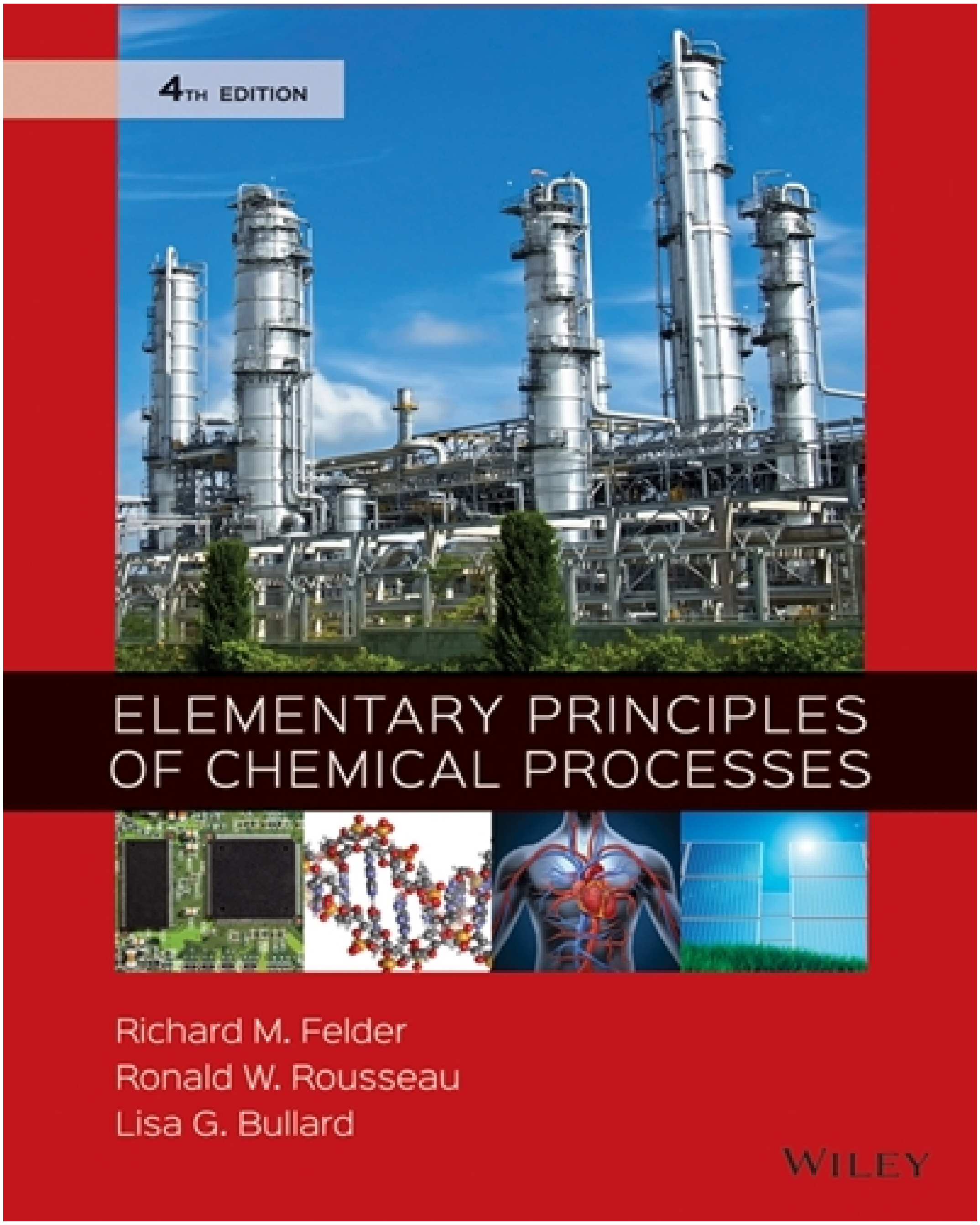
Solutions for Elementary Principles of Chemical Processes 4th Edition by Felder



Solutions

2.1 (a)

$$\frac{2\ \text{wk}}{\ }\bigg|\frac{7\ \text{d}}{1\ \text{wk}}\bigg|\frac{24\ \text{h}}{1\ \text{d}}\bigg|\frac{3600\ \text{s}}{1\ \ \text{h}}\bigg|\frac{10^{6}\ \mu\text{s}}{1\ \ \ \text{s}} = 1.2096\times10^{12}\,\mu\text{s} = \underline{\underline{1\times10^{12}\ \mu\text{s}}}$$

(b)

$$\frac{38.1\ \text{ft/s}}{\ }\bigg|\frac{0.3048\ \text{m}}{1\ \text{ft}}\bigg|\frac{1\ \text{km}}{1000\ \text{m}}\bigg|\frac{3600\ \text{s}}{1\ \text{h}} = \underline{\underline{41.8\ \text{km/h}}}$$

(c)

$$\frac{554\ \text{m}^{4}}{\text{d}\cdot\text{kg}}\bigg|\frac{1\ \text{d}}{24\ \text{h}}\bigg|\frac{1\ \text{h}}{60\ \text{min}}\bigg|\frac{0.453593\ \text{kg}}{1\ \text{lb}_{\text{m}}}\bigg|\frac{1\ \text{ft}^{4}}{(0.3048\ \text{m})^{4}} = \underline{\underline{20.2\ \text{ft}^{4}/\text{min}\cdot\text{lb}_{\text{m}}}}$$

2.2 **(a)**
$$\begin{array}{c|c|c} 1760\ \text{mi} & 0.001\ \text{km} & 1\ \ \text{h} \\ \hline \text{h} & 0.0006214\ \text{mi} & 3600\ \text{s} \end{array} = \underline{\underline{0.787\ \text{km/s}}}$$

(b)
$$\begin{array}{c|c|c} 1400\ \text{kg} & 2.20462\ \text{lb}_\text{m} & 1\ \ \ \text{m}^3 \\ \hline \text{m}^3 & 1\ \text{kg} & 35.3145\ \text{ft}^3 \end{array} = \underline{\underline{87.4\ \text{lb}_\text{m}/\text{ft}^3}}$$

(c)
$$\begin{array}{c|c|c} 5.37\times 10^3\ \text{kJ} & 1000\ \text{J} & 1.34\times 10^{-3}\ \text{hp} \\ \hline \text{s} & 1\ \text{kJ} & 1\ \text{J/s} \end{array} = 7195.8\ \text{hp} \Rightarrow \underline{\underline{7200\ \text{hp}}}$$

2.3 Assume that a baseball occupies the space equivalent to a $3\text{ in }\times 3\text{ in }\times 3\text{ in}$ cube. For a classroom with dimensions $40\text{ ft}\times 40\text{ ft}\times 15\text{ ft}$:

$$n_{\text{balls}} = \frac{40\times 40\times 15\text{ ft}^3}{} \left| \frac{(12)^3\text{ in}^3}{\text{ft}^3} \right| \frac{1\ \text{ ball}}{3^3\ \text{ in}^3} = 1.536\times 10^6 \approx \underline{\underline{1.5\text{ million baseballs}}}$$

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

2.4

$$\begin{array}{l|l|l|l|l|l|l} 4.3\text{ light yr} & 365\text{ d} & 24\text{ h} & 3600\text{ s} & 1.86\times10^{5}\text{ mi} & 3.2808\text{ ft} & 1\text{ step} \\ \hline & 1\text{ yr} & 1\text{ d} & 1\text{ h} & 1\text{ s} & 0.0006214\text{ mi} & 2\text{ ft} \end{array} = \underline{\underline{7\times10^{16}\text{ steps}}}$$

2.5

$$\text{Site A: } \frac{\begin{array}{c|c} 50 \text{ microns } \left(\mu m\right) & 100 \text{ cm} \end{array}}{\begin{array}{c|c} \phantom{50 \text{ microns } \left(\mu m\right)} & 10^{6}\ \mu m \end{array}} = 0.005 \text{ cm}$$

$$\text{Site B: } \frac{\begin{array}{c|c|c} 3 \text{ mil} & 10^{-3} \text{ in} & 30.48 \text{ cm} \end{array}}{\begin{array}{c|c|c} \phantom{3 \text{ mil}} & 1 \text{ mil} & 12 \text{ in} \end{array}} = 0.00762 \text{ cm}$$

$0.005 \text{ cm} < 0.00762 \text{ cm} \Rightarrow$ $\underline{\underline{\text{Site B is selling the thicker liner.}}}$

2.6 Distance from the earth to the moon = 238857 miles

$$\begin{array}{c|c|c} 238857\ \text{mi} & 1\ \ \ \ \ \ \text{m} & 1\ \text{report} \\ \hline & 0.0006214\ \text{mi} & 0.001\ \text{m} \end{array} = \underline{\underline{4\times10^{11}\ \text{reports}}}$$

2.7 $$\begin{array}{c|c|c|c} 19\text{ km} & 1000\text{ m} & 0.0006214\text{ mi} & 1000\text{ L} \\ \hline 1\text{ L} & 1\text{ km} & 1\text{ m} & 264.17\text{ gal} \end{array} = 44.7\text{ mi/gal}$$

Calculate the total cost to travel x miles:

$$\text{Total Cost}_{\text{American}} = \$28{,}500 + \begin{array}{c|c|c} \$3.25 & 1\text{ gal} & x\text{ (mi)} \\ \hline \text{gal} & 28\text{ mi} & \end{array} = 28{,}500 + 0.1161x$$

$$\text{Total Cost}_{\text{European}} = \$35{,}700 + \begin{array}{c|c|c} \$3.25 & 1\text{ gal} & x\text{ (mi)} \\ \hline \text{gal} & 44.7\text{ mi} & \end{array} = 35{,}700 + 0.07271x$$

Equate the two costs: $x = \underline{\underline{1.7\times10^{5}\text{ miles}}}$

2.8 (a)

$$\frac{100\times10^{6}\ \text{J}}{\text{s}}\,\Bigg|\,\frac{3600\ \text{s}}{1\ \text{hr}}\,\Bigg|\,\frac{24\ \text{hr}}{1\ \text{d}}\,\Bigg|\,\frac{365\ \text{d}}{1\ \text{yr}}=\underline{\underline{3.15\times10^{15}\ \text{J/yr}}}$$

(b) The question asks "how much power does a 100 MW plant generate annually?" The answer is implied in the units. The question should ask, "How much energy does a 100 MW plant generate annually?", e.g. in units of J/yr.

(c) The unit of MW is equivalent to J/s; power is energy/time, so MW is already a rate-based unit. We know that 100MW = 100MJ/s.

