)}{0.30} = \underline{\underline{583 \text{ kg/h}}}$
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:

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

Energy balance on i^{th} effect:

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

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

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

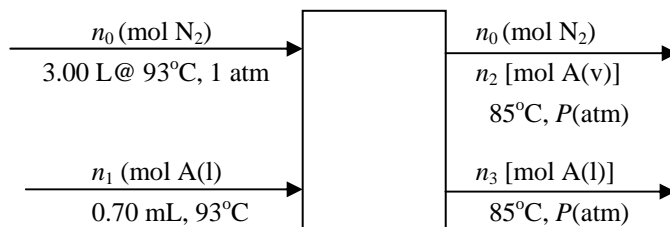
$$\dot{n}_{Li} = (\dot{n}_v)_{i-1} + (\dot{n}_L)_{i-1} \Rightarrow (\dot{n}_L)_{i-1} = \dot{n}_{Li} - (\dot{n}_v)_{i-1} \quad (3)$$

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. $(C_p)_v = (C_p)_l = \underline{\underline{20 \text{ cal}/(\text{mol} \cdot ^\circ\text{C})}}$; $(C_v)_v \approx (C_p)_v - R \approx (10 - 2) \frac{\text{cal}}{\text{mol} \cdot ^\circ\text{C}} = \underline{\underline{8 \text{ cal}/(\text{mol} \cdot ^\circ\text{C})}}$

b.



$$n_0 = \frac{3.00 \text{ L}}{(273 + 93) \text{ K}} \left| \frac{273 \text{ K}}{22.4 \text{ L(STP)}} \right| \frac{1 \text{ mol}}{1} = 0.100 \text{ mol N}_2$$

$$n_1 = \frac{70.0 \text{ mL}}{1 \text{ mL}} \left| \frac{0.90 \text{ g}}{42 \text{ g}} \right| \frac{1 \text{ mol}}{1} = 1.5 \text{ mol A}(l)$$

Energy balance $\Rightarrow \Delta U = 0 \Rightarrow \sum_{\text{out}} n_i \hat{U}_i - \sum_{\text{in}} n_i \hat{U}_i = 0$

c. References: $\text{N}_2(g)$, $\text{A}(l)$ (85°C, 1 atm)

Substance	n_{in}	\hat{U}_{in}	n_{out}	\hat{U}_{out}	
N_2	0.10	39.8	0.10	0	n in mol
$\text{A}(l)$	1.5	160	n_3	0	\hat{U} in cal/mol
$\text{A}(v)$	—	—	n_2	20050	

$\text{A}(l, 93^\circ\text{C})$ and $\text{N}_2(g, 93^\circ\text{C})$: $\hat{U} = C_v(93 - 85)$

$\text{A}(v, 85^\circ\text{C})$: $\hat{U}_{\text{A}(v)} = 20(90 - 85) + 20,000 + 10(85 - 90) = 20050 \text{ cal/mol}$

$\Delta U = 0 \Rightarrow n_{v1}(20050) - (0.10)(39.8) - (1.5)(160) = 0 \Rightarrow n_{v1} = 0.012 \text{ mol A evaporate}$

$$\Rightarrow \frac{0.012 \text{ mol A}}{1 \text{ mol A}} \left| \frac{42 \text{ g A}}{1} \right| = \underline{\underline{0.51 \text{ g evaporate}}}$$

d. Ideal gas equation of state

$$P = \frac{(n_0 + n_2)RT}{V} = \frac{0.112 \text{ mol}}{3.00 \text{ liters}} \left| \frac{(273 + 85) \text{ K}}{1} \right| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} = 1.097 \text{ atm}$$

Raoult's law

$$p_A^*(85^\circ\text{C}) = y_A P = \frac{n_2}{n_0 + n_2} P = \frac{0.012 \text{ mol}}{0.112 \text{ mol}} \left| \frac{1.097 \text{ atm}}{1} \right| = \underline{\underline{0.117 \text{ atm}}} \quad (= 89.3 \text{ mmHg})$$

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

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

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

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

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

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

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

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

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

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

$$\underline{\text{Expt. 2}} \Rightarrow n = 0.0232 \text{ mol} \left[\text{from (ii)} \right]$$

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

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

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

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

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

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

$$\text{v) } \underline{\text{Expt. 3}} \Rightarrow T = 315 \text{ K}, p^* = (763 - 564) \text{ mm Hg} = 199 \text{ mm Hg}$$

$$T = 334 \text{ K}, p^* = 401 \text{ mm Hg}$$

$$T = 354 \text{ K}, p^* = 761 \text{ mm Hg}$$

$$T = 379 \text{ K}, p^* = 1521 \text{ mm Hg}$$

8.61 (cont'd)

Plot p^* (log scale) vs. $1/T$ (linear scale); straight line fit yields

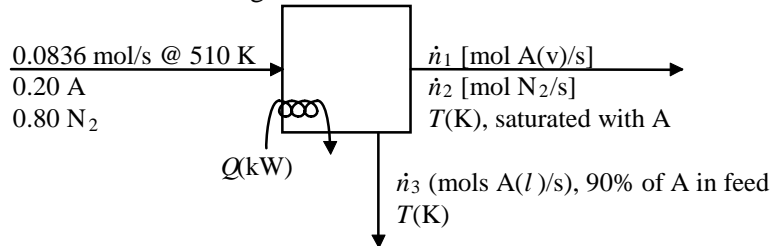
$$\ln p^* = \frac{-3770}{T(\text{K})} + 17.28 \quad \text{or} \quad p^* = 3.196 \times 10^7 \exp(-3770/T)$$

$$\text{vi) } p^* = 760 \text{ mm Hg} \Rightarrow \underset{\substack{\uparrow \\ \text{Part v}}}{\frac{1}{T_b}} = \frac{17.28 - \ln(760)}{3770} = 2.824 \times 10^{-3} \text{ K}^{-1} \Rightarrow \underline{T_b = 354 \text{ K}}$$

$$\text{vii) } \frac{\Delta \hat{H}_v}{R} = 3770(\text{K}) \Rightarrow \Delta \hat{H}_v = (3770 \text{ K})(8.314 \text{ J/mol} \cdot \text{K}) \Rightarrow \underline{\Delta \hat{H}_v = 31,300 \text{ J/mol}}$$

(b) Basis: $\frac{3.5 \text{ L feed}}{\text{s}} \mid \frac{273 \text{ K}}{510 \text{ K}} \mid \frac{1 \text{ mol}}{22.4 \text{ l(STP)}} = 0.0836 \text{ mol/s feed gas}$

Let A denote the drug



N₂ balance: $\dot{n}_2 = (0.800)(0.0836 \text{ mol/s}) = 0.0669 \text{ mol N}_2/\text{s}$

90% condensation: $\dot{n}_3 = (0.900)(0.200 \times 0.0836) = 0.01505 \text{ mol A}(l)/\text{s}$

$$\dot{n}_1 = (0.100)(0.200 \times 0.0836) = 1.67 \times 10^{-3} \text{ mol A}(v)/\text{s}$$

Partial pressure of A in outlet gas:

$$p_A = \frac{\dot{n}_1}{(\dot{n}_1 + \dot{n}_2)} P = \frac{1.67 \times 10^{-3} \text{ mol}}{0.0686 \text{ mol}} (760 \text{ mm Hg}) = 18.5 \text{ mm Hg} = p_A^*(T)$$

⇓ Part (a) - (v)

$$\frac{1}{T} = \frac{17.28 - \ln(18.5)}{3770} = 3.81 \times 10^{-3} \text{ K}^{-1}$$

⇓

$$T = 262 \text{ K}$$

(c) Reference states: N₂, A(l) at 262 K

substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{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)

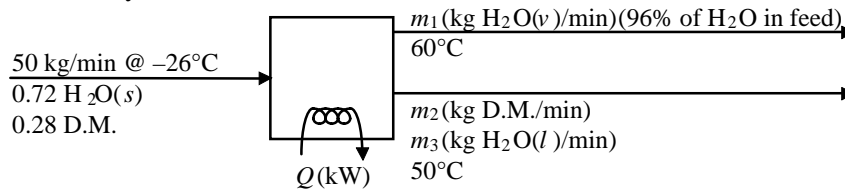
$$\begin{aligned} \underline{N_2(510\text{ K}): } \hat{H}_{N_2}(510\text{ K}) - \hat{H}_{N_2}(262\text{ K}) &= \hat{H}_{N_2}(237^\circ\text{C}) - \hat{H}_{N_2}(-11^\circ\text{C}) \\ &\stackrel{\text{Table B.8}}{\downarrow} \\ &= [6.24 - (-1.05)] \text{ kJ/mol} = 7.286 \text{ kJ/mol} = 7286 \text{ J/mol} \end{aligned}$$

$$\begin{aligned} \underline{A(v, 262\text{ K}): } \hat{H} &= C_{pl}(T_b - 262) + \Delta\hat{H}_v(359\text{ K}) + \int_{T_b}^{262} C_{pv}dT \\ &\stackrel{\text{Part (a) results for } T_b, C_{pl}, C_{pv}, \Delta\hat{H}_v}{\downarrow} \\ \hat{H} &= 24(354 - 262) + 31300 + \left[4.245 + 0.05052 \frac{T^2}{2} \right]_{354}^{262} = 31686 \text{ J/mol} \end{aligned}$$

$$\underline{A(v, 510\text{ K}): } \hat{H} = C_{pl}(T_b - 262) + \Delta\hat{H}_v(354\text{ K}) + \int_{T_b}^{510} C_{pv}dT = 37575 \text{ J/mol}$$

$$\underline{\text{Energy balance:}} \quad \dot{Q} = \Delta\dot{H} = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \frac{-1060 \text{ J/s}}{-10^3 \text{ kJ/s}} \bigg| \frac{1 \text{ kW cooling}}{1} = \underline{\underline{1.06 \text{ kW}}}$$

8.62 a. Basis: 50 kg wet steaks/min
D.M. = dry meat



96% vaporization:

$$\dot{m}_1 = 0.96(0.72 \times 50 \text{ kg/min}) = 34.56 \text{ kg H}_2\text{O}(v)/\text{min}$$

$$\dot{m}_3 = 0.04(0.72 \times 50 \text{ kg/min}) = 1.44 \text{ kg H}_2\text{O}(l)/\text{min}$$

Dry meat balance:

$$\dot{m}_2 = (0.28)(50) = 14.0 \text{ kg D.M./min}$$

Reference states: Dry meat at -26°C , $\text{H}_2\text{O}(l, 0^\circ\text{C})$

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
$\text{H}_2\text{O}(s, -26^\circ\text{C})$	36.0	-390	—	—	\hat{H} in kJ/kg
$\text{H}_2\text{O}(l, 50^\circ\text{C})$	—	—	1.44	209	
$\text{H}_2\text{O}(v, 60^\circ\text{C})$	—	—	34.56	2599	

$$\underline{\text{Dry meat:}} \quad \hat{H}(50^\circ\text{C}) = C_p[50 - (-26)] = \frac{1.38 \text{ kJ}}{\text{kg} \cdot ^\circ\text{C}} \bigg| \frac{76^\circ\text{C}}{1} = 105 \text{ kJ/kg}$$

$$\underline{\text{H}_2\text{O}(s, -26^\circ\text{C}): } \text{H}_2\text{O}(l, 0^\circ\text{C}) \rightarrow \text{H}_2\text{O}(s, 0^\circ\text{C}) \rightarrow \text{H}_2\text{O}(s, -26^\circ\text{C})$$

8.62 (cont'd)

$$\Delta \hat{H} = -\Delta \hat{H}_m(0^\circ \text{C}) + \int_0^{-26} C_p dT = \frac{-6.01 \text{ kJ}}{\text{mol}} \left| \frac{1 \text{ mol}}{18.02 \text{ g}} \right| \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| + \frac{2.17 \text{ kJ}}{\text{kg} \cdot ^\circ \text{C}} \left| \frac{-26^\circ \text{C}}{1} \right| = -390 \text{ kJ/kg}$$

\uparrow
 Table B.1

$$\underline{\text{H}_2\text{O}(l, 50^\circ \text{C})}: \text{H}_2\text{O}(l, 0^\circ \text{C}) \rightarrow \text{H}_2\text{O}(l, 50^\circ \text{C})$$

$$\Delta \hat{H} = \int_0^{50} C_p dT = \frac{0.0754 \text{ kJ}}{\text{mol} \cdot ^\circ \text{C}} \left| \frac{(50 - 0)^\circ \text{C}}{1} \right| \left| \frac{1 \text{ mol}}{18.02 \text{ g}} \right| \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right| = 209 \text{ kJ/kg}$$

\uparrow
 Table B.2

$$\underline{\text{H}_2\text{O}(v, 60^\circ \text{C})}: \text{H}_2\text{O}(l, 0^\circ \text{C}) \rightarrow \text{H}_2\text{O}(l, 100^\circ \text{C}) \rightarrow \text{H}_2\text{O}(v, 100^\circ \text{C}) \rightarrow \text{H}_2\text{O}(v, 60^\circ \text{C})$$

$$\Delta \hat{H} = \frac{0.0754 \text{ kJ}}{\text{mol} \cdot ^\circ \text{C}} \left| \frac{(100 - 0)^\circ \text{C}}{1} \right| + 40.656 \frac{\text{kJ}}{\text{mol}} + \int_{100}^{60} (C_p)_{\text{H}_2\text{O}(v)} dT$$

\uparrow
 Table B.2

\uparrow
 Table B.1 ($\Delta \hat{H}_v$)

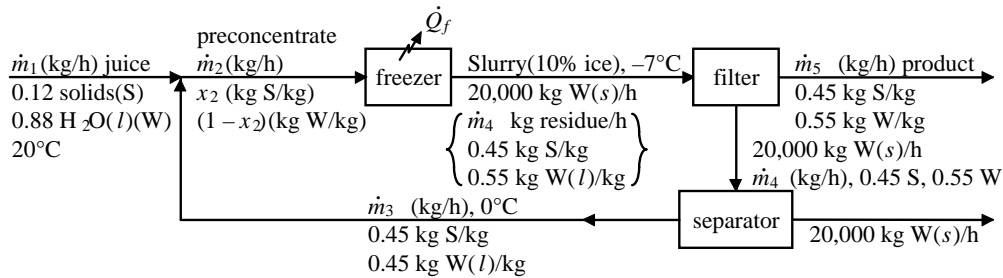
\uparrow
 Table B.2

$$= \frac{46.830 \text{ kJ}}{\text{mol}} \left| \frac{1 \text{ mol}}{18.02 \text{ g}} \right| \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right| = 2599 \text{ kJ/kg}$$

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} m_i \hat{H}_i - \sum_{\text{in}} m_i \hat{H}_i = \frac{1.06 \times 10^5 \text{ kJ}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = \underline{\underline{1760 \text{ kW}}}$$