2.9 (a) $$\begin{array}{c|c|c} 25.0\ \text{lb}_\text{m} & 32.1714\ \text{ft/s}^2 & 1\quad \text{lb}_\text{f} \\ \hline & & 32.1714\ \text{lb}_\text{m}\cdot\text{ft/s}^2 \end{array} = \underline{\underline{25.0\ \text{lb}_\text{f}}}$$

(b) $$\begin{array}{c|c|c} 25\ \text{N} & 1 & 1\ \text{kg}\cdot\text{m/s}^2 \\ \hline & 9.8066\ \text{m/s}^2 & 1\ \text{N} \end{array} = 2.55\ \text{kg} \Rightarrow \underline{\underline{2.6\ \text{kg}}}$$

(c) $$\begin{array}{c|c|c|c|c} 10\ \text{ton} & 1\ \text{lb}_\text{m} & 1000\ \text{g} & 980.66\ \text{cm/s}^2 & 1\ \text{dyne} \\ \hline & 5\times10^{-4}\ \text{ton} & 2.20462\ \text{lb}_\text{m} & & 1\ \text{g}\cdot\text{cm/s}^2 \end{array} = \underline{\underline{9\times10^9\ \text{dynes}}}$$

2.10

$$\begin{array}{c|c|c|c|c} 50\times 25\times 2\ \text{m}^3 & 35.3145\ \text{ft}^3 & 75.3\ \text{lb}_\text{m} & 32.174\ \text{ft} & 1\ \text{lb}_\text{f} \\ \hline & 1\ \text{m}^3 & 1\ \text{ft}^3 & 1\ \text{s}^2 & 32.174\ \text{lb}_\text{m}/\text{ft}\cdot\text{s}^2 \end{array} = \underline{\underline{6.6\times 10^6\ \text{lb}_\text{f}}}$$

2.11

$$\begin{array}{c|c|c|c} 500\ \text{lb}_\text{m} & 1\quad \text{kg} & 1\quad \text{m}^3 & 35.3145\ \text{ft}^3 \\ \hline & 2.20462\ \text{lb}_\text{m} & 12.5\ \text{kg} & 1\ \text{m}^3 \end{array} \approx 500\left(\frac{1}{2}\right)\left(\frac{1}{10}\right)\left(\frac{40}{1}\right) \approx \underline{\underline{1000\ \text{ft}^3}}$$

2.12

$$\begin{array}{c|c|c|c|c} 31{,}000\text{ tons} & 1\text{ lb}_\text{m} & 0.453593\text{ kg} & 0.012\text{ m}^3 & 365\text{ days} \\ \hline 1\text{ day} & 5\times10^{-4}\text{ tons} & 1\text{ lb}_\text{m} & \text{kg} & 1\text{ yr} \end{array} = 1.2318\times10^{8}\text{ m}^3/\text{yr} \Rightarrow \underline{\underline{1.2\times10^{8}\text{ m}^3}}$$

2.13 **(a)**

(i) Electricity generated in a month by one panel :

$$=\begin{array}{c|c|c|c|c} 140\ \text{J} & 3600\ \text{s} & 5\ \text{hrs} & 30\ \text{days} & 2.778\times10^{-7}\ \text{kWh} \\ \hline \text{s} & 1\ \text{hr} & 1\ \text{day} & 1\ \text{month} & 1\ \text{J} \end{array}$$

$$=21\ \text{kWh}$$

The number of panels needed $= 948\text{kWh}/21\text{kWh}/\text{panel} = 45.11\ \text{panels} \rightarrow \underline{\underline{46\ \text{panels}}}$

Cost $= 46\ \text{panels}\ \times \$210/\text{panel} = \underline{\underline{\$9660}}$

(ii) Electricity generated in a month by one panel :

$$=\begin{array}{c|c|c|c|c} 240\ \text{J} & 3600\ \text{s} & 5\ \text{hrs} & 30\ \text{days} & 2.778\times10^{-7}\ \text{kWh} \\ \hline \text{s} & 1\ \text{hr} & 1\ \text{day} & 1\ \text{month} & 1\ \text{J} \end{array}$$

$$=36\ \text{kWh}$$

The number of panels needed $= 948\text{kWh}/36\text{kWh}/\text{panel} = 26.33\ \text{panels} \rightarrow \underline{\underline{27\ \text{panels}}}$

Cost $= 27\ \text{panels}\ \times \$260/\text{panel} = \underline{\underline{\$7020}}$

240W panel will be more beneficial.

(b) The amount of excess electricity in a month:

$$= 27\ \text{panels}\ \times 36\ \text{kWh}/\text{panel} - 948\ \text{kWh} = 24\ \text{kWh}$$

$$\text{Total cost savings} = \begin{array}{c|c|c|c} 24\ \text{kWh} & 12\ \text{months} & 3\ \text{yr} & \$\ 0.15 \\ \hline \text{month} & 1\ \text{yr} & & 1\ \text{kWh} \end{array} = \underline{\underline{\$129.6}}$$

Student Response

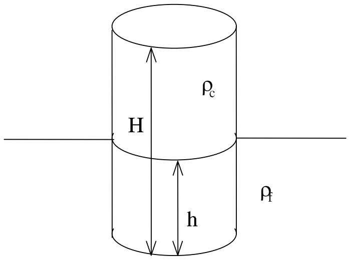
(c) Student Response

2.14 **(a)** $m_{\text{displaced fluid}} = m_{\text{cylinder}} \Rightarrow \rho_{\text{f}} V_{\text{f}} = \rho_{\text{c}} V_{\text{c}} \Rightarrow \rho_{\text{f}} h \pi r^2 = \rho_{\text{c}} H \pi r^2$

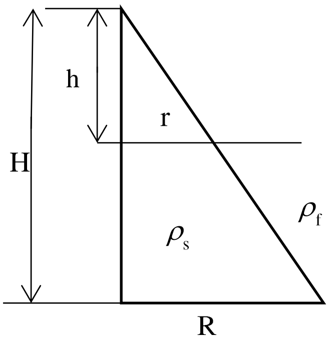
$$\rho_{\text{c}} = \frac{\rho_{\text{f}} h}{H} = \frac{(30\text{ cm} - 13.5\text{ cm})(1.00\text{ g/cm}^3)}{30\text{ cm}} = \underline{\underline{0.55\text{ g/cm}^3}}$$

(b) $$\rho_{\text{f}} = \frac{\rho_{\text{c}} H}{h} = \frac{(30\text{ cm})(0.55\text{ g/cm}^3)}{(30\text{ cm} - 18.9\text{ cm})} = \underline{\underline{1.49\text{ g/cm}^3}}$$

(c) Student Response



2.15



$$V_s = \frac{\pi R^2 H}{3}; \;\; V_f = \frac{\pi R^2 H}{3} - \frac{\pi r^2 h}{3} \;\; ; \;\; \frac{R}{H} = \frac{r}{h} \Rightarrow r = \frac{R}{H} h$$

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

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

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

2.16 **(a)** $\underline{h = 0}$, the drum is empty:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-0}{r}\right)-(r-0)\sqrt{r^2-(r-0)^2}\right]=\underline{\underline{0}}$$

$\underline{h = r}$, the drum is half full/empty:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-r}{r}\right)-(r-r)\sqrt{r^2-(r-r)^2}\right]=L\left[r^2\cos^{-1}(0)\right]=\underline{\underline{\frac{\pi}{2}Lr^2}}$$

$\underline{h = 2\text{r}}$, the drum is full:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-2r}{r}\right)-(r-2r)\sqrt{r^2-(r-2r)^2}\right]=L\left[r^2\cos^{-1}(-1)\right]=\underline{\underline{\pi Lr^2}}$$

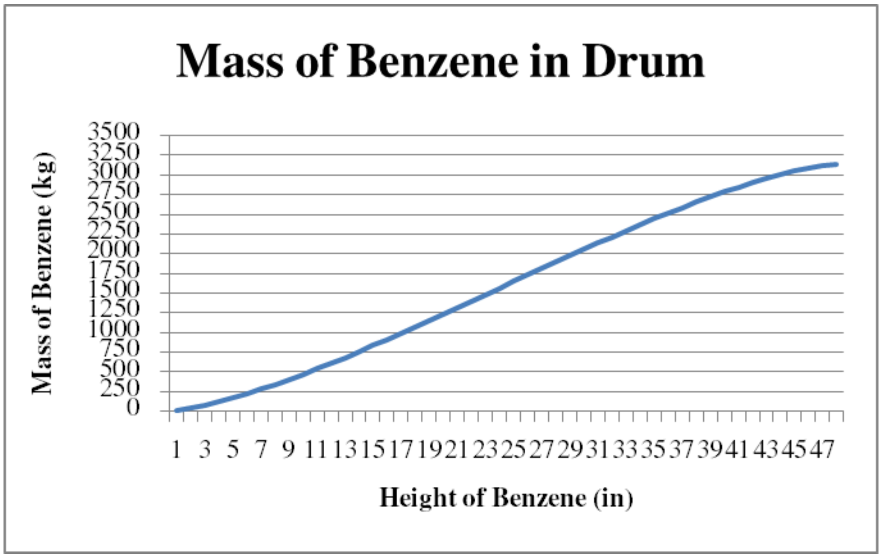
(b) $L = 10$ ft, $r = 2$ ft, $h = 4$ in, $\cos^{-1}$ found in radians

$$h=\frac{4\ \text{in}}{}\bigg|\frac{1\ \text{ft}}{12\ \text{in}}=0.333\ \text{ft}$$

$$V=(10)\left[(2\ \text{ft})^2\cos^{-1}\left(\frac{2\ \text{ft}-0.333\ \text{ft}}{2\ \text{ft}}\right)-(2\ \text{ft}-0.333\ \text{ft})\sqrt{(2\ \text{ft})^2-(2\ \text{ft}-0.333\ \text{ft})^2}\right]=4.99435\ \text{ft}^3$$

$$m=\frac{4.99435\ \text{ft}^3}{}\bigg|\frac{10^6\ \text{cm}^3}{35.3145\ \text{ft}^3}\bigg|\frac{0.879\ \text{g}}{1\ \text{cm}^3}\bigg|\frac{1\ \text{kg}}{10^3\ \text{g}}=124.313\ \text{kg}\Rightarrow\underline{\underline{124\ \text{kg}}}$$

(c)



2.17 $1\ \text{lb}_\text{f} = 1\ \text{slug}\cdot\text{ft/s}^2 = 32.174\ \text{lb}_\text{m}\cdot\text{ft/s}^2 \Rightarrow 1\ \text{slug}{=}32.174\ \text{lb}_\text{m}$

$1\ \text{poundal} = 1\ \text{lb}_\text{m}\cdot\text{ft/s}^2$

(a) (i) On the earth:

$$M = \frac{135\ \text{lb}_\text{m}}{}\bigg|\frac{1\ \text{slug}}{32.174\ \text{lb}_\text{m}} = \underline{\underline{4.20\ \text{slugs}}}$$

$$W = \frac{135\ \text{lb}_\text{m}}{}\bigg|\frac{32.174\ \text{ft}}{\text{s}^2}\bigg|\frac{1\ \text{poundal}}{1\ \text{lb}_\text{m}\cdot\text{ft/s}^2} = \underline{\underline{4.34\times 10^3\ \text{poundals}}}$$

(ii) On the moon

$$M = \frac{135\ \text{lb}_\text{m}}{}\bigg|\frac{1\ \text{slug}}{32.174\ \text{lb}_\text{m}} = \underline{\underline{4.20\ \text{slugs}}}$$

$$W = \frac{135\ \text{lb}_\text{m}}{}\bigg|\frac{32.174\ \text{ft}}{6\ \text{s}^2}\bigg|\frac{1\ \text{poundal}}{1\ \text{lb}_\text{m}\cdot\text{ft/s}^2} = \underline{\underline{724\ \text{poundals}}}$$

(b)

$$F = ma \Rightarrow a = F/m = \frac{405\ \text{poundals}}{35.0\ \text{slugs}}\bigg|\frac{1\ \text{lb}_\text{m}\cdot\text{ft/s}^2}{1\ \text{poundal}}\bigg|\frac{1\quad\text{slug}}{32.174\ \text{lb}_\text{m}}\bigg|\frac{1\ \text{m}}{3.2808\ \text{ft}}$$

$$= 0.1096\ \text{m/s}^2 \Rightarrow \underline{\underline{0.110\ \text{m/s}^2}}$$

2.18 **(a)**

$$F = ma \Rightarrow 1\ \text{doozy} = (1\ \text{cuz})(32.174\ \text{ft/s}^2)\left(\frac{1}{6}\right) = \underline{\underline{5.3623\ \text{cuz}\cdot\text{ft/s}^2}}$$

$$\Rightarrow \frac{1\ \text{doozy}}{\underline{\underline{5.3623\ \text{cuz}\cdot\text{ft/s}^2}}}$$

(b) On the moon: $W = \begin{array}{c|c|c} 3\ \text{cuz} & 32.174\ \text{ft} & 1\ \text{doozy} \\ \hline & 6\quad \text{s}^2 & 5.3623\ \text{cuz}\cdot\text{ft/s}^2 \end{array} = \underline{\underline{3\ \text{doozies}}}$

In Lizard Lick, NC: $W = (3)(32.174)/5.3623 = \underline{\underline{17\ \text{doozies}}}$

2.19 **(a)** First we need to make assumptions about how many doses were taken per day by a patient. While there are 6 four hour periods in one calendar day, it is unlikely a patient would wake up at 4 in the morning to take a dose. If a person was awake for 16 hours, they would take, at most, 4 doses (Waking, mid-day, before sleep):

$$V_{\mathrm{D}} = 4\text{ doses} \times \frac{3\text{ teaspoon}}{\text{dose}} = 12\text{ teaspoons}$$

The volume of a teaspoon is roughly 5 mL/teaspoon:

$$V_{\mathrm{D}} = 12\text{ teaspoon} \times \frac{5\text{ mL}}{\text{teaspoon}} = \underline{\underline{60\text{ mL}}}\text{ consumed in a day}$$

(b)

$$m_{\text{patient, max}} = \begin{array}{c|c|c} 60\text{ mL} & \text{kg body mass} & 2.20462\text{ lb}_m \\ \hline & 1.4\text{ mL} & \text{kg} \end{array} = 94.5\text{ lb}_{\mathrm{m}} \approx \underline{\underline{95\text{ lb}_{\mathrm{m}}}}$$

Anyone under 95 lb_{m} would be fatally poisoned. The intuitive answer is that a highly poisonous substance should not be taken even if the quantities are supposedly below a lethal level. Glycol (antifreeze) poisoning is attended with severe symptoms even if death is not the ultimate result. If the lethal dose is in error or has some variability, then even those above that body mass are at risk.

(c)

$$N_{\mathrm{p}} = \frac{V}{V_{\mathrm{d}}} = \frac{240\text{ gal}}{60\text{ mL}} \times \frac{10^6\text{ mL}}{264.17\text{ gal}} = \underline{\underline{15{,}141\text{ people}}}$$

(d)

- Research chemist might have turned up a possible alternate solvent. Definitely would have discovered DEG's poisonous qualities.
- Product made with almost nonexistent testing for quality, storage life, toxicity, etc. Proper testing would have prevented the poisoning and otherwise improved the product.
- Product released unrestricted without initial clinical field testing. Send out a test batch or two and see what the results are.

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

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

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

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

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

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

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

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

2.21 $R \approx \dfrac{(7\times10^{-1})(3\times10^{5})(6)(5\times10^{4})}{(3)(5\times10^{6})} \approx 42\times10^{2} \approx \underline{\underline{4\times10^{3}}}$ (Any digit in range 2-6 is acceptable)

$R_{\text{exact}} = 3812.5 \Rightarrow \underline{\underline{3810}} \Rightarrow \underline{\underline{3.81\times10^{3}}}$

2.22 **(a)** A: $R = 73.1 - 72.4 = \underline{\underline{0.7^\circ\text{C}}}$

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

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

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

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

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

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

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

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

2.23

(a)

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

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

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

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

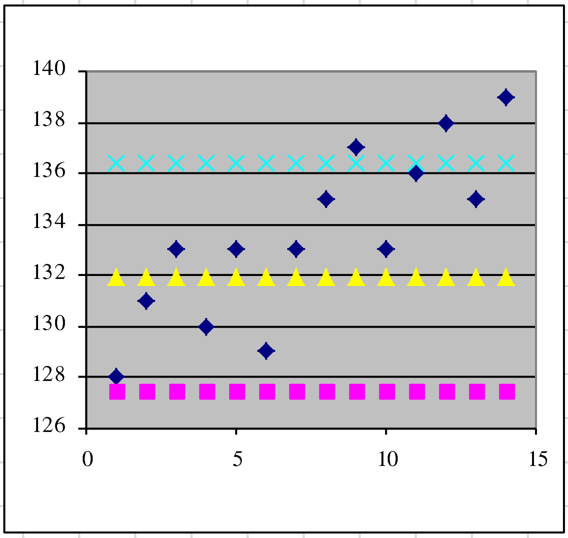
(c) Inadequate cleaning between batches, impurities in raw materials, variations in reactor temperature (failure of reactor control system), problems with the color measurement system, operator carelessness

2.24

(a),(b)

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

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



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

2.25 **(a)**

$$Q' = \begin{array}{r|r|r|r} 2.36\times10^{-4}\ \text{kg}\cdot\text{m}^2 & 2.10462\ \text{lb} & 3.2808^2\ \text{ft}^2 & 1\quad \text{h} \\ \hline \text{h} & \text{kg} & \text{m}^2 & 3600\ \text{s} \end{array}$$

(b)

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

$$Q'_{\text{exact}} = \underline{\underline{1.48\times10^{-6}\ \text{lb}\cdot\text{ft}^2/\text{s}}} = \underline{\underline{0.00000148\ \text{lb}\cdot\text{ft}^2/\text{s}}}$$

2.26

$$N_{\text{Pr}} = \frac{C_{\text{p}}\mu}{k} = \begin{array}{c|c|c|c|c} 0.583\ \text{J/g}\cdot{}^{\text{o}}\,\text{C} & 1936\ \text{lb}_{\text{m}} & 1\ \ \text{h} & 3.2808\ \text{ft} & 1000\ \text{g} \\ \hline 0.286\ \text{W/m}\cdot{}^{\text{o}}\,\text{C} & \text{ft}\cdot\text{h} & 3600\ \text{s} & \text{m} & 2.20462\ \text{lb}_{\text{m}} \end{array}$$

$$N_{\text{Pr}} \approx \frac{(6\times10^{-1})(2\times10^{3})(3\times10^{3})}{(3\times10^{-1})(4\times10^{3})(2)} \approx \frac{3\times10^{3}}{2} \approx \underline{\underline{1.5\times10^{3}}}.\ \ \text{The calculator solution is}\ \underline{\underline{1.63\times10^{3}}}$$

2.27 $$\text{Re} = \frac{Du\rho}{\mu} = \begin{array}{r|r|c|r|r|r|l} 0.48\text{ ft} & 1\ \ \text{ m} & 2.067\text{ in} & 1\ \ \text{m} & 0.805\text{ g} & 1\ \text{kg} & 10^6\ \text{cm}^3 \\ \hline \text{s} & 3.2808\text{ ft} & 0.43\times10^{-3}\ \text{kg/m}\cdot\text{s} & 39.37\text{ in} & \text{cm}^3 & 1000\text{ g} & 1\ \ \text{m}^3 \end{array}$$

$$\text{Re} \approx \frac{(5\times10^{-1})(2)(8\times10^{-1})(10^6)}{(3)(4\times10)(10^3)(4\times10^{-4})} \approx \frac{5\times10^{1-(-3)}}{3} \approx 2\times10^4 \Rightarrow \underline{\underline{\text{the flow is turbulent}}}$$

2.28

(a) $$\frac{k_{\mathrm{g}} d_{\mathrm{p}} y}{D} = 2.00 + 0.600\left(\frac{\mu}{\rho D}\right)^{1/3}\left(\frac{d_{\mathrm{p}} u \rho}{\mu}\right)^{1/2}$$

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

$$= 44.426 \Rightarrow \frac{k_{\mathrm{g}}(0.00500\ \mathrm{m})(0.100)}{1.00\times 10^{-5}\ \mathrm{m^2/s}} = 44.426 \Rightarrow k_{\mathrm{g}} = \underline{\underline{0.888\ \mathrm{m/s}}}$$

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

(c)

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

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

(b)
$$r = \left[\begin{array}{c|c|c} 200\text{ crystals} & 0.050\text{ in} & 25.4\text{ mm} \\ \hline \text{min}\cdot\text{mm} & & \text{in} \end{array}\right] - \left[\begin{array}{c|c|c} 10\text{ crystals} & 0.050^2\text{ in}^2 & (25.4)^2\text{ mm}^2 \\ \hline \text{min}\cdot\text{mm}^2 & & \text{in}^2 \end{array}\right]$$

$$= 238\text{ crystals/min} \Rightarrow \begin{array}{c|c} 238\text{ crystals} & 1\text{ min} \\ \hline \text{min} & 60\text{ s} \end{array} = \underline{\underline{4.0\text{ crystals/s}}}$$

(c)
$$D(\text{mm}) = \begin{array}{c|c} D'(\text{in}) & 25.4\text{ mm} \\ \hline & 1\text{ in} \end{array} = 25.4D'\text{; } r\left(\frac{\text{crystals}}{\text{min}}\right) = r' \begin{array}{c|c} \text{crystals} & 60\text{ s} \\ \hline \text{s} & 1\text{ min} \end{array} = 60r'$$

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

(d) The equation predicts that the diameter of the crystals will increase with the size of the crystals. This corresponds to an empirical formula since, as the rate is faster, the duration time is smaller, leaving less time for mixing and larger crystals.