8.63 Basis: 20,000 kg/h ice crystallized. S = solids in juice. W = water



(a) 10% ice in slurry $\Rightarrow \frac{20000}{\dot{m}_4} = \frac{10}{90} \Rightarrow \dot{m}_4 = 180000 \text{ kg/h}$ concentrate leaving freezer

$$\left. \begin{array}{l} \text{Overall S balance: } 0.12\dot{m}_1 = 0.45\dot{m}_5 \\ \text{Overall mass balance: } \dot{m}_1 = \dot{m}_5 + 20000 \end{array} \right\} \Rightarrow \dot{m}_1 = \underline{\underline{27273 \text{ kg/h feed}}}$$

$$\dot{m}_5 = \underline{\underline{7273 \text{ kg/h concentrate product}}}$$

Mass balance on filter: $20000 + \dot{m}_4 + \dot{m}_5 + 20000 + \dot{m}_6 \Rightarrow \dot{m}_6 = 172730 \text{ kg/h}$ recycle

$\dot{m}_4 = 180000$
 $\dot{m}_5 = 7273$

Mass balance on mixing point:

$$27273 + 172730 = \dot{m}_2 \Rightarrow \dot{m}_2 = \underline{\underline{2.000 \times 10^5 \text{ kg/h pre-concentrate}}}$$

8.63 (Cont'd)

S balance on mixing point:

$$(0.12)(27273) + (0.45)(172730) = 2.000 \times 10^5 X_2 \Rightarrow X_2 \cdot 100\% = \underline{\underline{40.5\% \text{ S}}}$$

- (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, $\text{H}_2\text{O}(l)$ at -7°C

substance	\dot{m}_{in}	\hat{H}_{in}	\dot{m}_{out}	\hat{H}_{out}	
12% soln	27273	108	—	—	$\dot{m}(\text{kg/h})$
45% soln	172730	28	180000	0	$\hat{H}(\text{kJ/kg})$
$\text{H}_2\text{O}(s)$	—	—	20000	-337	

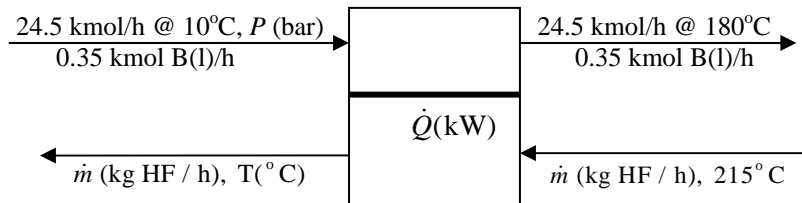
Solutions: $\hat{H}(T) = 4.00[T - (-7)] \text{ kJ/kg}$

Ice: $\hat{H} = -\Delta\hat{H}_m(-T^\circ\text{C}) \approx -\Delta\hat{H}_m(0^\circ\text{C})$
 $= -6.0095 \text{ kJ/mol} \Rightarrow -337 \text{ kJ/kg}$

↑ Table B.1

E.B. $\dot{Q}_c = \Delta\dot{H} = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \frac{-1.452 \times 10^7 \text{ kJ}}{\text{h}} \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = \underline{\underline{-4030 \text{ kW}}}$

- 8.64 a. B=n-butane, I=iso-butane, hf=heating fluid. $(C_p)_{\text{hf}} = 2.62 \text{ kJ} / (\text{kg} \cdot ^\circ\text{C})$



From the Cox chart (Figure 6.1-4)

$$p_B^*(10^\circ\text{C}) = 22 \text{ psi}, p_I^*(10^\circ\text{C}) = 32 \text{ psi}$$

$$p_{\text{min}} = p_B + p_I = x_B p_B^* + x_I p_I^* = 28.5 \text{ psi} \left(\frac{1.01325 \text{ bar}}{14.696 \text{ psi}} \right) = \underline{\underline{1.96 \text{ bar}}}$$

- b. $\text{B}(l, 10^\circ\text{C}) \xrightarrow{\Delta\hat{H}_v} \text{B}(v, 10^\circ\text{C}) \xrightarrow{\Delta\hat{H}_1} \text{B}(v, 180^\circ\text{C})$
 $\text{I}(l, 10^\circ\text{C}) \xrightarrow{\Delta\hat{H}_v} \text{I}(v, 10^\circ\text{C}) \xrightarrow{\Delta\hat{H}_2} \text{I}(v, 180^\circ\text{C})$

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

$$(\hat{H}_{out})_B = (\Delta\hat{H}_v)_B + \int_{10}^{180} (C_p)_B = 42.21 \text{ kJ / mol}$$

$$(\hat{H}_{out})_I = (\Delta\hat{H}_v)_I + \int_{10}^{180} (C_p)_I = 41.01 \text{ kJ / mol}$$

$$\Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = 8575(42.21) - 15925(41.01)$$

$$\underline{\underline{\Delta\dot{H} = 1.015 \times 10^6 \text{ kJ / h}}}$$

c. $Q = 1.015 \times 10^6 \text{ kJ / h} = \dot{m}_{hf} [2.62 \text{ kJ / (kg} \cdot ^\circ\text{C)}] [(215 - 45)^\circ\text{C}]$

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

d. $(2540 \text{ kg / h}) [2.62 \text{ kJ / (kg} \cdot ^\circ\text{C)}] [(215 - 45)^\circ\text{C}] = 1.131 \times 10^6 \text{ kJ / h}$

$$\text{Heat transfer rate} = 1.131 \times 10^6 - 1.015 \times 10^6 = \underline{\underline{1.16 \times 10^5 \text{ kJ / h}}}$$

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, $SG_{\text{Benzene}}=0.879$; $SG_{\text{Toluene}}=0.866$

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

$$V_{\text{total}} = \frac{50 \text{ g}}{0.879 \text{ g / cm}^3} + \frac{50 \text{ g}}{0.866 \text{ g / cm}^3} = 114.6 \text{ cm}^3$$

$$(x_f)_{\text{C}_6\text{H}_6} = \frac{0.640 \text{ mol C}_6\text{H}_6}{1.183 \text{ mol}} = \underline{\underline{0.541 \text{ mol C}_6\text{H}_6 / \text{mol}}}$$

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

$$T = 90^\circ\text{C} \Rightarrow p_{\text{C}_6\text{H}_6}^* = 1021 \text{ mm Hg}, p_{\text{C}_7\text{H}_8}^* = 407 \text{ mm Hg} \text{ (from Table 6.1-1)}$$

$$\text{Raoult's law: } p_{\text{tot}} = x_{\text{C}_6\text{H}_6} p_{\text{C}_6\text{H}_6}^* + x_{\text{C}_7\text{H}_8} p_{\text{C}_7\text{H}_8}^* = (0.541)(1021) + (0.459)(407)$$

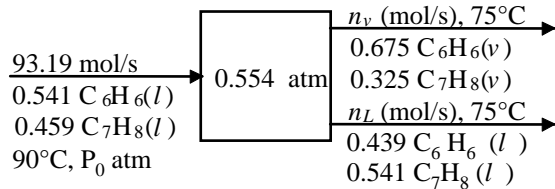
$$= \frac{739.2 \text{ mmHg}}{760 \text{ mmHg}} \left| \frac{1 \text{ atm}}{760 \text{ mmHg}} \right| = 0.973 \text{ atm} \Rightarrow \underline{\underline{P_0 > 0.973 \text{ atm}}}$$

8.65 (cont'd)

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

Raoult's law $\Rightarrow p_{\text{tank}} = x_{\text{C}_6\text{H}_6} p_{\text{C}_6\text{H}_6}^* + x_{\text{C}_7\text{H}_8} p_{\text{C}_7\text{H}_8}^* = (0.439)(648) + (0.561)(244)$
 $= (284 + 137) \text{ mm Hg} = 421 \text{ mm Hg} \Rightarrow \underline{\underline{P_{\text{tank}} = 0.554 \text{ atm}}}$

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



Mole balance: $93.19 = n_v + n_L$
C₆H₆ balance: $(0.541)(93.19) = 0.675n_v + 0.439n_L$ } $\Rightarrow \underline{\underline{n_v = 40.27 \text{ mol vapor/s}}}$
 $\underline{\underline{n_L = 52.92 \text{ mol liquid/s}}}$

(c) Reference states: C₆H₆(l), C₇H₈(l) at 75°C

Substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{out}	
C ₆ H ₆ (v)	—	—	27.18	31.0	\dot{n} in mol/s
C ₆ H ₆ (l)	50.41	2.16	23.23	0	\hat{H} in kJ/mol
C ₇ H ₈ (v)	—	—	13.09	35.3	
C ₇ H ₈ (l)	42.78	2.64	29.69	0	

C₆H₆(l, 90°C): $\hat{H} = (0.144)(90 - 75) = 2.16 \text{ kJ/mol}$

C₇H₈(l, 90°C): $\hat{H} = (0.176)(90 - 75) = 2.64 \text{ kJ/mol}$

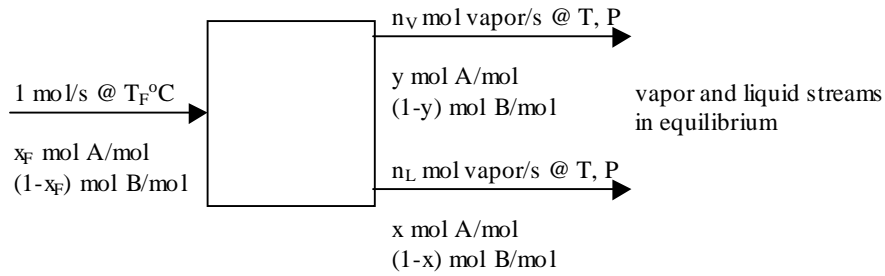
C₆H₆(v, 75°C): $\hat{H} = (0.144)(80.1 - 75) + \underset{\Delta \hat{H}_v(80.1^\circ\text{C})}{30.77} + \int_{80.1}^{75} [0.074 + 0.330 \times 10^{-3} T] dT$
 $= 31.0 \text{ kJ/mol}$

C₇H₈(v, 75°C): $\hat{H} = (0.176)(110.6 - 75) + 33.47 + \int_{110.6}^{75} [0.0942 + 0.380 \times 10^{-3} T] dT$
 $= 35.3 \text{ kJ/mol}$

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

- (d) The feed composition changed; the chromatographic analysis is wrong; the heating rate changed; the system is not at steady state; Raoult's law and/or the Antoine equation are only approximations; the vapor and liquid streams are not in equilibrium.
- (e) Heat is required to vaporize a liquid and heat is lost from any vessel for which $T > T_{\text{ambient}}$. If insufficient heat is provided to the vessel, the temperature drops. To run the experiment isothermally, a greater heating rate is required.

8.66 a. Basis: 1 mol feed/s



$$\text{Raoult's law} \Rightarrow x \cdot p_A^*(T) + (1-x) \cdot p_B^*(T) = P \Rightarrow x = \frac{P - p_B^*(T)}{p_A^*(T) - p_B^*(T)} \quad (1)$$

$$p_A = y \cdot P = x \cdot p_A^*(T) \Rightarrow y = \frac{x \cdot p_A^*(T)}{P} \quad (2)$$

$$\text{Mole balance: } 1 = \dot{n}_L + \dot{n}_V \Rightarrow \dot{n}_V = 1 - \dot{n}_L \quad (4)$$

$$\text{A balance: } (x_F)(1) = y \cdot \dot{n}_V + x \cdot \dot{n}_L \xrightarrow{\text{Substitute for } \dot{n}_V \text{ from (4)}} \dot{n}_L = \frac{y - x_F}{y - x} \quad (3)$$

$$\text{Energy balance: } \Delta \dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 0 \quad (5)$$

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
x _F	0.5	0.5	0.5					
T _f (deg.C)	110	110	150					
P(mm Hg)	760	1000	1000					
H _A F(kJ/mol)	16.6	16.6	24.4					
H _B F(kJ/mol)	18.4	18.4	27.0					
T(deg.C)	51.8	60.0	62.3					
p _A [*] (mm Hg)	1262	1609	1714					
p _B [*] (mm Hg)	432	573	617					
x	0.395	0.412	0.349					
y	0.656	0.663	0.598					
n _L (mol/s)	0.598	0.648	0.394					
n _V (mol/s)	0.402	0.352	0.606					
H _A L(kJ/mol)	5.2	6.8	7.3					
H _B L(kJ/mol)	5.8	7.6	8.0					
H _A V(kJ/mol)	31.4	32.5	32.8					
H _B V(kJ/mol)	42.4	43.7	44.1					
DH(kJ/s)	0.00	0.00	0.00					

8.66 (cont'd)

c.

```

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)

```

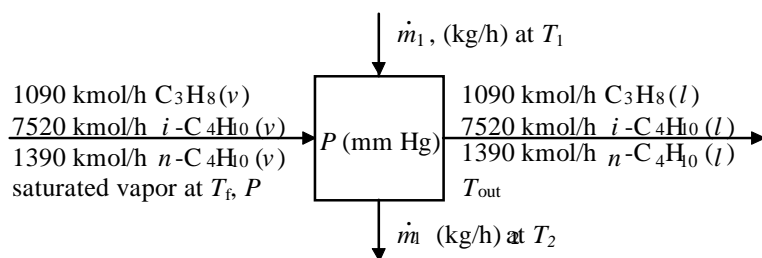
Solution:

$$\underline{T_{\text{evaporator}} = 52.2^{\circ}\text{C}}$$

$$\underline{n_L = 0.552 \text{ mol}, \left(x_{\text{C}_5\text{H}_{12}}\right)_{\text{liquid}} = 0.383 \text{ mol C}_5\text{H}_{12}/\text{mol liquid}}$$

$$\underline{n_v = 0.448 \text{ mol}, \left(x_{\text{C}_5\text{H}_{12}}\right)_{\text{vapor}} = 0.644 \text{ mol C}_5\text{H}_{12}/\text{mol liquid}}$$

8.67 Basis: $\frac{2500 \text{ kmol product}}{\text{h}} \mid \frac{1 \text{ kmol condensate}}{.25 \text{ kmol product}} = 10,000 \text{ kmol/h fed to condenser}$



(a) Refrigerant: $T_{\text{out}} = 0^\circ \text{C}$, $T_1 = T_2 = -6^\circ \text{C}$.