2.30 **(a)** $\underline{\underline{70.5\ \text{lb}_\text{m}/\text{ft}^3}}$; $\underline{\underline{8.27\times10^{-7}\ \text{in}^2/\text{lb}_\text{f}}}$

(b)

$$\rho=(70.5\ \text{lb}_\text{m}/\text{ft}^3)\exp\left[\frac{8.27\times10^{-7}\ \text{in}^2}{\text{lb}_\text{f}}\left|\frac{9\times10^6\ \text{N}}{\text{m}^2}\right|\frac{14.696\ \text{lb}_\text{f}/\text{in}^2}{1.01325\times10^5\ \text{N/m}^2}\right]$$

$$=\frac{70.57\ \text{lb}_\text{m}}{\text{ft}^3}\left|\frac{35.3145\ \text{ft}^3}{\text{m}^3}\right|\frac{1\quad \text{m}^3}{10^6\ \text{cm}^3}\left|\frac{1000\ \text{g}}{2.20462\ \text{lb}_\text{m}}\right.=\underline{\underline{1.13\ \text{g/cm}^3}}$$

(c)

$$\rho\left(\frac{\text{lb}_\text{m}}{\text{ft}^3}\right)=\rho'\frac{\text{g}}{\text{cm}^3}\left|\frac{1\ \text{lb}_\text{m}}{453.593\ \text{g}}\right|\frac{28{,}317\ \text{cm}^3}{1\ \text{ft}^3}=62.43\rho'$$

$$P\left(\frac{\text{lb}_\text{f}}{\text{in}^2}\right)=P'\frac{\text{N}}{\text{m}^2}\left|\frac{0.2248\ \text{lb}_\text{f}}{1\ \text{N}}\right|\frac{1^2\quad \text{m}^2}{39.37^2\ \text{in}^2}=1.45\times10^{-4}P'$$

$$\Rightarrow 62.43\rho'=70.5\exp\left[\left(8.27\times10^{-7}\right)\left(1.45\times10^{-4}P'\right)\right]\Rightarrow \underline{\underline{\rho'=1.13\exp\left(1.20\times10^{-10}P'\right)}}$$

$$P'=9.00\times10^6\ \text{N/m}^2\Rightarrow\rho'=1.13\exp[(1.20\times10^{-10})(9.00\times10^6)]=\underline{\underline{1.13\ \text{g/cm}^3}}$$

2.31

(a)

$$\begin{array}{c|c|c} t\ (\text{hr}) & 60\text{ min} & 60\text{ s} \\ \hline & 1\text{ hr} & 1\text{ min} \end{array} = 3600t\text{ s}$$

$$V\left(\text{in}^3\right) = \begin{array}{c|c} V\text{ cm}^3 & 1728\text{ in}^3 \\ \hline & 28317\text{ cm}^3 \end{array} = 0.06102V\left(\text{cm}^3\right)$$

$$\Rightarrow \underline{\underline{V\left(\text{in}^3\right) = 0.061a\cdot e^{3600b\cdot t(\text{hr})}}}$$

(b) $a = \text{cm}^3$, $b = \text{s}^{-1}$

2.32 **(a)** $\underline{\underline{3.00\text{ mol/L}}}$, $\underline{\underline{2.00\text{ min}^{-1}}}$

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

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

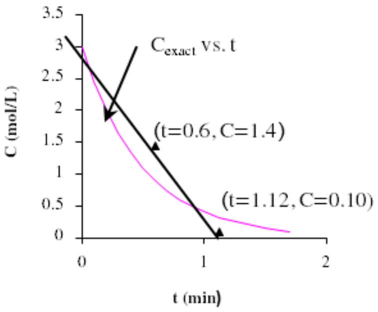
For t=0.6 min: $$C_{\text{int}} = \frac{0.406-3.00}{1-0}(0.6-0)+3.00 = \underline{\underline{1.4\text{ mol/L}}}$$

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

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

$$t_{\text{exact}} = -\frac{1}{2.00}\ln\frac{C}{3.00} = -\frac{1}{2}\ln\frac{0.10}{3.00} = \underline{\underline{1.70\text{ min}}}$$

(c)

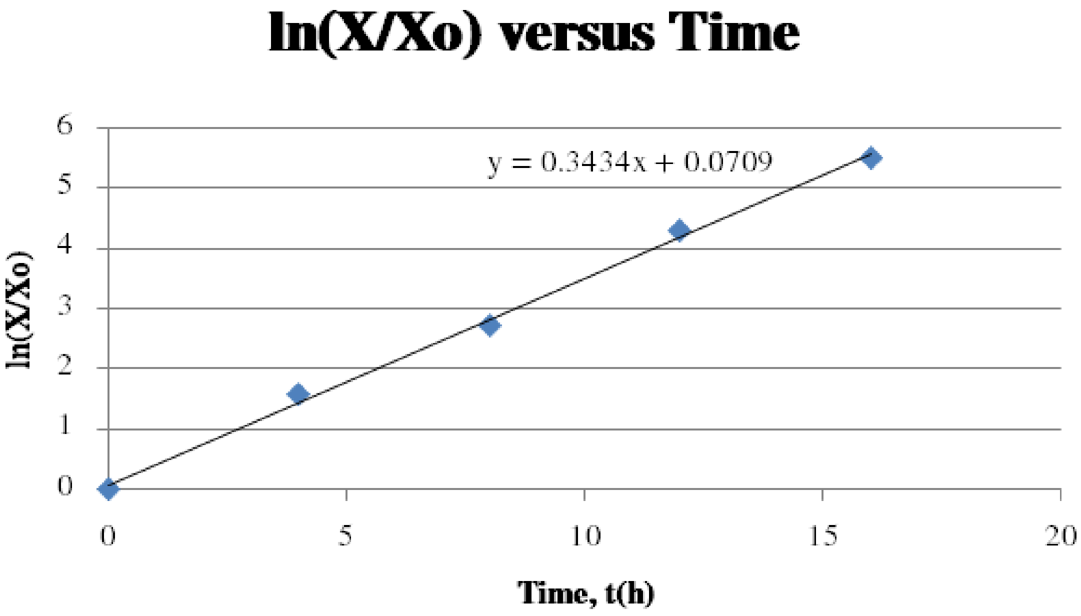


2.33 **(a)** $\mu = \text{h}^{-1}$

(b) i. $\ln\left(X/X_0\right)$ vs. t on rectangular axes.

ii. X/X_0 vs. t on semi-log axes.

(c)



μ is a slope of the graph, so $\mu = \underline{\underline{0.3434 \text{ h}^{-1}}}$

(d)

For doubling the ratio $X/X_0 = 2$

$\ln\left(X/X_0\right) = \mu t + b$

$t = (\ln(2) - 0.0709)/0.3434 \Rightarrow \underline{\underline{t = 1.81 \text{ hr}}}$

2.34 (a)

time, t (h)	Concentration, C	ln C
0 (8am)	x	ln x
3 (11am)	3850	8.2558
9 (5am)	36530	10.5059

i) exponential growth: $C = C_0 e^{kt} \Rightarrow \ln C = \ln C_0 + kt$

$$\begin{cases} 8.2558 = \ln C_0 + 3k \\ 10.5059 = \ln C_0 + 9k \end{cases} \Rightarrow \begin{array}{l} \underline{\underline{k = 0.375}} \\ \ln C_0 = 7.13075 \Rightarrow \underline{\underline{C_0 = 1250}} \end{array}$$

ii) linear growth: $C = C_0 + kt$

$$\begin{cases} 3850 = C_0 + 3k \\ 36530 = C_0 + 9k \end{cases} \Rightarrow \begin{array}{l} \underline{\underline{k = 5446.7}} \\ \underline{\underline{C_0 = -12490}} \end{array}$$

C_0 becomes negative, so linear relationship is not reasonable.

iii) power-law growth: $C = kt^b \Rightarrow \ln C = \ln k + b \ln t$

$$\begin{cases} 8.2558 = \ln k + b \ln 3 \\ 10.5059 = \ln k + b \ln 9 \end{cases} \Rightarrow \begin{array}{l} \ln k = 6.0057 \\ b = 2.048 \end{array}$$

$\underline{\underline{k = 405.7}}$

C_0 cannot be determined, so power-law relationship is not reasonable.

(b) exponential growth: $C = C_0 e^{kt}$ (see calculations below in Part (a) to verify)

(c) At $t = 0$, using the exponential growth relationship, $C = kt^b \Rightarrow \ln C = \ln k + b \ln t$

$\underline{\underline{C = C_o = 1250}}$ -- Assumptions: Student response.

(d)

$C = 2 \text{ million cells } = 2 \times 10^{6} \text{ cells}$

$\ln C = \ln C_0 + kt$

$\ln(2 \times 10^{6}) = 7.131 + 0.375t$

$\Rightarrow t = 19.67 \text{ hr} \approx 20 \text{ hr}$

$\therefore \underline{\underline{4 \text{ am}}}$

In the future, you might plant to start the experiment at a more convenient time so that you

don't have to make late night trips to the lab.

2.35

(a) Since the bacteria catalyze the production reaction, we would like to have an abundant population as soon as possible, which means we want a high bacterial growth rate, *dC/dt*. For a given concentration, *C*, the growth rate is μC, so a $\underline{\underline{\text{high}}}$ value of μ is desirable.