<u>Antoine constants</u>	<u>A</u>	<u>B</u>	<u>C</u>
C_3H_8	7.58163	1133.65	283.26
$i - \text{C}_4\text{H}_{10}$	6.78866	899.617	241.942
$n - \text{C}_4\text{H}_{10}$	6.82485	943.453	239.711

Calculate P for $T_{\text{out}} = T_{\text{bubble pt.}}$

$$P = \sum_i x_i p_i^*(0^\circ \text{C}) = 0.109(3797 \text{ mm Hg}) + 0.752(1176 \text{ mm Hg}) + 0.139(775 \text{ mm Hg})$$

$$\Rightarrow \underline{\underline{P = 1406 \text{ mm Hg}}}$$

Dew pt. $T_f = T_{\text{dp}} \Rightarrow f(T_f) = 1 - P \sum_i \frac{y_i}{p_i^*(T_f)} = 0$ trial & error to find $T_f \Rightarrow \underline{\underline{T_f = 5.00^\circ \text{C}}}$

Refs: $\text{C}_3\text{H}_8(l)$, $\text{C}_4\text{H}_{10}(l)$ 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	$\left. \begin{array}{l} \hat{H}_2(\text{vapor}) = \Delta \hat{H}_v(0^\circ \text{C}) \cdot \\ \int_0^{4.95} C_p dT (\text{Table B.2}) \end{array} \right\}$
$i - \text{C}_4\text{H}_{10}$	7520	21740	7520	0	
$n - \text{C}_4\text{H}_{10}$	1390	22760	1390	0	
Refrigerant	\dot{m}_1	0	\dot{m}_1	151	$\left. \begin{array}{l} \dot{m} \text{ (kg/h)} \\ \hat{H} \text{ (kJ/kmol)} \end{array} \right\} \hat{H} = \Delta \hat{H}_v$

E.B.:

$$\Delta H = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 0 \Rightarrow 151 \dot{m}_1 - 2.16 \times 10^6 = 0 \Rightarrow \dot{m}_1 = \underline{\underline{1.43 \times 10^6 \text{ kg/h refrigerant}}}$$

8.67 (cont'd)

(b) Cooling water: $T_{\text{out}} = 40^\circ\text{C}$, $T_2 = 34^\circ\text{C}$, $T_1 = 25^\circ\text{C}$

$$P = \sum_i x_i p_i^*(40^\circ\text{C}) = 0.109(11,877) + 0.752(3961) + 0.139(2831) = \underline{\underline{4667 \text{ mm Hg}}}$$

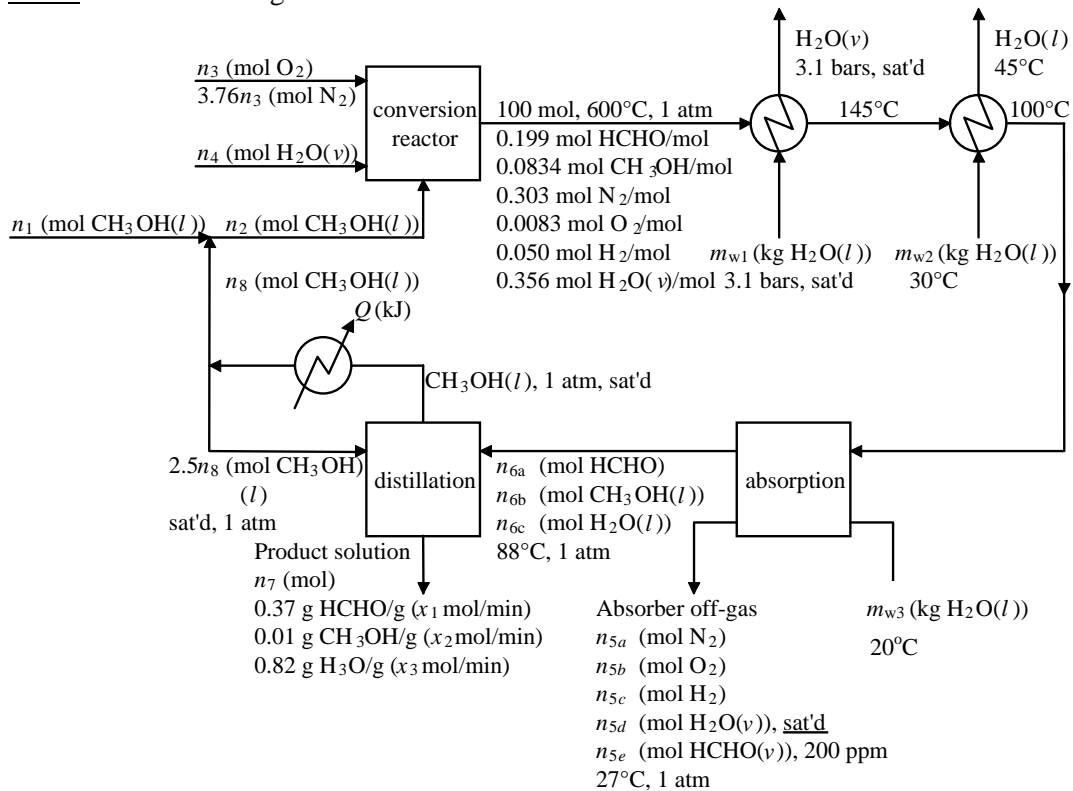
$$f(T_f) = 1 - P \sum_i \frac{y_i}{p_i^*(T_f)} = 0 \Rightarrow T_f = \underline{\underline{45.7^\circ\text{C}}}$$

Refs: $\text{C}_3\text{H}_8(l)$, $\text{C}_4\text{H}_{10}(l)$ @ 40°C , $\text{H}_2\text{O}(l)$ @ 25°C .

$$\Delta\dot{H} = 0 \Rightarrow 37.7\dot{m}_1 - 2.17 \times 10^8 = 0 \Rightarrow \underline{\underline{\dot{m}_1 = 5.74 \times 10^6 \text{ kg H}_2\text{O} / \text{h}}}$$

(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 $\Rightarrow n_{5c}$

$\left. \begin{array}{l} \text{H}_2\text{O saturation of absorber off-gas} \\ 200 \text{ ppm HCHO in absorber off-gas} \end{array} \right\} \Rightarrow n_{5d}, n_{5e}$

8.68 (cont'd)

HCHO balance on absorber $\Rightarrow n_{6a}$, CH₃OH balance on absorber $\Rightarrow n_{6b}$

Wt. fractions of product solution $\Rightarrow x_1, x_2, x_3$

HCHO balance on distillation column $\Rightarrow n_7$

CH₃OH balance on distillation column $\Rightarrow n_8$

CH₃OH 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:

$$n_2 = 19.9 \text{ mol HCHO} + 8.34 \text{ mol CH}_3\text{OH} = 28.24 \text{ mol CH}_3\text{OH}$$

N₂ balance on conversion reactor:

$$3.76n_3 = 30.3 \Rightarrow n_3 = 8.06 \text{ mol O}_2, 3.76 \times 8.06 = 30.3 \text{ mol N}_2 \text{ feed}$$

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)

N₂ balance on absorber: $30.3 = n_{5a} \Rightarrow n_{5a} = 30.3 \text{ mol N}_2$

O₂ balance on absorber: $0.83 = n_{5b} \Rightarrow n_{5b} = 0.83 \text{ mol O}_2$

H₂ balance on absorber: $5.00 = n_{5c} \Rightarrow n_{5c} = 5.00 \text{ mol H}_2$

H₂O saturation of off - gas:

$$y_w = \frac{p_w^*(27^\circ\text{C})}{P} = \left[\frac{26.739 \text{ mm Hg}}{760 \text{ mm Hg}} = \frac{n_{5d}}{30.3 + 0.83 + 5.00 + n_{5d} + n_{5e}} \right]$$

$$\Rightarrow n_{5d} = 0.03518(36.13 + n_{5d} + n_{5e}) [1]$$

$$\left. \begin{array}{l} \frac{200 \text{ ppm HCHO in off gas:}}{\Rightarrow \frac{n_{5e}}{36.13 + n_{5d} + n_{5e}} = \frac{200}{10^6} [2]} \right\} \begin{array}{l} \text{solve } n_{5d} = 1.318 \text{ mol H}_2\text{O} \\ n_{5e} = 7.49 \times 10^{-3} \text{ mol HCHO} \end{array}$$

Moles of absorber off-gas $= n_{5a} + n_{5b} + n_{5c} + n_{5e} = 37.46 \text{ mol off - gas}$

HCHO balance on absorber: $19.9 = n_{6a} + 7.49 \times 10^{-3} \Rightarrow n_{6a} = 19.89 \text{ mol HCHO}$

CH₃OH balance on absorber: $8.34 = n_{6b} \Rightarrow n_{6b} = 8.34 \text{ mol CH}_3\text{OH}$

Product solution

$$\left. \begin{array}{l} \text{Basis - 100 g} \Rightarrow 37.0 \text{ g HCHO} \xRightarrow{\%MW} 1.232 \text{ mol HCHO} \\ 1.0 \text{ g CH}_3\text{OH} \Rightarrow 0.031 \text{ mol CH}_3\text{OH} \\ 62.0 \text{ g H}_2\text{O} \Rightarrow 3.441 \text{ mol H}_2\text{O} \end{array} \right\} \begin{array}{l} x_1 = 0.262 \text{ mol HCHO/mol} \\ x_2 = 0.006 \text{ mol CH}_3\text{OH/mol} \\ x_3 = 0.732 \text{ mol H}_2\text{O/mol} \end{array}$$

8.68 (cont'd)

HCHO balance on distillation column (include the condenser + reflux stream within the system for this and the next balance):

$$19.89 = 0.262n_7 \Rightarrow n_7 = 75.9 \text{ mol product}$$

CH₃OH balance on distillation column:

$$8.34 = 0.006(75.9) + n_8 \Rightarrow n_8 = 7.88 \text{ mol CH}_3\text{OH}$$

CH₃OH 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°C), CH₃OH(*v*, 145°C); N₂, O₂, H₂, H₂O(*v*) at 25°C for product gas, H₂O(*l*, triple point) for boiler water

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
HCHO	19.9	22.55	19.9	0	$n \text{ (mol)}$
CH ₃ OH	8.34	32.02	8.34	0	
N ₂	30.3	17.39	30.3	3.51	$\hat{H} \text{ (kJ/mol)}$
O ₂	0.83	18.41	0.83	3.60	
H ₂	5.0	16.81	5.0	3.47	
H ₂ O	35.6	20.91	35.6	4.09	
H ₂ O (boiler)	m_{w1}	566.2	m_{w1}	2726.32	$m \text{ (kg)}$ $\hat{H} \text{ (kJ/kg)}$

$\left. \begin{array}{l} \text{HCHO} \\ \text{CH}_3\text{OH} \end{array} \right\} \hat{H} = \int_{145}^T C_p dT$
 $\left. \begin{array}{l} \text{N}_2 \\ \text{O}_2 \\ \text{H}_2 \\ \text{H}_2\text{O} \end{array} \right\} \hat{H} = \bar{C}_p(T)[T - 25]$
 $\left. \begin{array}{l} \text{H}_2\text{O (boiler)} \end{array} \right\} \hat{H} \text{ from steam tables}$

E.B. $\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -1814 + 2160m_{w1} = 0 \Rightarrow m_{w1} = \underline{\underline{0.84 \text{ kg 3.1 bar steam}}}$

8.68 (cont'd)

Gas cooler: Same refs. as above for product gas, $\text{H}_2\text{O}(l, 30^\circ\text{C})$ for cooling water

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
HCHO	19.9	0	19.9	-1.78	n (mol) \hat{H} (kJ/mol)
CH_3OH	8.34	0	8.34	-2.38	
N_2	30.3	3.51	30.3	2.19	
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)

$$\hat{H} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} (T - 30)^\circ\text{C}$$

E.B. $\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -158.1 + 62.6m_{w2} = 0 \Rightarrow m_{w2} = \underline{\underline{2.52 \text{ kg cooling water}}}$

Condenser: CH_3OH condensed $= n_8 + 2.5n_8 = (3.5)(7.88) = 27.58 \text{ mol CH}_3\text{OH condensed}$

E.B.: $Q = -n\Delta\hat{H}_v(1 \text{ atm}) = -(27.58 \text{ mol})(35.27 \text{ kJ/mol})$
 $= \underline{\underline{-973 \text{ kJ}}}$ (transferred from condenser)

b.
$$\frac{3.6 \times 10^4 \text{ tonne / y}}{1 \text{ metric ton}} \left| \frac{10^6 \text{ g}}{1 \text{ metric ton}} \right| \left| \frac{1 \text{ yr}}{350 \text{ d}} \right| \left| \frac{1 \text{ d}}{24 \text{ h}} \right| = 4.286 \times 10^6 \text{ g/h product soln}$$

$$\left. \begin{aligned} (0.37)(4.286 \times 10^6) &= 1.586 \times 10^6 \text{ g HCHO/h} \Rightarrow 5.281 \times 10^4 \text{ mol HCHO/h} \\ \Rightarrow (0.01)(4.286 \times 10^6) &= 4.286 \times 10^6 \text{ g CH}_3\text{OH/h} \Rightarrow 1338 \text{ mol CH}_3\text{OH/h} \\ (0.62)(4.286 \times 10^6) &= 2.657 \times 10^6 \text{ g H}_2\text{O/h} \Rightarrow 1.475 \times 10^5 \text{ mol H}_2\text{O/h} \end{aligned} \right\}$$

$$\Rightarrow 2.016 \times 10^5 \text{ mol/h} \Rightarrow \text{Scale factor} = \frac{2.016 \times 10^5 \text{ mol/h}}{75.9 \text{ mol}} = \underline{\underline{2657 \text{ h}^{-1}}}$$

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 $\approx \underline{\underline{0.856 \text{ m}^3 / \text{kg DA}}}$

Specific enthalpy $= (48 - 0.2) \text{ kJ / kg DA} = \underline{\underline{47.8 \text{ kJ / kg DA}}}$, Dew point $= \underline{\underline{13^\circ\text{C}}}$, $T_{wb} = \underline{\underline{17^\circ\text{C}}}$

(b) $\underline{\underline{24^\circ\text{C}}}$ (T_{db})

(c) $\underline{\underline{13^\circ\text{C}}}$ (Dew point)

(d) Water evaporates, causing your skin temperature to drop. $\underline{\underline{T_{skin} \approx 13^\circ\text{C}}}$ (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 $V_{\text{room}} = 141 \text{ ft}^3$. DA = dry air.

$$m_{\text{DA}} = \frac{140 \text{ ft}^3}{0.7302 \text{ ft}^3 \cdot \text{atm}} \left| \frac{\text{lb} \cdot \text{mol} \cdot ^\circ \text{R}}{\text{lb} \cdot \text{mol}} \right| \frac{29 \text{ lb}_m \text{ DA}}{1 \text{ lb} \cdot \text{mol}} \left| \frac{1 \text{ atm}}{550 ^\circ \text{R}} \right| = 10.1 \text{ lb}_m \text{ DA}$$

$$h_a = \frac{0.205 \text{ lb}_m \text{ H}_2\text{O}}{10.1 \text{ lb}_m \text{ DA}} = 0.0203 \text{ lb}_m \text{ H}_2\text{O} / \text{lb}_m \text{ DA}$$

From the psychrometric chart, $T_{\text{db}} = 90^\circ \text{F}$, $h_a = 0.0903$

$$\begin{array}{l} \Downarrow \\ \underline{h_r = 67\%} \quad \underline{T_{\text{wb}} = 80.5^\circ \text{F}} \quad \underline{\hat{V} = 14.3 \text{ ft}^3 / \text{lb}_m \text{ DA}} \\ \underline{T_{\text{dew point}} = 77.3^\circ \text{F}} \quad \underline{\hat{H} = 44.0 - 0.11 \cong 43.9 \text{ Btu} / \text{lb}_m} \end{array}$$