(b) To integrate this expression, separate the variables (bring all functions of *C* to one side and all functions of *t* to the other), and then integrate each side from the initial condition ($t=0$, $C=C_o$):

$$\frac{dC}{dt}=\mu C \Rightarrow \frac{dC}{C}=\mu dt \Rightarrow \int_{C_o}^{C}\frac{dC}{C}=\mu\int_0^t dt \Rightarrow \underline{\underline{\ln C-\ln C_o=\mu t}}$$

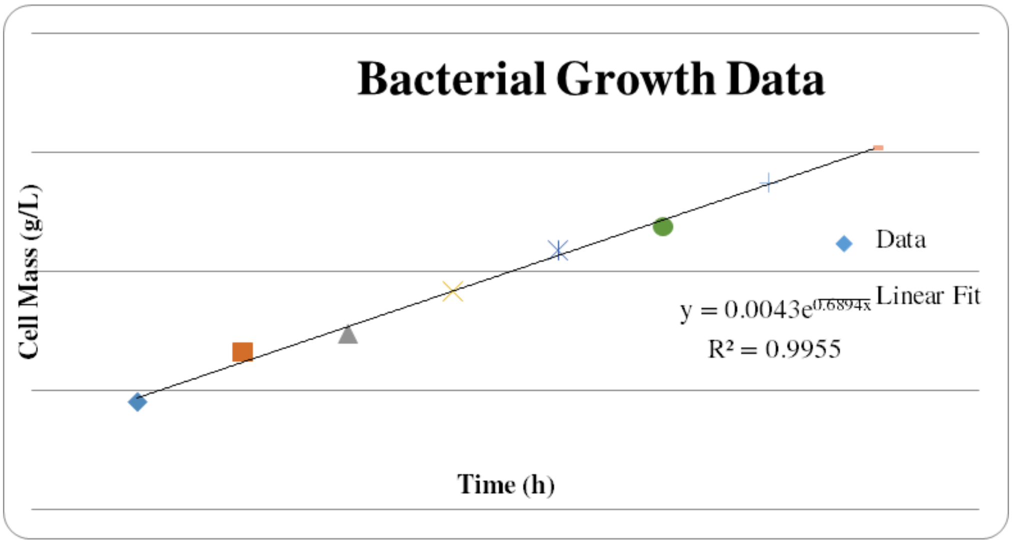
(Note: Since dC/C is dimensionless, $\mu(dt)$ must be as well, which means that μ must have units of inverse time. If t is in hours, then μ has units of h^{-1}.)

If the given expression is rewritten to $\ln C = \mu t + ln(C_o)$, it follows that

(ln *C*) vs. *t* on rectangular coordinates → straight line, slope μ, intercept $ln(C_o)$

C vs. *t* on semilog coordinates → straight line, slope μ, intercept C_o

(c) A semilog plot of the data in the table is shown below. The linearity of the plot indicates that balanced growth applies over the period of data collection.



From the slope of the plot, the specific growth rate is $\underline{\underline{\mu=0.689\ \mathrm{h}^{-1}}}$.

(d) To determine the doubling time, we can find the value of t for a value of $C = 2C_0$.

$$\ln C - \ln C_0 = \ln\frac{C}{C_0} = \mu t \xrightarrow[t=t_{1/2}]{C=2C_0} \ln 2 = \mu t_{1/2} \Rightarrow \underline{\underline{t_{1/2} = \frac{\ln 2}{\mu} = \frac{\ln 2}{0.689\ \mathrm{h}^{-1}} = 1.0\ \mathrm{h}}}$$

2.36 **(a)** This is a power law relationship: $y = a\,(x^b)$

(b) Express the equation as $\ln(y) = \ln(a) + b\,(\ln(x))$

$$\text{Slope } (=b) = \frac{\ln(C_{D2}) - \ln(C_{D1})}{\ln(C_{C2}) - \ln(C_{C1})} = \frac{\ln(2.27) - \ln(1.4)}{\ln(10) - \ln(2.8)} = 0.379$$

$\ln(2.95) = \ln(a) + 0.379 \ln(20)$

$\ln(a) = -0.054$

$a = 0.948$

$$C_D = 0.948 C_c^{0.379}$$

(c) When $C_D = 10$,

$$10 = 0.948\, C_C^{0.379}$$

Concentration of $C_C = 502.25$ mol/L

(d) Arguments for **not** stopping the reaction until $C_D = 13$ mol/L: More product C would be produced.

Arguments for **stopping** the reaction prior to $C_D = 13$ mol/L: Too close to the explosive limit of 15 mol/L, more hazardous product D to deal with.

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

(b)

$$p^*_{148.2} = 1+(100-1)\frac{148.2-98.5}{215.5-98.5} = \underline{\underline{43.05\ \text{mm Hg}}}$$

$$\left|\frac{10-43.05}{10}\right| \times 100 = \underline{\underline{330.5\%}}\ \underline{\underline{\text{error}}}$$

Student Response

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

OR

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

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

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

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

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

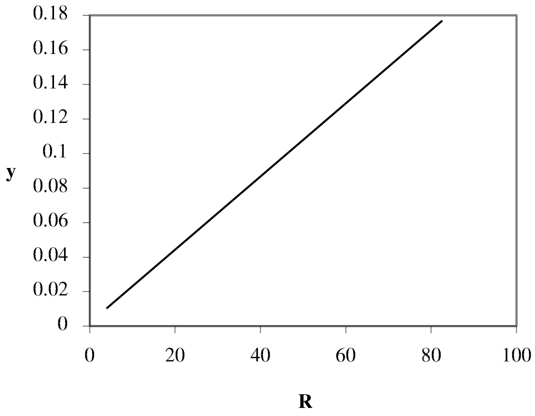
(f) $\log_{10}(xy) = a(x^2 + y^2) + b$

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

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

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

2.40 **(a)** A plot of y vs. R is a line through ($R = 5$, $y = 0.011$) and ($R = 80$, $y = 0.169$).

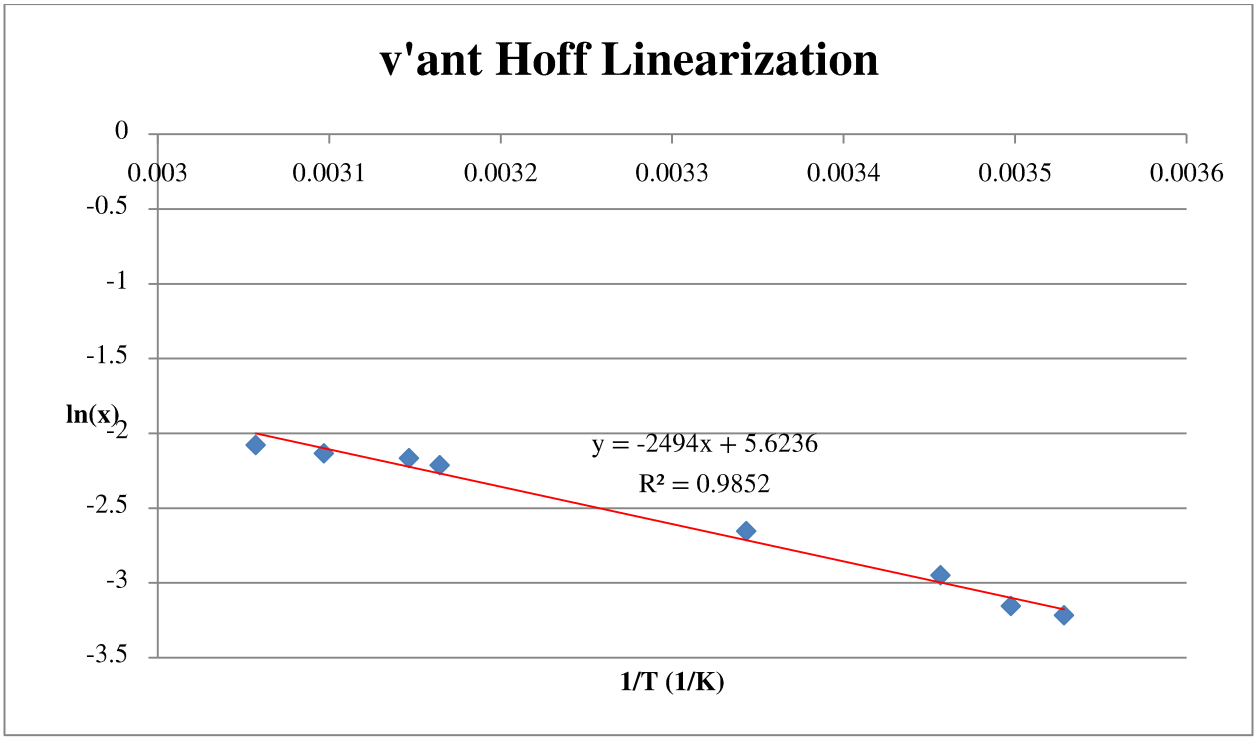


$$y = aR + b \qquad \left.\begin{array}{l} a = \dfrac{0.169 - 0.011}{80 - 5} = 2.11\times10^{-3} \\ b = 0.011 - \left(2.11\times10^{-3}\right)\left(5\right) = 4.50\times10^{-4} \end{array}\right\} \Rightarrow \underline{\underline{y = 2.11\times10^{-3}R + 4.50\times10^{-4}}}$$

(b) $R = 43 \Rightarrow y = \left(2.11\times10^{-3}\right)\left(43\right) + 4.50\times10^{-4} = 0.092 \text{ kg } H_2O/\text{kg}$

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

2.41



a = -2494 ˚K, *b* = 5.624 (unitless)

2.42 (a) $\ln T = \ln a + b\ln\phi \Rightarrow T = a\phi^{b}$

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

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

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

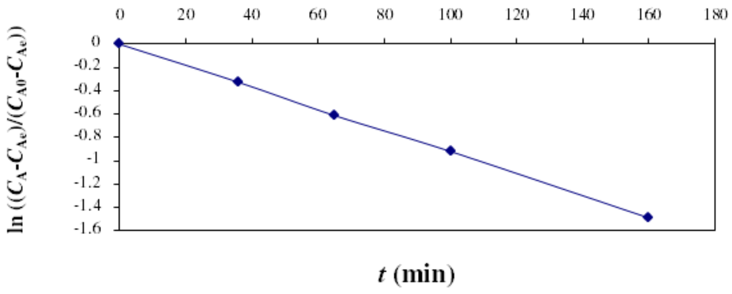
$$T = 85^{\circ}C \Rightarrow \phi = \left(9677.6/85\right)^{0.8403} = \underline{\underline{53.5\text{ L/s}}}$$

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

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

(c) The estimate for *T*=175°C is probably closest to the real value, because the value of temperature is in the range of the data originally taken to fit the line. The value of *T*=85°C is probably the least likely to be correct, because it is farthest away from the date range.

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



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

(b)

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

$$C_{\text{A}}(t=120\,\text{min}) = (0.1823-0.0495)e^{-(9.3\times10^{-3})(120)}+0.0495 = 9.300\times10^{-2}\ \text{g/L}$$

$$C_A(\text{t = 120 min}) = m/V \Rightarrow m_A = CV = \left(9.300\times10^{-2}\ \text{g/L}\right)\left(125\ \text{L}\right) = 11.625\ \text{g A}$$

$$m_{A0} = C_{A0}V = \left(0.1823\ \text{g/L}\right)\left(125\ \text{L}\right) = 22.787\ \text{g A}$$

This means that (22.787 - 11.625) = 11.16g of A have been consumed at t = 120 min. Since the reaction is 1:1, $\underline{\underline{\text{11.16 g B}}}$ have been generated.