8.71

$$\begin{array}{l} T_{\text{db}} = 35^\circ \text{C} \\ T_{\text{ab}} = 27^\circ \text{C} \Rightarrow \underline{h_r = 55\%} \quad \underline{\text{He wins}} \end{array}$$

8.72 a. $T_{\text{db}} = 40^\circ \text{C}$, $T_{\text{dew point}} = 20^\circ \text{C}$ $\xRightarrow{\text{Fig. 8.4-1}}$ $\underline{h_r = 33\%, h_a = 0.0148 \text{ kg H}_2\text{O/kg dry air}}$
 $\underline{T_{\text{wb}} = 25.5^\circ \text{C}}$

b. Mass of dry air: $m_{\text{da}} = \frac{2.00 \text{ L}}{10^3 \text{ L}} \left| \frac{1 \text{ m}^3}{0.92 \text{ m}^3} \right| \frac{1 \text{ kg dry air}}{0.92 \text{ m}^3} = 2.2 \times 10^{-3} \text{ kg dry air}$
 $\uparrow \text{ from Fig. 8.4-1}$

Mass of water: $\frac{2.2 \times 10^{-3} \text{ kg dry air}}{1 \text{ kg dry air}} \left| \frac{0.0148 \text{ kg H}_2\text{O}}{1 \text{ kg dry air}} \right| \frac{10^3 \text{ g}}{1 \text{ kg}} = \underline{0.033 \text{ g H}_2\text{O}}$

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)

$$\Delta H_{40 \rightarrow 20} = \frac{2.2 \times 10^{-3} \text{ kg dry air}}{\text{kg dry air}} \left| \frac{(57.5 - 77.4) \text{ kJ}}{1 \text{ kJ}} \right| \frac{10^3 \text{ J}}{1 \text{ kJ}} = \underline{-44 \text{ J}}$$

d. Energy balance: closed system

$$n = \frac{2.2 \times 10^{-3} \text{ kg dry air}}{1 \text{ kg}} \left| \frac{10^3 \text{ g}}{29 \text{ g}} \right| \frac{1 \text{ mol}}{29 \text{ g}} + \frac{0.033 \text{ g H}_2\text{O}}{18 \text{ g}} \left| \frac{1 \text{ mol}}{18 \text{ g}} \right| = 0.078 \text{ mol}$$

$$Q = \Delta U = n\Delta\hat{U} = n(\Delta\hat{H} - R\Delta T) = \Delta H - nR\Delta T$$

$$= -44 \text{ J} - \frac{0.078 \text{ mol}}{\text{mol} \cdot \text{K}} \left| \frac{8.314 \text{ J}}{1^\circ \text{C}} \right| \frac{(20 - 40)^\circ \text{C}}{1^\circ \text{C}} = \underline{-31 \text{ J}} \text{ (23 J transferred from the air)}$$

$$8.73 \text{ (a)} \quad \frac{400 \text{ kg}}{\text{min}} \left| \frac{2.44 \text{ kg water}}{97.56 \text{ kg air}} \right| = \underline{\underline{10.0 \text{ kg water evaporates / min}}}$$

$$(b) \quad h_a = \frac{10 \text{ kg H}_2\text{O/min}}{400 \text{ kg dry air/min}} = 0.025 \text{ kg H}_2\text{O/kg dry air}, T_{db} = 50^\circ\text{C}$$

$$\xrightarrow{\text{Fig. 8.4-1}} \hat{H} = (116 - 1.1) = 115 \text{ kJ/kg dry air}, T_{wb} = 33^\circ\text{C}, h_r = 32\%, T_{\text{dew point}} = 28.5^\circ\text{C}$$

$$(c) \quad T_{db} = 10^\circ\text{C}, \text{ saturated} \Rightarrow h_a = 0.0077 \text{ kg H}_2\text{O/kg dry air}, \hat{H} = 29.5 \text{ kJ/kg dry air}$$

$$(d) \quad \frac{400 \text{ kg dry air}}{\text{min}} \left| \frac{(0.0250 - 0.0077) \text{ kg H}_2\text{O}}{\text{kg dry air}} \right| = \underline{\underline{6.92 \text{ kg H}_2\text{O/min condense}}}$$

References: Dry air at 0°C , $\text{H}_2\text{O}(l)$ at 0°C

substance	\dot{m}_{in}	\hat{H}_{in}	\dot{m}_{out}	\hat{H}_{out}	
Air	400	115	400	29.5	\dot{m}_{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}_{air} in kJ/kg dry air, $\hat{H}_{\text{H}_2\text{O}}$ in kJ/kg

$\text{H}_2\text{O}(l, 0^\circ\text{C}) \rightarrow \text{H}_2\text{O}(l, 20^\circ\text{C})$:

$$\hat{H} = \frac{75.4 \text{ J}}{\text{mol} \cdot ^\circ\text{C}} \left| \frac{1 \text{ mol}}{18 \text{ g}} \right| \left| \frac{(10 - 0)^\circ\text{C}}{1} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right| \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| = 42 \text{ kJ/kg}$$

$$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \frac{-34027.8 \text{ kJ}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = \underline{\underline{-565 \text{ kW}}}$$

- (e) $T > 50^\circ\text{C}$, 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.

$$8.74 \text{ a. } \underline{\text{Outside air:}} \quad T_{db} = 87^\circ\text{F}, h_r = 80\% \Rightarrow h_a = 0.0226 \text{ lb}_m \text{ H}_2\text{O/lb}_m \text{ D.A.}, \\ \hat{H} = 45.5 - 0.01 = 45.5 \text{ Btu/lb}_m \text{ D.A.}$$

$$\underline{\text{Room air:}} \quad T_{db} = 75^\circ\text{F}, h_r = 40\% \Rightarrow h_a = 0.0075 \text{ lb}_m \text{ H}_2\text{O/lb}_m \text{ D.A.}, \\ \hat{H} = 26.2 - 0.02 = 26.2 \text{ Btu/lb}_m \text{ D.A.}$$

$$\underline{\text{Delivered air:}} \quad T_{db} = 55^\circ\text{F}, h_a = 0.0075 \text{ lb}_m \text{ H}_2\text{O/lb}_m \text{ D.A.} \\ \Rightarrow \hat{H} = 21.4 - 0.02 = 21.4 \text{ Btu/lb}_m \text{ D.A.}, \hat{V} = 13.07 \text{ ft}^3/\text{lb}_m \text{ D.A.}$$

$$\underline{\text{Dry air delivered:}} \quad \frac{1,000 \text{ ft}^3}{\text{min}} \left| \frac{1 \text{ lb}_m \text{ D.A.}}{13.07 \text{ ft}^3} \right| = 76.5 \text{ lb}_m \text{ D.A./min}$$

H_2O condensed:

$$\frac{76.5 \text{ lb}_m \text{ D.A.}}{\text{min}} \left| \frac{(0.0226 - 0.0075) \text{ lb}_m \text{ H}_2\text{O}}{\text{lb}_m \text{ D.A.}} \right| = \underline{\underline{1.2 \text{ lb}_m \text{ H}_2\text{O/min condensed}}}$$

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 $\Rightarrow T = 49^\circ\text{F}$

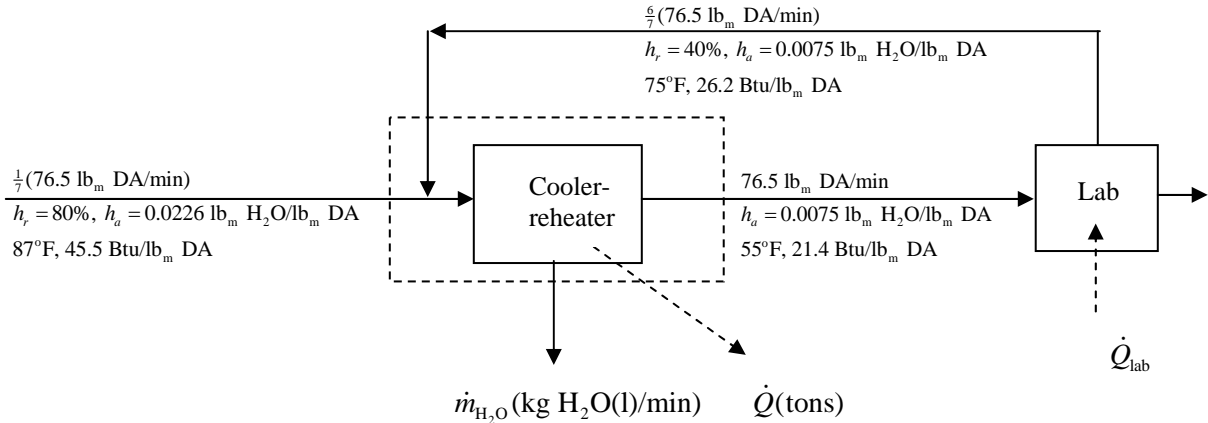
References: Same as Fig. 8.4-2 [including $\text{H}_2\text{O}(l, 32^\circ\text{F})$]

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 $\text{lb}_m \text{ D.A./min}$
$\text{H}_2\text{O}(l, 49^\circ\text{F})$	—	—	1.2	17.0	\hat{H}_{air} in $\text{Btu/lb}_m \text{ D.A.}$ $\dot{m}_{\text{H}_2\text{O}}$ in lb_m/min , $\hat{H}_{\text{H}_2\text{O}}$ in Btu/lb_m

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

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

b.



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

$$\frac{1}{7} \left(76.5 \frac{\text{lb}_m \text{ DA}}{\text{min}} \right) \left(0.0226 \frac{\text{lb}_m \text{ H}_2\text{O}}{\text{lb}_m \text{ DA}} \right) + \frac{6}{7} (76.5) (0.0075) = (76.5)(0.0075) + \dot{m}_{\text{H}_2\text{O}}$$

$$\Rightarrow \underline{\underline{\dot{m}_{\text{H}_2\text{O}} = 0.165 \text{ kg H}_2\text{O condensed/min}}}$$

8.74 (cont'd)

Energy balance on cooler-reheater

References: Same as Fig. 8.4-2 [including H₂O(l, 32°F)]

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

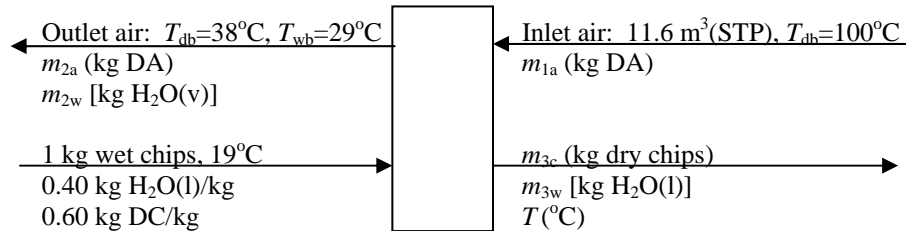
$$\dot{Q} = \Delta \dot{H} = \sum_{out} \dot{m}_i \hat{H}_i - \sum_{in} \dot{m}_i \hat{H}_i = \frac{-575.3 \text{ Btu}}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ h}} \right| \frac{1 \text{ ton cooling}}{-12,000 \text{ Btu/h}} = \underline{\underline{2.9 \text{ tons}}}$$

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

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



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

Outlet air:

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

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

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

8.75 (cont'd)

Moisture content of exiting chips:

$$\frac{0.065 \text{ kg water}}{0.600 \text{ kg dry chips} + 0.065 \text{ kg water}} \times 100\% = 9.8\% < 15\% \quad \therefore \text{meets design specification}$$

(c) References: Dry air, $\text{H}_2\text{O}(l)$, 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
$\text{H}_2\text{O}(l)$	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:

$$\Delta H = \sum m_{\text{out}} \hat{H}_{\text{out}} - \sum m_{\text{in}} \hat{H}_{\text{in}} = 0 \Rightarrow -136.8 + 1.532T = 0 \Rightarrow \underline{\underline{T = 89.3^\circ\text{C}}}$$

8.76 a. $T_{\text{db}} = 45^\circ\text{C}$
 $h_r = 10\%$ $\xrightarrow[\text{Fig. 8.4-1}]{} T_{\text{as}} = T_{\text{wb}} = \underline{\underline{21.0^\circ\text{C}}} \quad h_a = 0.0059 \text{ kg H}_2\text{O/kg DA}$

b. $T_{\text{wb}} = 21.0^\circ\text{C}$
 $h_r = 60\%$ $\xrightarrow[\text{Fig. 8.4-1}]{} T_{\text{db}} = \underline{\underline{26.8^\circ\text{C}}} \quad h_a = 0.0142 \text{ kg H}_2\text{O/kg DA}$

$$\underline{\text{H}_2\text{O added:}} \quad \frac{15 \text{ kg air}}{\text{min}} \left| \begin{array}{l} 1 \text{ kg D.A.} \\ 1.0059 \text{ kg air} \end{array} \right| \frac{(0.0142 - 0.0059) \text{ kg H}_2\text{O}}{1 \text{ kg D.A.}} = \underline{\underline{0.12 \text{ kg H}_2\text{O/min}}}$$

8.77 Inlet air: $T_{\text{db}} = 50^\circ\text{C}$
 $T_{\text{dew pt.}} = 4^\circ\text{C}$ $\left. \vphantom{\begin{array}{l} T_{\text{db}} = 50^\circ\text{C} \\ T_{\text{dew pt.}} = 4^\circ\text{C} \end{array}} \right\} \xrightarrow[\text{Fig. 8.4-1}]{} \underline{\underline{\hat{V} = 0.92 \text{ m}^3/\text{kg D.A.}, T_{\text{wb}} = 22^\circ\text{C}}}$
 $\underline{\underline{h_a = 0.0050 \text{ kg H}_2\text{O/kg D.A.}}}$

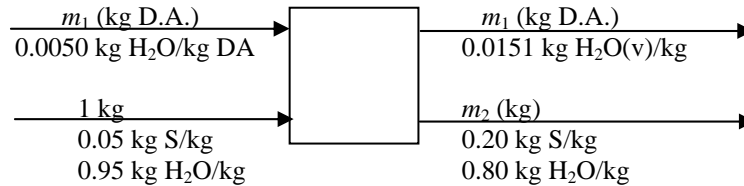
$$\frac{11.3 \text{ m}^3}{\text{min}} \left| \begin{array}{l} 1 \text{ kg D.A.} \\ 0.92 \text{ m}^3 \end{array} \right| = \underline{\underline{12.3 \text{ kg D.A./min}}}$$

Outlet air: $T_{\text{wb}} = T_{\text{as}} = 22^\circ\text{C}$
saturated $\Rightarrow \underline{\underline{T = 22^\circ\text{C}}} \quad h_a = 0.0165 \text{ kg H}_2\text{O/kg D.A.}$

$$\underline{\text{Evaporation:}} \quad \frac{12.3 \text{ kg D.A.}}{\text{min}} \left| \begin{array}{l} (0.0165 - 0.0050) \text{ kg H}_2\text{O} \\ \text{kg D.A.} \end{array} \right| = \underline{\underline{0.14 \text{ kg H}_2\text{O/min}}}$$

$$\begin{array}{l}
 \text{8.78 a. } \left. \begin{array}{l} T_{db} = 45^\circ\text{C} \\ T_{\text{dew point}} = 4^\circ\text{C} \end{array} \right\} \xrightarrow{\text{Fig. 8.4-1}} \begin{array}{l} (h_a)_{in} = 0.0050 \text{ kg H}_2\text{O/kg D.A.} \\ T_{wb} = 20.4^\circ\text{C}, \hat{V} = 0.908 \text{ m}^3/\text{kg D.A.} \\ T_{wb} = T_{as} = 20.4^\circ\text{C, saturated} \Rightarrow (h_a)_{out} = 0.0151 \text{ kg H}_2\text{O/kg D.A.} \end{array}
 \end{array}$$

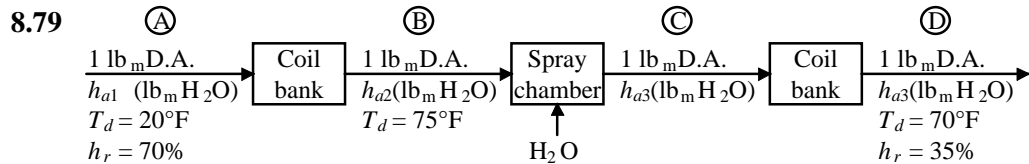
b. Basis: 1 kg entering sugar (S) solution



Sugar balance: $(0.05)(1) = (0.20)m_2 \Rightarrow m_2 = 0.25 \text{ kg}$

Water balance: $(m_1)(0.0050) + (1)(0.95) = (m_1)(0.0151) + (0.25)(0.80)$

$$\Rightarrow \left\{ \begin{array}{l} m_1 = 74 \text{ kg dry air} \\ V = \frac{74 \text{ kg dry air}}{1 \text{ kg D.A.}} \times 0.908 \text{ m}^3 = 67 \text{ m}^3 \end{array} \right.$$



Inlet air (A): $\left. \begin{array}{l} T_{db} = 20^\circ\text{F} \\ h_r = 70\% \end{array} \right\} \xrightarrow{\text{Fig. 8.4-2}} \begin{array}{l} h_{a1} \approx 0.0017 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.} \\ \hat{V} \approx 12.2 \text{ ft}^3/\text{lb}_m \text{ D.A.} \end{array}$

Outlet air (D): $\left. \begin{array}{l} T_{db} = 70^\circ\text{F} \\ h_r = 35\% \end{array} \right\} \xrightarrow{\text{Fig. 8.4-2}} h_{a3} = 0.0054 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.}$

a. Inlet of spray chamber (B): $\left. \begin{array}{l} h_a = 0.0017 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.} \\ T_{db} = 75^\circ\text{F} \end{array} \right\} \Rightarrow T_{wb} = 49.5^\circ\text{F}$

The state of the air at (C) must lie on the same adiabatic saturation curve as does the state at (B), or $T_{wb} = 49.5^\circ\text{F}$. Thus,

Outlet of spray chamber (C): $\left. \begin{array}{l} h_a = 0.0054 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ D.A.} \\ T_{wb} = 49.5^\circ\text{F} \end{array} \right\} \Rightarrow h_r = 52\%$

At point C, $T_{db} = 58.5^\circ\text{F}$

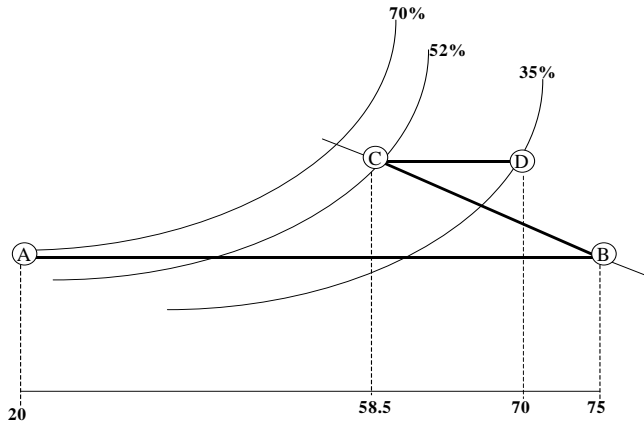
b. $\frac{(h_{a3} - h_{a1}) \text{ lb}_m \text{ H}_2\text{O evaporate}}{\text{lb}_m \text{ DA}} \bigg| \frac{\text{lb}_m \text{ DA}}{\hat{V}_A (\text{ft}^3 \text{ inlet air})} = \frac{(0.0054 - 0.0017)}{12.2} = 3.0 \times 10^{-4} \frac{\text{lb}_m \text{ H}_2\text{O}}{\text{ft}^3 \text{ air}}$

8.79 (cont'd)

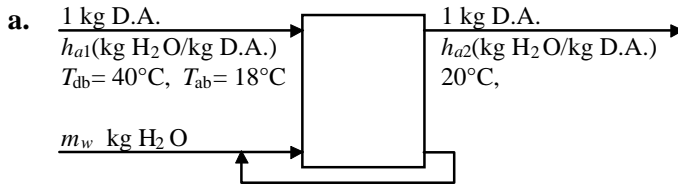
c. $Q_{BA} = \Delta H = \hat{H}_B - \hat{H}_A \cong \frac{(20 - 6.4) \text{ Btu} / \text{lb}_m \text{ dry air}}{12.2 \text{ ft}^3 / \text{lb}_m \text{ dry air}} = \underline{\underline{1.1 \text{ Btu} / \text{ft}^3}}$

$Q_{DC} = \Delta H = \hat{H}_D - \hat{H}_C \cong \frac{(23 - 20) \text{ Btu} / \text{lb}_m \text{ dry air}}{12.2 \text{ ft}^3 / \text{lb}_m \text{ dry air}} = \underline{\underline{0.25 \text{ Btu} / \text{ft}^3}}$

d.



8.80 Basis: 1 kg D.A.

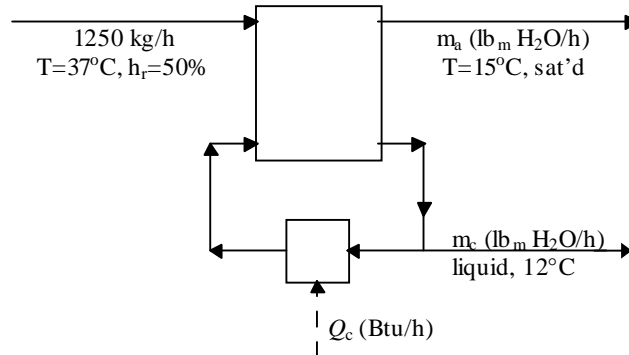


Inlet air: $T_{db} = 40^\circ \text{C}$
 $T_{wb} = 18^\circ \text{C} \Rightarrow h_{a1} = 0.0039 \text{ kg H}_2\text{O/kg D.A.}$

Outlet air: $T_{db} = 20^\circ \text{C}$
 $T_{wb} = 18^\circ \text{C (adiabatic humidification)} \Rightarrow h_{a2} = 0.0122 \text{ kg H}_2\text{O/kg D.A.}$

Overall H₂O balance: $m_w + (1)(h_{a1}) = (1)(h_{a2}) \Rightarrow m_w = (0.0122 - 0.0039) \text{ kg H}_2\text{O/kg D.A.}$
 $= \underline{\underline{0.0083 \text{ kg H}_2\text{O/kg D.A.}}}$

b.



8.80 (cont'd)

$$\text{Inlet air: } \left. \begin{array}{l} T_{\text{db}} = 37^\circ\text{C} \\ h_r = 50\% \end{array} \right\} \xRightarrow{\text{Fig. 8.4-1}} \left\{ \begin{array}{l} h_{a1} = 0.0198 \text{ kg H}_2\text{O/kg DA} \\ \hat{H}_1 = (88.5 - 0.5) \text{ kJ/kg DA} = 88.0 \text{ kJ/kg DA} \end{array} \right.$$

$$\text{Moles dry air: } \dot{m}_a = \frac{1250 \text{ kg}}{\text{h}} \left| \frac{1 \text{ kg DA}}{1.0198 \text{ kg}} \right| = 1226 \text{ kg DA/h}$$

$$\text{Outlet air: } T_{\text{db}} = 15^\circ\text{C, sat'd} \xRightarrow{\text{Fig. 8.4-1}} \left\{ \begin{array}{l} h_a = 0.0106 \text{ kg H}_2\text{O/kg DA} \\ \hat{H}_2 = 42.1 \text{ kJ/kg DA} \end{array} \right.$$

$$\begin{aligned} \text{Overall water balance } \Rightarrow \dot{m}_c &= \frac{1226 \text{ kg DA}}{\text{h}} \left| \frac{(0.0198 - 0.0106) \text{ kg H}_2\text{O}}{\text{kg DA}} \right| \\ &= \underline{\underline{11.3 \text{ kg H}_2\text{O/h withdrawn}}} \end{aligned}$$

$$\text{Reference states for enthalpy calculations: H}_2\text{O}(l), \text{ dry air at } 0^\circ\text{C. } (C_p)_{\text{H}_2\text{O}(l)} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}}$$

$$\text{H}_2\text{O}(l, 12^\circ\text{C}): \hat{H} = \int_0^{12} C_p dT = 50.3 \text{ kJ / kg}$$

Overall system energy balance:

$$\begin{aligned} \dot{Q}_c &= \Delta \dot{H} = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i \\ &= \left[\frac{11.3 \text{ kg H}_2\text{O}}{\text{h}} \left| \frac{50.3 \text{ kJ}}{\text{kg H}_2\text{O}} \right| + \frac{1226 \text{ kg DA}}{\text{h}} \left| \frac{(42.1 - 88) \text{ kJ}}{\text{kg DA}} \right| \right] \left(\frac{1 \text{ h}}{3600 \text{ s}} \right) \left(\frac{1 \text{ kW}}{1 \text{ kJ/s}} \right) \\ &= \underline{\underline{-15.5 \text{ kW}}} \end{aligned}$$

$$\mathbf{8.81} \quad \Delta H = \frac{400 \text{ mol NH}_3}{\text{mol NH}_3} \left| \frac{-78.2 \text{ kJ}}{\text{mol NH}_3} \right| = \underline{\underline{-31,280 \text{ kJ}}}$$

$$\mathbf{8.82 \text{ a.}} \quad \text{HCl}(g, 25^\circ\text{C}), \text{H}_2\text{O}(l, 25^\circ\text{C}) \rightarrow \text{HCl}(25^\circ\text{C}, r=5).$$

$$\Delta \hat{H} = \Delta \hat{H}_s(25^\circ\text{C}, r=5) \xrightarrow{\text{Table B.11}} \Delta \hat{H} = \underline{\underline{-64.05 \text{ kJ/mol HCl}}}$$

$$\mathbf{b.} \quad \text{HCl}(aq, r=\infty) \rightarrow \text{HCl}(r=5), \text{H}_2\text{O}(l)$$

$$\begin{aligned} \Delta \hat{H} &= \Delta \hat{H}_s(25^\circ\text{C}, n=5) - \Delta \hat{H}_s(25^\circ\text{C}, n=\infty) \\ &= (-64.05 + 75.14) \text{ kJ/mol HCl} = \underline{\underline{11.09 \text{ kJ / mol HCl}}} \end{aligned}$$

8.83 Basis: 100 mol solution \Rightarrow 20 mol NaOH, 80 mol H₂O

$$\Rightarrow r = \frac{80 \text{ mol H}_2\text{O}}{20 \text{ mol NaOH}} = 4.00 \text{ mol H}_2\text{O/mol NaOH}$$

Refs: NaOH(s), H₂O(l)@25°C

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
NaOH(s)	20.0	0.0	—	—	n in mol
H ₂ O(l)	80.0	0.0	—	—	\hat{H} in kJ/mol
NaOH($r = 4.00$)	—	—	20.0	-34.43	$\leftarrow n$ in mol NaOH

$$\hat{H}(\text{NaOH}, r = 4.00) = -34.43 \text{ kJ/mol NaOH (Table B.11)}$$

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = (20)(-34.43) = \frac{-688.6 \text{ kJ}}{10^{-3} \text{ kJ}} \left| \frac{9.486 \times 10^{-4} \text{ Btu}}{10^{-3} \text{ kJ}} \right| = -653.2 \text{ Btu}$$

$$Q = \frac{-653.2 \text{ Btu}}{[20.0(40.00) + 80.0(18.01)]\text{g}} \left| \frac{10^3 \text{ g}}{2.20462 \text{ lb}_m} \right| = \underline{\underline{-132.3 \text{ Btu/lb}_m \text{ product solution}}}$$

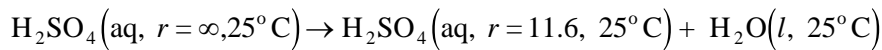
8.84 Basis: 1 liter solution

$$n_{\text{H}_2\text{SO}_4} = \frac{1 \text{ L}}{1 \text{ L}} \left| \frac{8 \text{ g - eq}}{2 \text{ g - eq}} \right| \frac{1 \text{ mol}}{2 \text{ g - eq}} = 4 \text{ mol H}_2\text{SO}_4 \times \left(\frac{0.09808 \text{ kg}}{1 \text{ mol}} \right) = 0.392 \text{ kg H}_2\text{SO}_4$$

$$m_{\text{total}} = \frac{1 \text{ L}}{1 \text{ L}} \left| \frac{1.230 \text{ kg}}{1 \text{ L}} \right| = 1.230 \text{ kg solution}$$

$$n_{\text{H}_2\text{O}} = \frac{(1.230 - 0.392) \text{ kg H}_2\text{O}}{18.02 \text{ kg H}_2\text{O}} \left| \frac{1000 \text{ mol H}_2\text{O}}{18.02 \text{ kg H}_2\text{O}} \right| = 46.5 \text{ mol H}_2\text{O}$$

$$\Rightarrow r = \frac{n_{\text{H}_2\text{O}}}{n_{\text{H}_2\text{SO}_4}} = \frac{46.49 \text{ mol H}_2\text{O}}{4 \text{ mol H}_2\text{SO}_4} = 11.6 \frac{\text{mol H}_2\text{O}}{\text{mol H}_2\text{SO}_4}$$



$$\Delta \hat{H}_1 = \Delta \hat{H}_s(r = 11.6) - \Delta \hat{H}_s(r = \infty) \stackrel{\text{Table B.11}}{=} (-67.6 + 96.19) = 28.6 \frac{\text{kJ}}{\text{mol H}_2\text{SO}_4}$$

$$\begin{aligned} \hat{H}(\text{H}_2\text{SO}_4, r = 11.6, 60^\circ \text{C}) &= \frac{\left[n_{\text{H}_2\text{SO}_4} \Delta H_1 + m \int_{25}^{60} C_p dT \right] \text{kJ}}{n_{\text{H}_2\text{SO}_4} (\text{mol H}_2\text{SO}_4)} \\ &= \frac{1}{4 \text{ mol H}_2\text{SO}_4} \left\{ \frac{4 \text{ mol H}_2\text{SO}_4}{1 \text{ mol H}_2\text{SO}_4} \left| \frac{28.6 \text{ kJ}}{\text{mol H}_2\text{SO}_4} \right| + \frac{1.230 \text{ kg}}{\text{kg} \cdot ^\circ \text{C}} \left| \frac{3.00 \text{ kJ}}{\text{kg} \cdot ^\circ \text{C}} \right| (60 - 25)^\circ \text{C} \right\} \\ &= \underline{\underline{60.9 \text{ kJ/mol H}_2\text{SO}_4}} \end{aligned}$$

$$8.85 \quad 2 \text{ mol H}_2\text{SO}_4 = 0.30(2.00 + n_{\text{H}_2\text{O}}) \Rightarrow n_{\text{H}_2\text{O}} = 4.67 \text{ mol H}_2\text{O} \Rightarrow r = \frac{4.67}{2} = 2.33 \frac{\text{mol H}_2\text{O}}{\text{mol H}_2\text{SO}_4}$$

a. For this closed constant pressure system,

$$Q = \Delta H = n_{\text{H}_2\text{SO}_4} \Delta \hat{H}_s(25^\circ\text{C}, r = 2.33) = \frac{2 \text{ mol H}_2\text{SO}_4}{\text{mol H}_2\text{SO}_4} \left| \frac{-44.28 \text{ kJ}}{\text{mol H}_2\text{SO}_4} \right| = \underline{\underline{-88.6 \text{ kJ}}}$$