(c) $$\ln\left(\frac{C_{\text{A}}-C_{\text{Ae}}}{C_{\text{A0}}-C_{\text{Ae}}}\right) = -kt \Rightarrow t = \frac{-1}{k}\ln\left(\frac{C_{\text{A}}-C_{\text{Ae}}}{C_{\text{A0}}-C_{\text{Ae}}}\right)$$

$$\rightarrow C_{\text{A}} = 1.1C_{\text{Ae}} = 1.1\left(0.0495\ \text{g/L}\right) = 0.05445\ \text{g/L}$$

$$t = \frac{-1}{0.0093\ \text{min}^{-1}}\ln\left(\frac{0.05445\ \text{g/L}-0.0495\ \text{g/L}}{0.1823\ \text{g/L}-0.0495\text{g/L}}\right) = 353.705\ \text{min} \Rightarrow \underline{\underline{354\ \text{min}}}$$

$$m_{\text{A}} = \left(0.05445\ \text{g/L}\right)\left(125\ \text{L}\right) = 6.80625\ \text{g A}$$

As in part (b), $m_{\text{B}} = 22.787-6.80625 = \underline{\underline{15.98\ \text{g B}}}$

$$\rightarrow C_{\text{A}} = 1.05C_{\text{Ae}} = 1.1\left(0.0495\ \text{g/L}\right) = 0.051975\ \text{g/L}$$

$$t = \frac{-1}{0.0093\ \text{min}^{-1}}\ln\left(\frac{0.051975\ \text{g/L}-0.0495\ \text{g/L}}{0.1823\ \text{g/L}-0.0495\text{g/L}}\right) = 428.237\ \text{min} \Rightarrow \underline{\underline{428\ \text{min}}}$$

$$m_{\text{A}} = \left(0.051975\ \text{g/L}\right)\left(125\ \text{L}\right) = 6.49875\ \text{g A}$$

$$m_{\text{B}} = 22.787-6.49875 = \underline{\underline{16.29\ \text{g B}}}$$

$$\rightarrow C_A = 1.01 C_{Ae} = 1.1\left(0.0495 \text{ g/L}\right) = 0.049995 \text{ g/L}$$

$$t = \frac{-1}{0.0093 \text{ min}^{-1}} \ln\left(\frac{0.049995 \text{ g/L} - 0.0495 \text{ g/L}}{0.1823 \text{ g/L} - 0.0495 \text{g/L}}\right) = 601.2948 \text{ min} \Rightarrow \underline{\underline{601 \text{ min}}}$$

$$m_A = \left(0.049995 \text{ g/L}\right)\left(125 \text{ L}\right) = 6.249375 \text{ g A}$$

$$m_B = 22.787 - 6.249375 = \underline{\underline{16.54 \text{ g B}}}$$

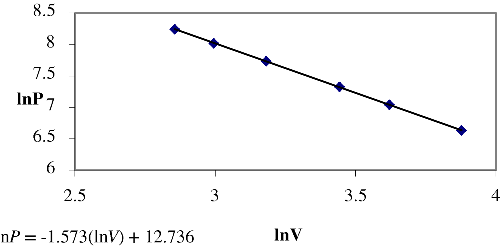
2.44 (a) ft^3 and h^{-2}, respectively

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

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

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

2.45 $PV^k = C \Rightarrow P = C/V^k \Rightarrow \ln P = \ln C - k \ln V$

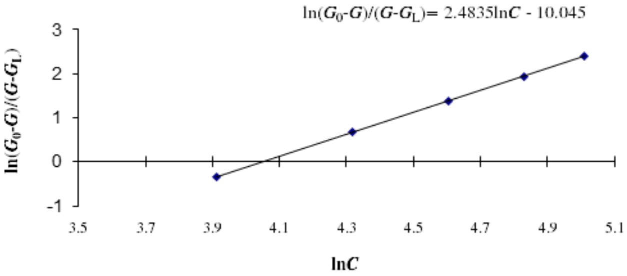


ln*P* = -1.573(ln*V*) + 12.736

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

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

2.46 (a) $\dfrac{G-G_{\mathrm{L}}}{G_0-G}=\dfrac{1}{K_{\mathrm{L}}C^m}\Rightarrow\dfrac{G_0-G}{G-G_{\mathrm{L}}}=K_{\mathrm{L}}C^m\Rightarrow\ln\dfrac{G_0-G}{G-G_{\mathrm{L}}}=\ln K_{\mathrm{L}}+m\ln C$



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

$\text{Intercept}=\ln K_{\mathrm{L}}=-10.045\Rightarrow K_{\mathrm{L}}=\underline{\underline{4.340\times10^{-5}\ \text{ppm}^{-2.483}}}$

(b) $C=475\Rightarrow\dfrac{G-1.80\times10^{-3}}{3.00\times10^{-3}-G}=4.340\times10^{-5}(475)^{2.483}\Rightarrow G=\underline{\underline{1.806\times10^{-3}}}$

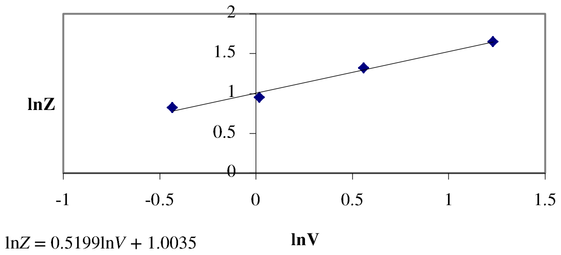
C=475 ppm is well beyond the range of the data.

2.47 **(a)** For runs 2, 3 and 4:

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

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

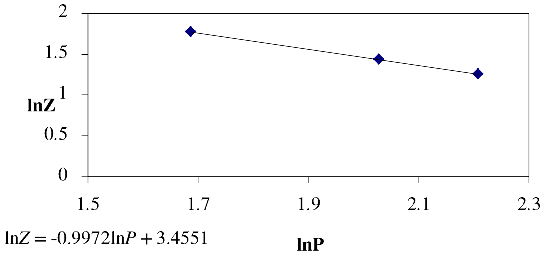
(b) When P is constant (runs 1 to 4), plot $\ln Z$ vs. $\ln\dot{V}$. Slope=b, Intercept= $\ln a + c\ln p$



$$b = \text{slope} = \underline{\underline{0.52}}$$

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

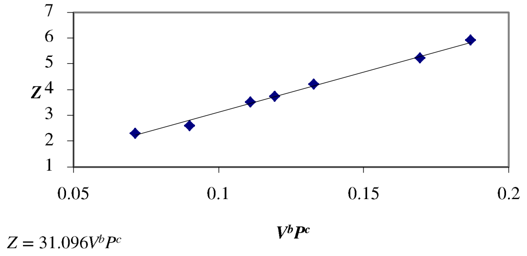
When $\dot{V}$ is constant (runs 5 to 7), plot ln$Z$ vs. ln$P$. Slope=c, Intercept= $\ln a + c\ln\dot{V}$



$$c = \text{slope} = -0.997 \Rightarrow \underline{\underline{1.0}}$$

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

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



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

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

2.48 (a)

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

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

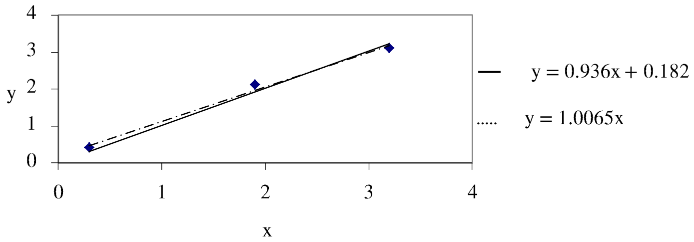
$$s_{\mathrm{x}} = \frac{1}{n}\sum_{i=1}^{n} x_{\mathrm{i}} = (0.3+1.9+3.2)/3 = 1.8; \quad s_{\mathrm{y}} = \frac{1}{n}\sum_{i=1}^{n} y_{\mathrm{i}} = (0.4+2.1+3.1)/3 = 1.867$$

$$a = \frac{s_{\mathrm{xy}} - s_{\mathrm{x}} s_{\mathrm{y}}}{s_{\mathrm{xx}} - \left(s_{\mathrm{x}}\right)^2} = \frac{4.677-(1.8)(1.867)}{4.647-(1.8)^2} = 0.936$$

$$b = \frac{s_{\mathrm{xx}} s_{\mathrm{y}} - s_{\mathrm{xy}} s_{\mathrm{x}}}{s_{\mathrm{xx}} - \left(s_{\mathrm{x}}\right)^2} = \frac{(4.647)(1.867)-(4.677)(1.8)}{4.647-(1.8)^2} = 0.182$$

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

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



2.49 (a)

$<t> =$	5.0
$<T> =$	32.9
$<t^2> =$	36.667
$<t>^2 =$	25
$<t*T> =$	182.933

$$T = mt + b$$

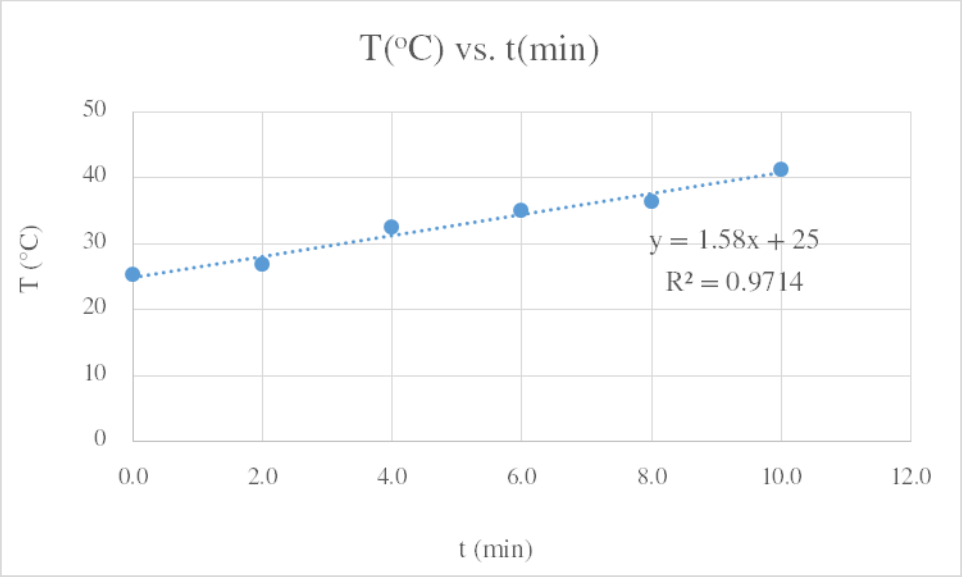
$$m = \frac{<tT> - <t><T>}{<t^2> - <t>^2} = 1.56$$

$$b = <T> - m<t> = 25$$

$$\Rightarrow \underline{\underline{T = 1.56t + 25}}$$

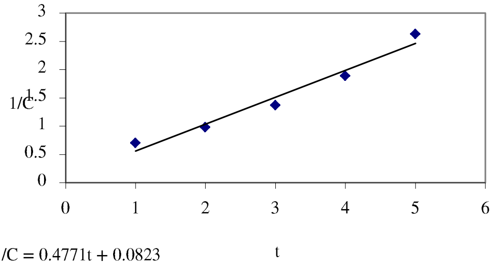
Convert it to a formula for $t(T)$: $t = \dfrac{T-25}{1.56} = \underline{\underline{0.641T - 16.03}}$