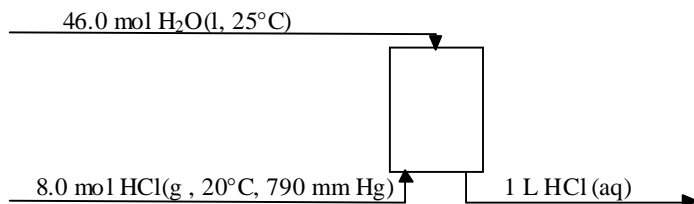
$$\text{b. } m_{\text{solution}} = \frac{2 \text{ mol H}_2\text{SO}_4}{\text{mol}} \left| \frac{98.08 \text{ g H}_2\text{SO}_4}{\text{mol}} \right| + \frac{4.67 \text{ mol H}_2\text{O}}{\text{mol}} \left| \frac{18.0 \text{ g H}_2\text{O}}{\text{mol}} \right| = 280.2 \text{ g}$$

$$\Delta H = 0 \Rightarrow n_{\text{H}_2\text{SO}_4} \Delta \hat{H}_s(25^\circ\text{C}, r = 2.33) + m \int_{25}^T C_p dT = 0$$

$$-88.6 \text{ kJ} + \frac{(280.6 + 150) \text{ g}}{\text{g} \cdot ^\circ\text{C}} \left| \frac{3.3 \text{ J}}{\text{g} \cdot ^\circ\text{C}} \right| \left| \frac{(T - 25)^\circ\text{C}}{1000 \text{ J}} \right| = 0 \Rightarrow \underline{\underline{T = 87^\circ\text{C}}}$$

$$8.86 \text{ a. Basis: } \frac{1 \text{ L product solution}}{\text{L}} \left| \frac{1.12(10^3 \text{ g})}{\text{L}} \right| = 1120 \text{ g solution}$$

$$\frac{1 \text{ L}}{\text{L}} \left| \frac{8 \text{ mol HCl}}{\text{L}} \right| \left| \frac{36.47 \text{ g HCl}}{\text{mol HCl}} \right| = 292 \text{ g HCl}$$



$$1120 \text{ g} - 292 \text{ g} = 828 \text{ g H}_2\text{O}$$

$$\frac{828 \text{ g H}_2\text{O}}{18.0 \text{ g}} \left| \frac{\text{mol}}{18.0 \text{ g}} \right| = 46.0 \text{ mol H}_2\text{O}$$

$$n = \frac{46.0 \text{ mol H}_2\text{O}}{8.0 \text{ mol HCl}} = 5.75 \text{ mol H}_2\text{O/mol HCl}$$

Assume all HCl is absorbed

Volume of gas:

$$\frac{8 \text{ mol}}{273 \text{ K}} \left| \frac{293 \text{ K}}{273 \text{ K}} \right| \left| \frac{760 \text{ mm Hg}}{790 \text{ mm Hg}} \right| \left| \frac{22.4 \text{ L (STP)}}{\text{mol}} \right| = \underline{\underline{185 \text{ liter (STP) gas feed/L HCl solution}}}$$

b. Ref: 25°C

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
H ₂ O(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)

$$\begin{aligned}\hat{H}(\text{HCl}, n = 5.75) &= \Delta\hat{H}_s(25^\circ\text{C}, n = 5.75) + \frac{1}{n_{\text{HCl}}} \int_{25}^{40} m C_p dT \\ &= -64.87 \text{ kJ/mol} + \frac{1120 \text{ g}}{8 \text{ mols}} \left| \frac{0.66 \text{ cal}}{\text{g} \cdot ^\circ\text{C}} \right| \left| \frac{(40 - 25)^\circ\text{C}}{\text{cal}} \right| \left| \frac{4.184 \text{ J}}{10^3 \text{ J}} \right| \text{ kJ}\end{aligned}$$

$$\begin{aligned}\hat{H}(\text{HCl}, 20^\circ\text{C}) &= \int_{25}^{20} [0.02913 - 0.1341 \times 10^{-5} T + 0.9715 \times 10^{-8} T^2 - 4.335 \times 10^{-12} T^3] dT \\ &= -0.15 \text{ kJ/mol}\end{aligned}$$

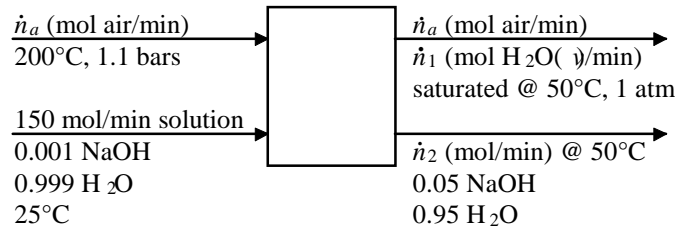
$$Q = \Delta H = -471 \text{ kJ/L product}$$

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

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

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

8.87 Basis: Given solution feed rate



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

H₂O balance: $(0.999)(150) = \dot{n}_1 + 0.95(3.0) \Rightarrow \dot{n}_1 = 147 \text{ mol H}_2\text{O/min}$

Raoult's law: $y_{\text{H}_2\text{O}} P = \frac{\dot{n}_1}{\dot{n}_1 + \dot{n}_a} P = p_{\text{H}_2\text{O}}^*(50^\circ\text{C}) \stackrel{\text{Table B.4}}{=} 92.51 \text{ mm Hg} \Rightarrow \dot{n}_a = 1061 \frac{\text{mol air}}{\text{min}}$
 $\dot{n}_1 = 147$
 $P = 760$

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

References for enthalpy calculations: H₂O(l), NaOH(s), air @ 25°C

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

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

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

$$\begin{aligned}\hat{H}(50^\circ\text{C}) &= \Delta\hat{H}_s(25^\circ\text{C}) + m \int_{25}^{50} C_p dT \\ &= -42.81 \frac{\text{kJ}}{\text{mol NaOH}} + \frac{382 \text{ g}}{\text{mol NaOH}} \left| \frac{4.184 \text{ J}}{1 \text{ g} \cdot ^\circ\text{C}} \right| \left| \frac{(50 - 25)^\circ\text{C}}{10^3 \text{ J}} \right| = -2.85 \text{ kJ}\end{aligned}$$

8.87 (cont'd)

Air @ 200°C: Table B.8 $\Rightarrow \hat{H} = 5.15 \text{ kJ/mol}$

Air (dry) @ 50°C: Table B.8 $\Rightarrow \hat{H} = 0.73 \text{ kJ/mol}$

H₂O(v, 50°C): Table B.5 $\Rightarrow \hat{H} = \frac{(2592 - 104.8) \text{ kJ}}{\text{kg}} \left| \frac{1 \text{ kg}}{10^3 \text{ g}} \right| \frac{18.0 \text{ g}}{1 \text{ mol}} = 44.81 \text{ kJ/mol}$

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 ₂ O(v)	—	—	147	44.81	\hat{H} in kJ/mol
Dry air	1061	5.15	1061	0.73	

Energy balance: $\dot{Q} = \Delta \dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 1900 \text{ kJ/min}$ transferred to unit
(neglect ΔE_n)

8.88 a. Basis: 1 L 4.00 molar H₂SO₄ solution (S.G. = 1.231)

$$\frac{1 \text{ L}}{\text{L}} \left| \frac{1231 \text{ g}}{\text{L}} \right| = 1231 \text{ g} \Rightarrow \frac{4.00 \text{ mol H}_2\text{SO}_4}{392.3 \text{ g H}_2\text{SO}_4} \Rightarrow \frac{1231 - 392.3 = 838.7 \text{ g H}_2\text{O}}{46.57 \text{ mol H}_2\text{O}}$$

$$\Rightarrow r = 11.64 \text{ mol H}_2\text{O} / \text{mol H}_2\text{SO}_4 \xrightarrow{\text{Table B.11}} \Delta \hat{H}_s = -67.6 \text{ kJ} / \text{mol H}_2\text{SO}_4$$

Ref: H₂O(l, 25°C), H₂SO₄(25°C)

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
H ₂ O(l)	46.57	0.0754(T - 25)	—	—	n in mol
H ₂ SO ₄ (l)	4.00	0	—	—	\hat{H} in kJ/mol
H ₂ SO ₄ (25°C, $n = 11.64$)	—	—	4.00	-67.6	

$$Q = \Delta H = 0 = 4.00(-67.6) - 46.57(0.0754)(T - 25) \Rightarrow T = -52^\circ\text{C}$$

(The water would not be liquid at this temperature \Rightarrow impossible alternative!)

b. Ref: H₂O(l, 25°C), H₂SO₄(25°C)

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
H ₂ O(l)	n_l	0.0754(0 - 25)	—	—	n in mols
H ₂ O(s)	n_s	-6.01 + 0.0754(0 - 25)	—	—	\hat{H} in kJ/mol
H ₂ SO ₄ (l)	4.00	0	—	—	
H ₂ SO ₄ (25°C, $n = 11.64$)	—	—	4.00	-67.61	

$$\Delta \hat{H}_m(\text{H}_2\text{O}, 0^\circ\text{C}) = 6.01 \text{ kJ/mol}$$

↑
Table B.1

$$\left. \begin{aligned} n_l + n_s &= 46.57 \\ \Delta H = 0 &= 4.00(-67.61) - n_l(-1.885) - (46.57 - n_l)(-7.895) \end{aligned} \right\} \Rightarrow \begin{aligned} n_l &= 16.18 \text{ mol liquid H}_2\text{O} \\ n_s &= 30.39 \text{ mol ice} \end{aligned}$$

$\Rightarrow 291.4 \text{ g H}_2\text{O}(\ell) + 547.3 \text{ g H}_2\text{O}(s) @ 0^\circ\text{C}$

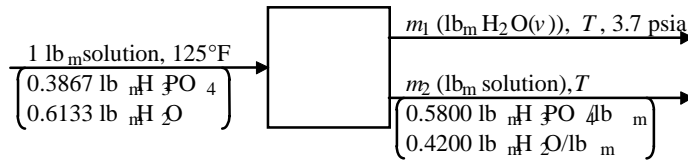


$$\text{a. } \text{wt\% P}_2\text{O}_5 = \frac{n(141.96)}{m_t} \times 100\% \quad , \quad \text{wt\% H}_3\text{PO}_4 = \frac{\overset{\text{mol H}_3\text{PO}_4}{\downarrow} 2n \quad \overset{\text{g H}_3\text{PO}_4/\text{mol}}{\downarrow} (98.00)}{\underset{\text{g total}}{\uparrow} m_c} \times 100\%$$

where $n = \text{mol P}_2\text{O}_5$ and $m_t = \text{total mass}$.

$$\text{wt\% H}_3\text{PO}_4 = \frac{2(98.00)}{141.96} \quad \text{wt\% P}_2\text{O}_5 = 1.381 \quad \text{wt\% P}_2\text{O}_5$$

b. Basis: 1 lb_m feed solution 28 wt% P₂O₅ ⇒ 38.67 wt% H₃PO₄



H₃PO₄ balance: $0.3867 = 0.5800m_2 \Rightarrow m_2 = 0.667 \text{ lb}_m \text{ solution}$

Total balance: $1 = m_1 + m_2 \Rightarrow m_1 = 0.3333 \text{ lb}_m \text{ H}_2\text{O}(r)$

Evaporation ratio: $\frac{0.3333 \text{ lb}_m \text{ H}_2\text{O}(v)}{\text{lb}_m \text{ feed solution}}$

c. Condensate:

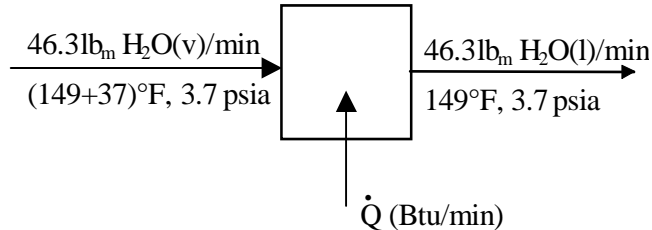
$P = 3.7 \text{ psia } (0.255 \text{ bar})$

Table B.6
 $\Rightarrow T_{\text{sat}} = 65.4^\circ\text{C} = 149^\circ\text{F}, \quad V_{\text{liq}} = \frac{0.00102 \text{ m}^3}{\text{kg}} \left| \frac{35.3145 \text{ ft}^3 / \text{m}^3}{2.205 \text{ lb}_m / \text{kg}} \right| = 0.0163 \frac{\text{ft}^3}{\text{lb}_m \text{ H}_2\text{O}(l)}$

$\dot{m} = \frac{100 \text{ tons feed}}{\text{day}} \left| \frac{2000 \text{ lb}_m}{1 \text{ ton}} \right| \left| \frac{1 \text{ lb}_m \text{ H}_2\text{O}}{3 \text{ lb}_m} \right| \left| \frac{1 \text{ day}}{(24 \times 60) \text{ min}} \right| = 46.3 \text{ lb}_m / \text{min}$

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

Heat of condensation process:



8.89 (cont'd)

$$\text{Table B.6} \Rightarrow \begin{cases} \hat{H}_{H_2O(v)}(186^\circ \text{F} = 85.6^\circ \text{C}) = (2652 \text{ kJ} / \text{kg}) \left(0.4303 \frac{\text{Btu/lb}_m}{\text{kJ/kg}} \right) = 1141 \text{ Btu} / \text{lb}_m \\ \hat{H}_{H_2O(l)}(149^\circ \text{F} = 65.4^\circ \text{C}) = (274 \text{ kJ} / \text{kg})(0.4303) = 118 \text{ Btu} / \text{lb}_m \end{cases}$$

$$\dot{Q} = \dot{m} \Delta \hat{H} = (46.3 \frac{\text{lb}_m}{\text{min}}) \left[(118 - 1141) \frac{\text{Btu}}{\text{lb}_m} \right] = -47,360 \text{ Btu} / \text{min}$$

$$\Rightarrow \underline{\underline{4.74 \times 10^4 \text{ Btu/min available at } 149^\circ \text{F}}}$$

d. Refs: $\text{H}_3\text{PO}_4(l)$, $\text{H}_2\text{O}(l)$ @ 77°F

substance	m_{in}	\hat{H}_{in}	m_{out}	\hat{H}_{out}	
$\text{H}_3\text{PO}_4(28\%)$	1.00	13.95	—	—	m in lb_m
$\text{H}_3\text{PO}_4(42\%)$	—	—	0.667	34.13	\hat{H} in Btu/lb _m
$\text{H}_2\text{O}(v)$	—	—	0.3333	1099	

$$\begin{aligned} \hat{H}(\text{H}_3\text{PO}_4, 28\%) &= \frac{-5040 \text{ Btu}}{\text{lb} - \text{mole } \text{H}_3\text{PO}_4} \left| \frac{1 \text{ lb} - \text{mole } \text{H}_3\text{PO}_3}{98.00 \text{ lb}_m \text{ H}_3\text{PO}_4} \right| \frac{0.3867 \text{ lb}_m \text{ H}_3\text{PO}_4}{1.00 \text{ lb}_m \text{ soln}} \\ &+ \frac{0.705 \text{ Btu}}{\text{lb}_m \cdot ^\circ \text{F}} \left| \frac{(125 - 77)^\circ \text{F}}{1} \right| = 13.95 \text{ Btu/lb}_m \text{ soln} \end{aligned}$$

$$\begin{aligned} \hat{H}(\text{H}_3\text{PO}_4, 42\%) &= \frac{-5040 \text{ Btu}}{\text{lb} - \text{mole } \text{H}_3\text{PO}_4} \left| \frac{1 \text{ lb} - \text{mole } \text{H}_3\text{PO}_4}{98.00 \text{ lb}_m \text{ H}_3\text{PO}_4} \right| \frac{0.5800 \text{ lb}_m \text{ H}_3\text{PO}_4}{1.00 \text{ lb}_m \text{ sol.}} \\ &+ \frac{0.705 \text{ Btu}}{\text{lb}_m \cdot ^\circ \text{F}} \left| \frac{(186.7 - 77)^\circ \text{F}}{1} \right| = 34.13 \text{ Btu/lb}_m \text{ soln} \end{aligned}$$

$$\hat{H}(\text{H}_2\text{O}) = \hat{H}(3.7 \text{ psia}, 186^\circ \text{F}) - \hat{H}(l, 77^\circ \text{F}) = (2652 - 104.7) \text{ kJ/kg} \Rightarrow 1096 \text{ Btu/lb}_m$$

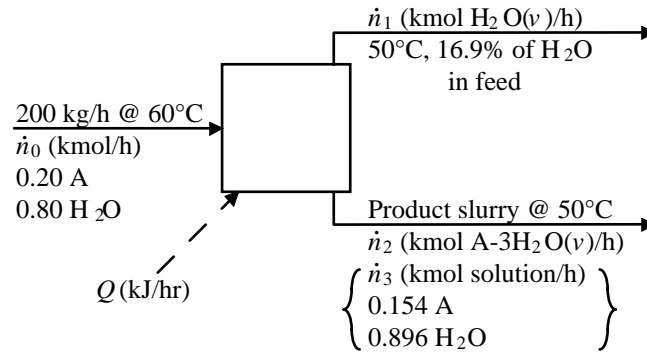
$$\text{At } 27.6 \text{ psia } (=1.90 \text{ bar}), \text{ Table B.6 } \Rightarrow \Delta \hat{H}_v = 2206 \text{ kJ} / \text{kg} = 949 \text{ Btu} / \text{lb}_m$$

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 375 \text{ Btu} = m_{\text{steam}} \Delta \hat{H}_v \Rightarrow m_{\text{steam}} = \frac{375 \text{ Btu}}{949 \text{ Btu} / \text{lb}_m} = 0.395 \text{ lb}_m \text{ steam}$$

$$\Rightarrow \frac{0.395 \text{ lb}_m \text{ steam}}{\text{lb}_m 28\% \text{ H}_3\text{PO}_4} \left| \frac{100 \times 2000 \text{ lb}_m \text{ H}_3\text{PO}_4}{\text{day}} \right| \frac{1 \text{ day}}{24 \text{ h}} = \underline{\underline{3292 \text{ lb}_m \text{ steam} / \text{h}}}$$

$$\Rightarrow \frac{3292 \text{ lb}_m \text{ steam}}{(46.3 \times 60) \text{ lb}_m \text{ H}_2\text{O evaporated} / \text{h}} = \underline{\underline{1.18 \frac{\text{lb}_m \text{ steam}}{\text{lb}_m \text{ H}_2\text{O evaporated}}}}$$

8.90 Basis: 200 kg/h feed solution. $A = \text{NaC}_2\text{H}_3\text{O}_2$



- a. Average molecular weight of feed solution: $\bar{M} = 0.200 M_A + 0.800 M_{\text{H}_2\text{O}}$
 $= (0.200)(82.0) + (0.800)(18.0) = 30.8 \text{ kg/k}$

Molar flow rate of feed: $n_0 = \frac{200 \text{ kg}}{\text{h}} \left| \frac{1 \text{ kmol}}{30.8 \text{ kg}} \right| = \underline{\underline{6.49 \text{ kmol/h}}}$

- b. 16.9% evaporation $\Rightarrow n_1 = (0.169)(0.80)(6.49 \text{ kmol/h}) = 0.877 \text{ kmol H}_2\text{O}(v)/\text{h}$

A balance: $(0.20)(6.49 \text{ kmol/h}) = \frac{n_2 (\text{kmol A} \cdot 3 \text{ H}_2\text{O})}{\text{h}} \left| \frac{1 \text{ mole A}}{1 \text{ mole A} \cdot 3 \text{ H}_2\text{O}} \right| + 0.154 n_3$
 $\Rightarrow n_2 + 0.154 n_3 = 1.30$ (1)

H₂O balance: $(0.80)(6.49 \text{ kmol/h}) = 0.877 + \frac{n_2 (\text{kmol A} \cdot 3 \text{ H}_2\text{O})}{\text{h}} \left| \frac{3 \text{ moles H}_2\text{O}}{1 \text{ mole A} \cdot 3 \text{ H}_2\text{O}} \right| + 0.846 n_3$
 $\Rightarrow 3 n_2 + 0.846 n_3 = 4.315$ (2)

Solve (1) and (2) simultaneously $\Rightarrow n_2 = 1.13 \text{ kmol A} \cdot 3 \text{ H}_2\text{O}(s)/\text{h}$
 $n_3 = 1.095 \text{ kmol solution/h}$

Mass flow rate of crystals

$$\frac{1.13 \text{ kmol A} \cdot 3 \text{ H}_2\text{O}}{\text{h}} \left| \frac{136 \text{ kg A} \cdot 3 \text{ H}_2\text{O}}{1 \text{ kmol}} \right| = \underline{\underline{\frac{154 \text{ kg NaC}_2\text{H}_3\text{O}_2 \cdot 3 \text{ H}_2\text{O}(s)}{\text{h}}}}$$

Mass flow rate of product solution

$$\frac{200 \text{ kg feed}}{\text{h}} - \frac{154 \text{ kg crystals}}{\text{h}} - \frac{(0.877)(18.0) \text{ kg H}_2\text{O}(v)}{\text{h}} = \underline{\underline{30 \text{ kg solution/h}}}$$

- c. References for enthalpy calculations: $\text{NaC}_2\text{H}_3\text{O}_2(s)$, $\text{H}_2\text{O}(l)$ @ 25°C

Feed solution: $n\hat{H} = n_A \Delta \hat{H}_s(25^\circ\text{C}) + m \int_{25}^{60} C_p dT$ (form solution at 25°C , heat to 60°C)

$$n\hat{H} = \frac{(0.20)6.49 \text{ kmol A}}{\text{h}} \left| \frac{-1.71 \times 10^4 \text{ kJ}}{\text{kmol A}} \right| + \frac{200 \text{ kg}}{\text{hr}} \left| \frac{3.5 \text{ kJ}}{\text{kg} \cdot ^\circ\text{C}} \right| \frac{(60 - 25)^\circ\text{C}}{\text{h}} = 2300 \text{ kJ/h}$$

8.90 (cont'd)

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

$$= \frac{(0.154)1.095 \text{ kmol A}}{\text{h}} \left| \frac{-1.71 \times 10^4 \text{ kJ}}{\text{kmol A}} \right| + \frac{30 \text{ kg}}{\text{h}} \left| \frac{3.5 \text{ kJ}}{\text{kg} \cdot ^\circ\text{C}} \right| \frac{(50 - 25)^\circ\text{C}}{1} = -259 \text{ kJ/h}$$

Crystals: $n\hat{H} = n_A \Delta\hat{H}_{\text{hydration}} + m \int_{25}^{50} C_p dT$ (hydrate at 25°C , heat to 50°C)

$$= \frac{1.13 \text{ kmol A} \cdot 3\text{H}_2\text{O(s)}}{\text{h}} \left| \frac{-3.66 \times 10^4 \text{ kJ}}{\text{kmol}} \right| + \frac{154 \text{ kg}}{\text{h}} \left| \frac{1.2 \text{ kJ}}{\text{kg} \cdot ^\circ\text{C}} \right| \frac{(50 - 25)^\circ\text{C}}{1} = -36700 \text{ kJ/h}$$

H₂O(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)

$$= \frac{0.877 \text{ kmol H}_2\text{O}}{\text{h}} \left| \frac{[4.39 \times 10^4 + (32.4)(50 - 25)] \text{ kJ}}{1} \right| = 39200 \text{ kJ/h}$$

Energy balance: $Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = [(-259 - 36700 + 39200) - (2300)] \text{ kJ/h}$
 (neglect ΔE_R)

$$= -60 \text{ kJ/h} \quad (\text{Transfer heat from unit})$$

8.91 $\left. \begin{array}{l} \frac{50 \text{ mL H}_2\text{SO}_4}{\text{mL}} \left| \frac{1.834 \text{ g}}{\text{mL}} \right| = 91.7 \text{ g H}_2\text{SO}_4 \Rightarrow 0.935 \text{ mol H}_2\text{SO}_4 \\ \frac{84.2 \text{ mL H}_2\text{O(l)}}{\text{mL}} \left| \frac{1.00 \text{ g}}{\text{mL}} \right| = 84.2 \text{ g H}_2\text{O(l)} \Rightarrow 4.678 \text{ mol H}_2\text{O(l)} \end{array} \right\} \Rightarrow r = 5.00 \text{ mol H}_2\text{O/mol H}_2\text{SO}_4$

Ref: H₂O, H₂SO₄ @ 25 °C

$$\hat{H}(\text{H}_2\text{O(l)}, 15^\circ\text{C}) = [0.0754 \text{ kJ / (mol} \cdot ^\circ\text{C)}](15 - 25)^\circ\text{C} = -0.754 \text{ kJ / mol}$$

$$\hat{H}(\text{H}_2\text{SO}_4, r = 5.00) = -58.03 \frac{\text{kJ}}{\text{mol}} + \frac{(91.7 + 84.2) \text{ g}}{0.935 \text{ mol H}_2\text{SO}_4} \left| \frac{2.43 \text{ J}}{\text{g} \cdot ^\circ\text{C}} \right| \frac{(T - 25)^\circ\text{C}}{1} \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right|$$

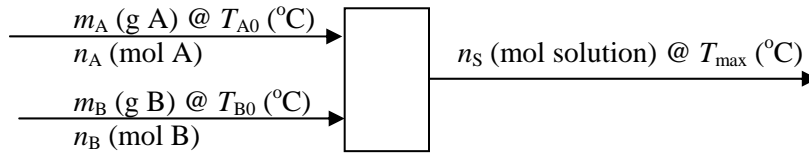
$$= (-69.46 + 0.457T) (\text{kJ / mol H}_2\text{SO}_4)$$

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
H ₂ O(l)	4.678	-0.754	—	—	n in mol
H ₂ SO ₄	0.935	0.0	—	—	\hat{H} in kJ/mol
H ₂ SO ₄ ($r = 4.00$)	—	—	0.935	$(-69.46 + 0.457T)$	n (mol H ₂ SO ₄)

Energy Balance: $\Delta H = 0 = 0.935(-69.46 + 0.457T) - 4.678(-0.754) \Rightarrow T = 144^\circ\text{C}$

Conditions: Adiabatic, negligible heat absorbed by the solution container.

8.92 a.



Refs: A(l), B(l) @ 25 °C

substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
A	n_A	\hat{H}_A	—	—	n in mol
B	n_B	\hat{H}_B	—	—	\hat{H} in J / mol
S	—	—	n_A	\hat{H}_S (J/mol A)	

Moles of feed materials: n_A (mol A) = $\frac{m_A \text{ (g A)}}{M_A \text{ (g A / mol A)}}$, $n_B = \frac{m_B}{M_B}$

Enthalpies of feeds and product

$$\hat{H}_A = m_A C_{pA} (T_{A0} - 25^\circ \text{C}), \quad \hat{H}_B = m_B C_{pB} (T_{B0} - 25^\circ \text{C})$$

$$r \text{ (mol B/mol A)} = n_B / n_A = \frac{m_B / M_B}{m_A / M_A}$$

$$\hat{H}_S \left(\frac{\text{J}}{\text{mol A}} \right) = \frac{1}{n_A \text{ (mol A)}} \left[n_A \text{ (mol A)} \times \Delta \hat{H}_m(r) \left(\frac{\text{J}}{\text{mol A}} \right) + (m_A + m_B) (\text{g soln}) \times C_{ps} \left(\frac{\text{J}}{\text{g soln} \cdot ^\circ \text{C}} \right) \times (T_{\max} - 25) (^\circ \text{C}) \right]$$

$$\Rightarrow \hat{H}_S = \frac{1}{n_A} \left[n_A \Delta \hat{H}_m(r) + (m_A + m_B) C_{ps} (T_{\max} - 25) \right]$$

Energy balance

$$\Delta H = n_A \hat{H}_S - n_A \hat{H}_A - n_B \hat{H}_B = 0$$

$$\Rightarrow \frac{m_A}{M_A} \Delta \hat{H}_m(r) + (m_A + m_B) C_{ps} (T_{\max} - 25) - m_A C_{pA} (T_{A0} - 25) - m_B C_{pB} (T_{B0} - 25) = 0$$

$$\Rightarrow T_{\max} = 25 + \frac{m_A C_{pA} (T_{A0} - 25) + m_B C_{pB} (T_{B0} - 25) - \frac{m_A}{M_A} \Delta \hat{H}_m(r)}{(m_A + m_B) C_{ps}}$$

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. $\left. \begin{array}{llll} m_A = 100.0 \text{ g} & M_A = 40.00 & T_{A0} = 25^\circ \text{C} & C_{pA} = ? (\text{irrelevant}) \\ m_B = 225.0 \text{ g} & M_B = 18.01 & T_{B0} = 40^\circ \text{C} & C_{pB} = 4.18 \text{ J/(g} \cdot ^\circ \text{C)} \end{array} \right\} \Rightarrow r = 5.00 \frac{\text{mol H}_2\text{O}}{\text{mol NaOH}}$

$$C_{ps} = 3.35 \text{ J/(g} \cdot ^\circ \text{C)} \quad \Delta \hat{H}_m(n = 5.00) = -37,740 \text{ J/mol A} \Rightarrow \underline{\underline{T_{\max} = 125^\circ \text{C}}}$$

8.93 Refs: Sulfuric acid and water @ 25 °C

b.