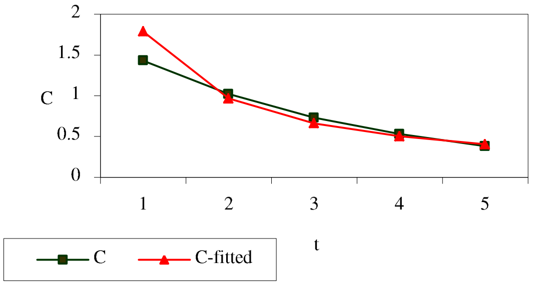
(b)



2.50 (a) 1/C vs. t Slope = b, intercept = a

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





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

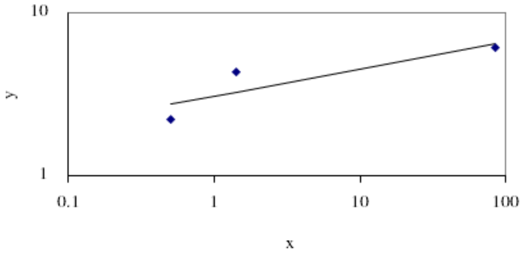
$$t = (1/C - a)/b = (1/0.01 - 0.082)/0.477 = 209.5\ \text{h}$$

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

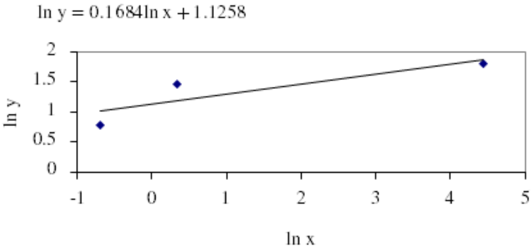
(e) The concentration of the hazardous substance could be enough to cause damage to the biotic resources in the river; the treatment requires an extremely large period of time; some of the hazardous substances might remain in the tank instead of being converted; the decomposition products might not be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

(f) Student Response

2.51 (a) and (c)



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

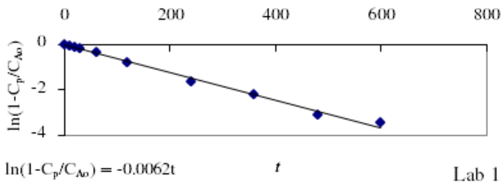


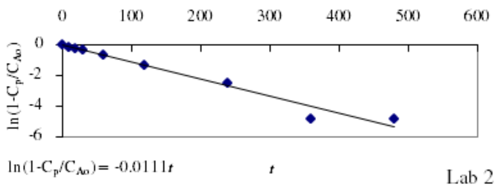
$b = \text{slope} = \underline{\underline{0.168}}$

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

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

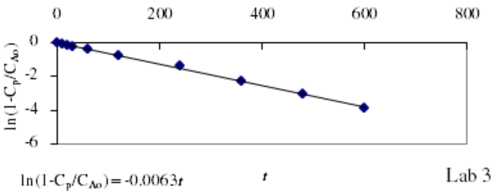
(b)

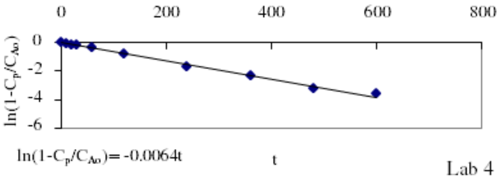




$k = \underline{\underline{0.0062\ \text{s}^{-1}}}$

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





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

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

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

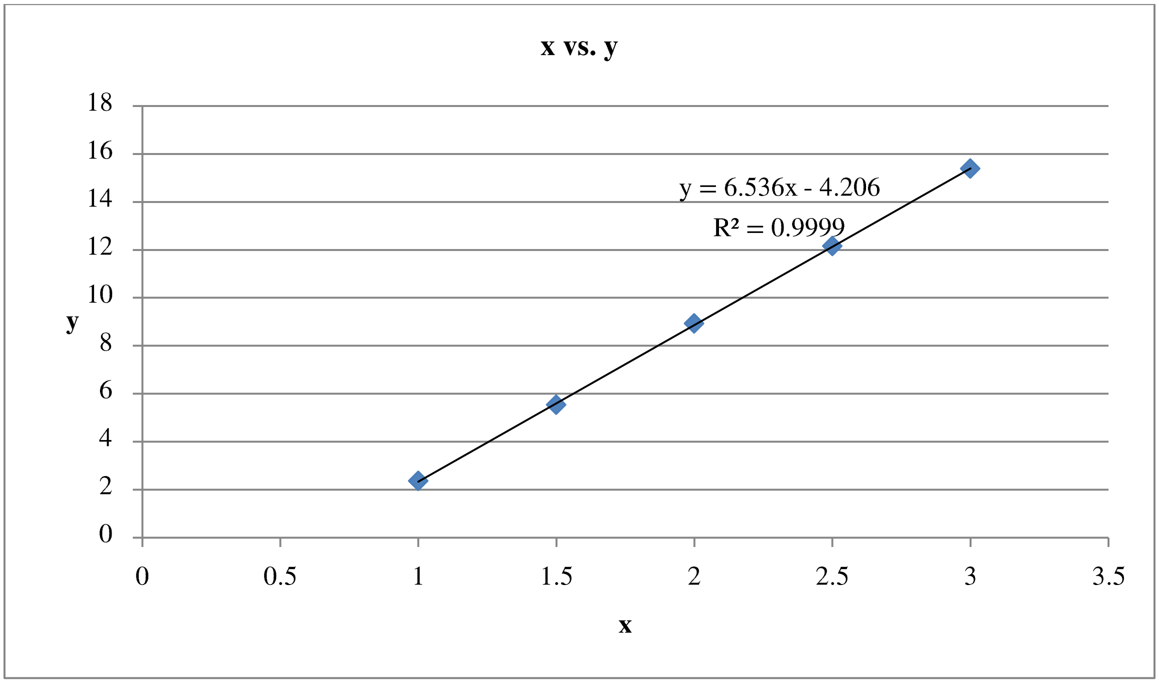
(d) Errors in measurement of concentration, poor temperature control, errors in time measurements, delays in taking the samples, impure reactants, impurities acting as catalysts, inadequate mixing, poor sample handling, clerical errors in the reports, dirty reactor.

2.53

$$y_{\mathrm{i}} = ax_{\mathrm{i}} \Rightarrow \phi(a) = \sum_{i=1}^{n} d_{\mathrm{i}}^{2} = \sum_{i=1}^{n}\left(y_{\mathrm{i}} - ax_{\mathrm{i}}\right)^{2} \Rightarrow \frac{d\phi}{da} = 0 = \sum_{i=1}^{n} 2\left(y_{\mathrm{i}} - ax_{\mathrm{i}}\right)x_{\mathrm{i}} \Rightarrow \sum_{i=1}^{n} y_{\mathrm{i}}x_{\mathrm{i}} - a\sum_{i=1}^{n} x_{\mathrm{i}}^{2} = 0$$

$$\Rightarrow \underline{\underline{a = \sum_{i=1}^{n} y_{\mathrm{i}}x_{\mathrm{i}} \Big/ \sum_{i=1}^{n} x_{\mathrm{i}}^{2}}}$$

2.54



x	y	y=ax+b (Excel)	Deviation	Absolute Deviation
1	2.35	2.33	0.02	0.02
1.5	5.53	5.598	-0.068	0.068
2	8.92	8.866	0.054	0.054
2.5	12.15	12.134	0.016	0.016
3	15.38	15.402	-0.022	0.022

The average deviation is 0.036, which indicates a good fit (consistent with the $R^2 = 0.999$). The linear parameters are obtained from Excel: $a = 6.536 \quad b = -4.206$

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

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

(c)

T(K)	D(cm2/s)		1/T	ln D
347.0	1.34E-06		0.0028818	-13.52284
374.2	2.50E-06		0.0026724	-12.89922
396.2	4.55E-06		0.002524	-12.30038
420.7	8.52E-06		0.002377	-11.67309
447.7	1.407E-05		0.0022336	-11.17147
471.2	1.999E-05		0.0021222	-10.82028

Use points (0.02882, -13.523) and (0.002672, -12.899)

$$\begin{cases} -13.523 = 0.002882a + b \\ -12.899 = 0.002672a + b \end{cases}$$

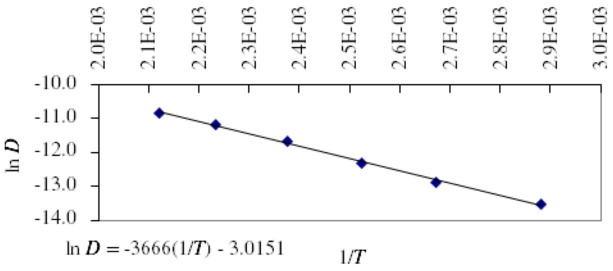
solve these equations for a and b

$$a = -2971.43 = -\frac{E}{R} \Rightarrow E = (2971.43\text{ K})(1.987\text{ cal/mol}\cdot\text{K}) = \underline{\underline{5904\text{ cal/mol}}}$$

$$b = -4.959 = \ln D_0 \Rightarrow D_0 = \exp(-4.959) = \underline{\underline{0.00702\text{ cm}^2/\text{s}}}$$

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

(d) Using a spreadsheet:



$$\ln D_0 = -3.0151$$

$$D_0 = \exp(-3.0151) = \underline{\underline{0.0490\ \text{cm}^2/\text{s}}}$$

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

CASE STUDY 1

Production of Formaldehyde*

World formaldehyde production is estimated to be about 8 million metric tons per year, most of which is eventually used in the manufacture of rigid plastic objects such as telephones and dishes. Formaldehyde is also used as a raw material in the production of slow-release nitrogen fertilizers, dyes, cosmetics, and explosives. The principal method of producing formaldehyde is the reaction of methanol on a stationary silver or iron–molybdenum oxide catalyst in a fixed-bed reactor. Two reactions occur in series in the production process:

$$CH_3OH \rightarrow HCHO + H_2 \qquad \textbf{(CS 1.1)}$$

$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O \qquad \textbf{(CS 1.2)}$$

If all of the hydrogen formed in Reaction CS 1.1 is consumed in Reaction CS 1.2, the overall stoichiometry is

$$CH_3OH + \tfrac{1}{2}\,O_2 \rightarrow HCHO + H_2O \qquad \textbf{(CS 1.3)}$$

PROCESS DESCRIPTION

Fresh and recycled methanol are mixed and fed to a vaporizer operating at a pressure of 1 atm. Ambient air is drawn into a blower, which increases its pressure to 76 cm of H_2O; the air is then bubbled into the vaporizer through a sparger and leaves the vaporizer saturated with methanol. The methanol–air mixture is then heated to 145°C.