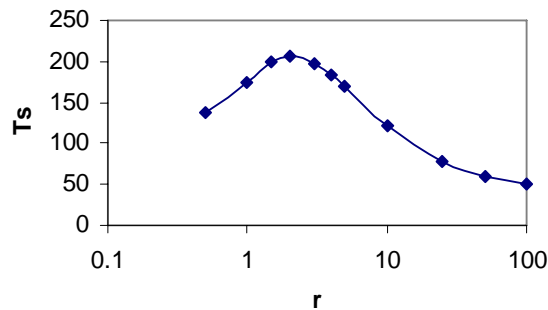
substance	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}	
H ₂ SO ₄	1	$M_A C_{pA}(T_0 - 25)$	—	—	n in mol
H ₂ O	r	$M_w C_{pw}(T_0 - 25)$	—	—	\hat{H} in J/mol
H ₂ SO ₄ (aq)	—	—	1	$\Delta\hat{H}_m(r) + (M_A + rM_w)C_{ps}(T_s - 25)$	(J/mol H ₂ SO ₄)

$$\begin{aligned}\Delta H = 0 &= \Delta\hat{H}_m(r) + (M_A + rM_w)C_{ps}(T_s - 25) - M_A C_{pA}(T_0 - 25) - rM_w C_{pw}(T_0 - 25) \\ &= \Delta\hat{H}_m(r) + (98 + 18r)C_{ps}(T_s - 25) - (98C_{pA} + 18rC_{pw})(T_0 - 25) \\ \Rightarrow T_s &= 25 + \frac{1}{(98 + 18r)C_{ps}} \left[(98C_{pA} + 18rC_{pw})(T_0 - 25) - \Delta\hat{H}_m(r) \right]\end{aligned}$$

c.

	C_p (J/mol-K)	C_p (J/g-K)
H ₂ O(l)	75.4	4.2
H ₂ SO 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. Ideal gas equation of state $n_{A0} = P_0 V_g / RT_0$ (1)

Total moles of B: $n_{B0}(\text{mol B}) = \frac{V_l(\text{L}) \times (SG_B \times 1 \text{ kg} / \text{L})(10^3 \text{ g} / \text{kg})}{M_B (\text{g} / \text{mol B})}$ (2)

Total moles of A: $n_{Ao} = n_{Av} + n_{Al}$ (3)

Henry's Law: $r\left(\frac{\text{mol A(l)}}{\text{mol B}}\right) = k_s p_A \Rightarrow \frac{n_{Al}}{n_{B0}} = (c_0 + c_1 T) \frac{n_{Av} RT}{V_g}$ (4)

Solve (3) and (4) for n_{Al} and n_{Av} .

$$n_{Al} = \frac{\frac{n_{B0} RT}{V_g} (c_0 + c_1 T)}{\left[1 + \frac{n_{B0} RT}{V_g} (c_0 + c_1 T)\right]} \quad (5)$$

$$n_{Av} = \frac{n_{Ao}}{\left[1 + \frac{n_{B0} RT}{V_g} (c_0 + c_1 T)\right]} \quad (6)$$

Ideal gas equation of state

$$P = \frac{n_{Av} RT}{V_g} \stackrel{(6)}{=} \frac{n_{A0} RT}{V_g + n_{B0} RT (c_0 + c_1 T)} \quad (7)$$

Refs: $A(g), B(l)$ @ 298 K

substance	n_{in}	\hat{U}_{in}	n_{eq}	\hat{U}_{eq}
$A(g)$	n_{Ao}	$M_A C_{vA} (T_0 - 298)$	n_{Av}	$M_A C_{vA} (T - 298)$
$B(l)$	n_{B0}	$M_B C_{vB} (T_0 - 298)$	—	—
Solution	—	—	n_{Al}	$\hat{U}_1 (\text{kJ/mol A})$

n in mol
 \hat{U} in kJ/mol

$$\hat{U}_1 = \Delta \hat{U}_s + \frac{1}{n_{Al}} (n_{Al} M_A + n_{B0} M_B) C_{vs} (T - 298)$$

E.B.: $\Delta U = 0 = \sum_{\text{out}} n_i \hat{U}_i - \sum_{\text{in}} n_i \hat{U}_i$

$$0 = (n_{Av} C_{vA} + (n_{Al} M_A + n_{B0} M_B) C_{vs}) (T - 298) + n_{Al} \Delta \hat{U}_s - (n_{Ao} C_{vA} + n_{B0} C_{vB}) (T_0 - 298)$$

$$\Rightarrow T = 298 + \frac{n_{Al} (-\Delta \hat{U}_s) + (n_{Ao} C_{vA} + n_{B0} C_{vB}) (T_0 - 298)}{n_{Av} C_{vA} + (n_{Al} M_A + n_{B0} M_B) C_{vs}}$$

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

Vi	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) * (T0 - 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					

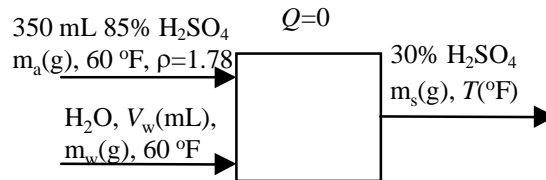
Program Output

T (assumed) (K)	P (atm)	N _{av} (mols)	N _{al} (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)	N _{av} (mols)	N _{al} (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.

$$V_w = \frac{350 \text{ mL feed} \mid 1.78 \text{ g} \mid [0.85(70/30) - 0.15] \text{ g H}_2\text{O added} \mid 1 \text{ mL water}}{1 \text{ mL feed} \mid \text{g feed} \mid 1 \text{ g water}}$$

$$= \underline{\underline{1140 \text{ mL H}_2\text{O}}}$$

b. Fig. 8.5-1 $\Rightarrow \hat{H}_a \approx -103 \text{ Btu/lb}_m$; Water: $\hat{H}_{\text{water}} \approx 27 \text{ Btu/lb}_m$

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: $\Delta H = 0 = m_p \hat{H}_{\text{product}} - m_a \hat{H}_a - m_w \hat{H}_w \Rightarrow \hat{H}_s = \frac{m_f \hat{H}_f + m_w \hat{H}_w}{m_p}$

$$\Rightarrow \hat{H}_{\text{product}} = \frac{(623)(-103) + (1140)(27)}{1765} = \underline{\underline{-18.9 \text{ Btu/lb}_m}}$$

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 $x_{\text{acid}}=1$ to $x_{\text{acid}}=0.9$ can lead to a temperature increase of 200°F or more.

8.96 a. $2.30 \text{ lb}_m \text{ 15.0 wt\% H}_2\text{SO}_4$
 $@ 77^\circ\text{F} \Rightarrow \hat{H}_1 = -10 \text{ Btu / lb}_m$

$m_2 (\text{lb}_m) \text{ 80.0 wt\% H}_2\text{SO}_4$
 $@ 60^\circ\text{F} \Rightarrow \hat{H}_2 = -120 \text{ Btu / lb}_m$

adiabatic mixing $\rightarrow m_3 (\text{lb}_m) \text{ 60.0 wt\% H}_2\text{SO}_4 @ T^\circ\text{F}, \hat{H}_3$

Total mass balance: $2.30 + m_2 = m_3$
H₂SO₄ mass balance: $2.30(0.150) + m_2(0.800) = m_3(0.600)$

$\Rightarrow \begin{cases} m_2 = 5.17 \text{ lb}_m (80\%) \\ m_3 = 7.47 \text{ lb}_m (60\%) \end{cases}$

b. Adiabatic mixing $\Rightarrow Q = \Delta H = 0$

$$(7.47)\hat{H}_3 - (2.30)(-10) - (5.17)(-120) = 0 \Rightarrow \hat{H}_3 = -86.1 \text{ Btu / lb}_m$$

\Downarrow Figure 8.5 - 1

T = 140° F

c. $\hat{H}(60 \text{ wt\%, } 77^\circ\text{F}) = -130 \text{ Btu / lb}_m$

$$Q = m_3 [\hat{H}(60 \text{ wt\%, } 77^\circ\text{F}) - \hat{H}_3] = (7.475)(-130 + 86.1) = \underline{\underline{-328 \text{ Btu}}}$$

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. $x_{\text{NH}_3} = 0.30 \xrightarrow{\text{Fig. 8.5-2}} y_{\text{NH}_3} = \underline{\underline{0.96 \text{ lb}_m \text{ NH}_3 / \text{lb}_m \text{ vapor}, T = 80^\circ\text{F}}}$

b. Basis: $1 \text{ lb}_m \text{ system mass} \Rightarrow 0.90 \text{ lb}_m \text{ liquid} \xrightarrow{x_{\text{NH}_3}=0.30} \begin{matrix} 0.27 \text{ lb}_m \text{ NH}_3 \\ 0.63 \text{ lb}_m \text{ H}_2\text{O} \end{matrix}$

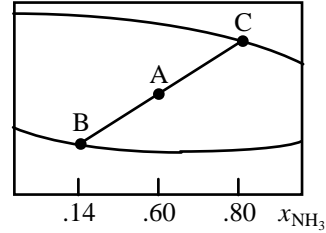
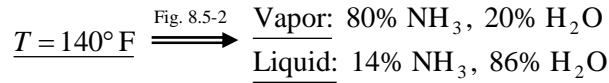
$\Rightarrow 0.10 \text{ lb}_m \text{ vapor} \xrightarrow{y_{\text{NH}_3}=0.96} \begin{matrix} 0.096 \text{ lb}_m \text{ NH}_3 \\ 0.004 \text{ lb}_m \text{ H}_2\text{O} \end{matrix}$

Mass fractions: $z_{\text{NH}_3} = \frac{(0.27 + 0.096) \text{ lb}_m \text{ NH}_3}{1 \text{ lb}_m} = \underline{\underline{0.37 \text{ lb}_m \text{ NH}_3 / \text{lb}_m}}$

$1 - 0.37 = \underline{\underline{0.63 \text{ lb}_m \text{ H}_2\text{O} / \text{lb}_m}}$

Enthalpy: $\hat{H} = \frac{0.90 \text{ lb}_m \text{ liquid}}{1 \text{ lb}_m} \left| \frac{-25 \text{ Btu}}{1 \text{ lb}_m \text{ liquid}} \right| + \frac{0.10 \text{ lb}_m \text{ vapor}}{1 \text{ lb}_m} \left| \frac{670 \text{ Btu}}{1 \text{ lb}_m \text{ vapor}} \right| = \underline{\underline{44 \text{ Btu / lb}_m}}$

8.98



Basis: 250 g system mass

$\Rightarrow m_v$ (g vapor), m_L (g liquid)

Mass Balance: $m_v + m_L = 250$

NH₃ Balance: $0.80m_v + 0.14m_L = (0.60)(250) \Rightarrow m_v = 175 \text{ g}, m_L = 75 \text{ g}$

$\Rightarrow \begin{cases} \text{Vapor: } m_{\text{NH}_3} = (0.80)(175 \text{ g}) = \underline{\underline{140 \text{ g NH}_3, 35 \text{ g H}_2\text{O}}} \\ \text{Liquid: } m_{\text{NH}_3} = (0.14)(75 \text{ g}) = \underline{\underline{10.5 \text{ g NH}_3, 64.5 \text{ g H}_2\text{O}}} \end{cases}$

8.99 Basis: 200 lb_m feed/h

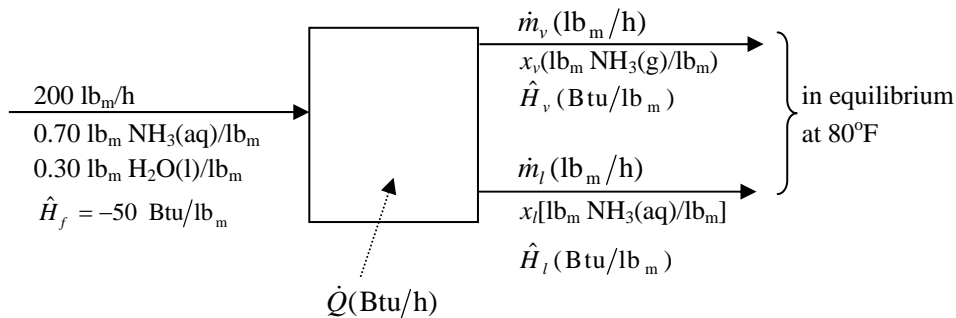


Figure 8.5-2 \Rightarrow Mass fraction of NH₃ in vapor: $x_v = 0.96 \text{ lb}_m \text{ NH}_3/\text{lb}_m$

Mass fraction of NH₃ in liquid: $x_l = 0.30 \text{ lb}_m \text{ NH}_3/\text{lb}_m$

Specific enthalpies: $\hat{H}_v = 650 \text{ Btu/lb}_m, \hat{H}_l = -30 \text{ Btu/lb}_m$

Mass balance: $200 = \dot{m}_v + \dot{m}_l$

Ammonia balance: $(0.70)(200) = 0.96\dot{m}_v + 0.30\dot{m}_l \Rightarrow \begin{cases} \dot{m}_v = 120 \text{ lb}_m/\text{h} \text{ vapor} \\ \dot{m}_l = 80 \text{ lb}_m/\text{h} \text{ liquid} \end{cases}$

Energy balance: Neglect $\Delta \hat{E}_k$.

$$\begin{aligned} \dot{Q} = \Delta \dot{H} &= \sum_{\text{out}} \dot{m}_i \hat{H}_i - \dot{m}_f \hat{H}_f = \frac{120 \text{ lb}_m}{\text{h}} \left| \frac{650 \text{ Btu}}{\text{lb}_m} \right| + \frac{80 \text{ lb}_m}{\text{h}} \left| \frac{-30 \text{ Btu}}{\text{lb}_m} \right| - \frac{200 \text{ lb}_m}{\text{h}} \left| \frac{-50 \text{ Btu}}{\text{lb}_m} \right| \\ &= \underline{\underline{86,000 \frac{\text{Btu}}{\text{h}}}} \end{aligned}$$