Saturated steam at 4.1 bars is metered into the air–methanol stream, and the combined stream then flows to the reactor. Feed rates of air and steam are determined from specified ratios of air to methanol and steam to methanol. A primary consideration in the specification of the methanol-to-air ratio is that a mixture containing between 6.7 and 36.5 vol% methanol in air at 1 atm constitutes a severe explosion hazard.

After entering the reactor, the feed gas passes through the catalyst bed. The bed consists of pure silver crystals, 0.5 to 3 mm in diameter, packed to a depth of about 3 cm, and supported on a stainless-steel wire mesh. The ratio of steam to methanol is fixed so that the outlet temperature is 600°C. The reactor may be considered adiabatic.

Gases leaving the reactor are fed directly to a waste-heat boiler, where they are cooled to 145°C. Saturated steam at 3.1 bars is generated in the boiler from saturated liquid water at 3.1 bars. The gases are cooled further to slightly above their dew point (100°C) and fed to an absorption column, where methanol and formaldehyde are absorbed in water. Pure water at 30°C is fed to the top of the column. The gases that leave the absorber contain 200 parts of formaldehyde per million parts (by volume) of total off-gas. Liquid streams are removed from the column at two locations, cooled in heat exchangers, and recycled to entry points higher in the column.

The aqueous solution leaving the bottom of the absorber is fed to a distillation column. The final product solution is removed from the reboiler at the bottom of the distillation column while pure methanol is removed at the top of the column and condensed. A portion of the condensate

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* This case study was developed for the first edition of the text with the assistance of the late James R. Fair, then of the Monsanto Company and subsequently the University of Texas at Austin.

(the reflux) is fed back into the top of the column, and the rest is recycled to the reactor. The distillation column, reboiler, and condenser operate at approximately 1 atm.

A plant is to be constructed to produce 3.6×10^4 metric tons per year of formaldehyde solution. From experience with other plants, there will be about 350 operating days per calendar year. The product solution has an analytical specification of 37 wt% formaldehyde, 1 wt% methanol, and the remainder water. The methanol-to-air ratio in the feed stream to the reactor will be 42:58 (molar basis). Data from other plants indicate that the specified process conditions should yield a conversion of 70 percent of the methanol entering the reactor, and that the effluent from the reactor will be 5 vol% hydrogen. The off-gas from the absorber will be at 27°C and saturated with water, and the liquid stream leaving the absorber will be at 88°C. Process cooling water is available at 30°C. To reduce scaling on the heat exchange tubes, temperature increases of cooling water are limited to 15°C. The ratio of the overhead returned to the column to that recycled to the reactor (the reflux ratio) is 2.5. Ambient conditions may be assumed to be 27°C and 1 atm.

PHYSICAL PROPERTY DATA

The specific gravity and heat capacity of the product solution are 1.11 and 0.8 cal/g·°C, respectively. The heat of solution of formaldehyde gas at 25°C in water or aqueous alcohol solutions is −15 kcal/mol HCHO(g).

Phase equilibrium data for the methanol–water–formaldehyde system are shown in Figures CS 1.1 and CS 1.2. The triangular coordinates on the two figures give liquid-phase weight percentages of the three components. The curved coordinates of Figure CS 1.1 give the equilibrium vapor-phase compositions at 1 atm, and the curved coordinates of CS 1.2 give the corresponding equilibrium temperatures. For example, a liquid mixture consisting of 50 wt% CH_3OH, 30% H_2O, and 20% HCHO is in equilibrium at 1 atm with a vapor containing 18 vol% H_2O, 8% HCHO, and 74% CH_3OH at a temperature of 80°C.

As part of an economic evaluation of this process, you have been asked to answer the following questions.

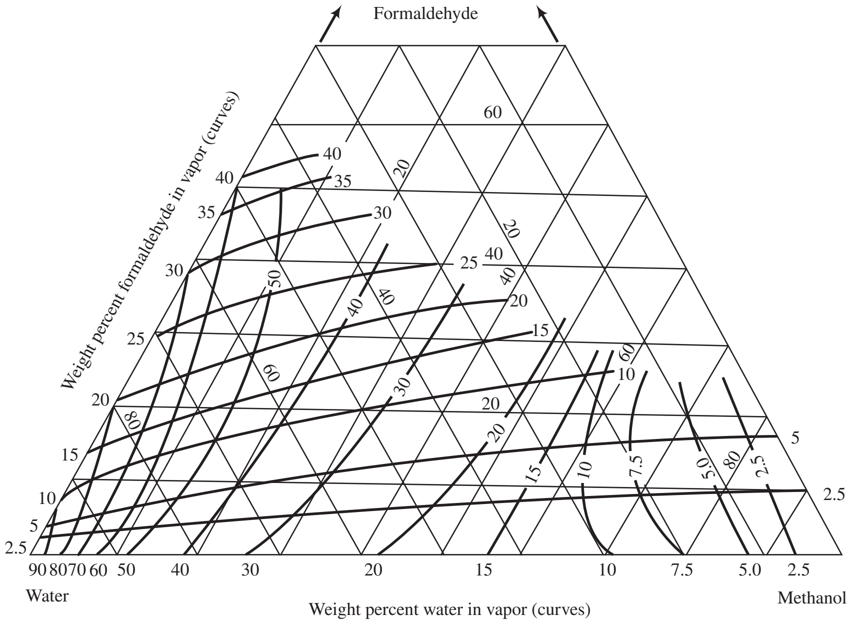


FIGURE CS 1.1 Vapor–liquid equilibria of methanol–water–formaldehyde system at 1 atm. Triangular coordinates are weight percentages in the liquid phase, and the curves are weight percentages in the vapor phase. Reprinted with permission from S. J. Green and R. E. Vener, *Ind. Eng. Chem.*, **47**, 103 (1955). © American Chemical Society.

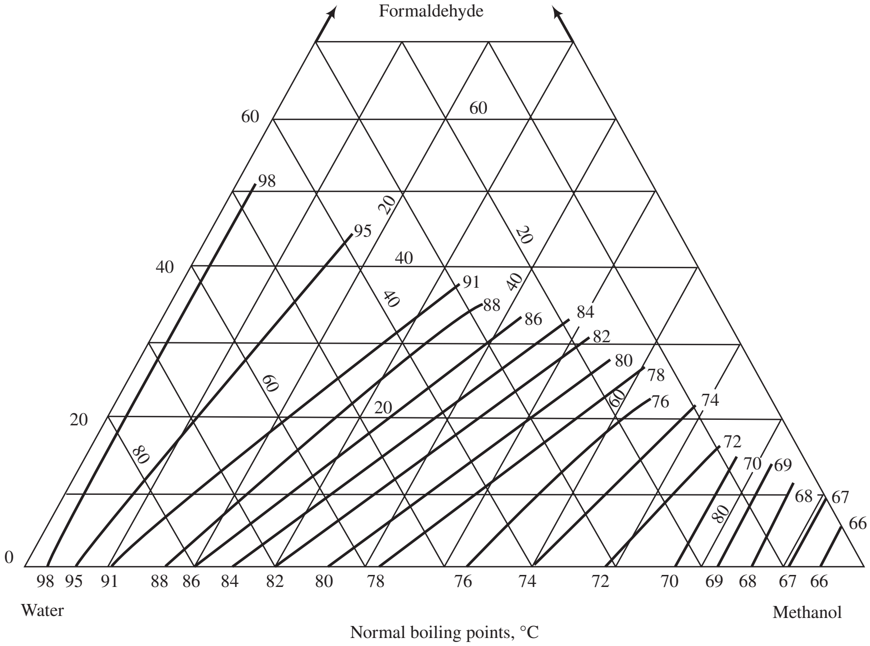


FIGURE CS 1.2 Normal boiling points of methanol–water–formaldehyde system. Triangular coordinates are weight percentages in the liquid phase. Reprinted with permission from S. J. Green and R. E. Vener, *Ind. Eng. Chem.*, **47**, 103 (1955). © American Chemical Society.

PROBLEMS

CS 1.1. What is the world production rate of formaldehyde in kg/h?

CS 1.2. Construct a detailed flowchart showing known compositions, flow rates, and temperatures. Use this chart to keep track of your calculations and as a basis for a final flowchart to be prepared when you have finished the case study.

CS 1.3. Determine the feed rate of methanol to the process (kg/h), neglecting trace amounts of formaldehyde and methanol in the off-gas stream from the absorber.

CS 1.4. What is the percentage conversion of methanol for the process?

CS 1.5. At what rate is methanol recycled to the reactor?

CS 1.6. Does the specified air flow rate produce a gas mixture with a composition outside the explosion limits?

CS 1.7. What is the flow rate of air to the reactor in (a) kmol/h and (b) standard cubic meters/min?

CS 1.8. At what temperature should the vaporizer operate?

CS 1.9. Because of its high solubility, essentially no methanol leaves the absorber in the off-gas stream. Determine the flow rates of water and formaldehyde in this stream.

CS 1.10. What is the feed rate of water to the absorber? By increasing the water flow, the size of the absorber could be decreased. Why, then, is it desirable to limit the water flow rate to this amount? (*Hint:* Consider the ultimate fate of the water fed to the absorber.)

CS 1.11. If the liquid leaving the column were saturated, could it be made to absorb any more methanol and formaldehyde without first being cooled? Explain.

CS 1.12. The liquid and vapor streams leaving the reboiler are in equilibrium. What is the temperature of each stream and the composition of the vapor stream?

CS 1.13. Is it possible to determine directly from the presented equilibrium data the dew point of the gas leaving the reactor? Compare the dew-point temperature of this gas as calculated from Raoult's law with the observed value of ≈ 100°C. Does the solution behavior follow Raoult's law? Explain.

CS 1.14. Examine the process flowchart and description carefully and itemize the utility consumption units (those that require steam, cooling water, and electricity).

CS 1.15. Determine the minimum energy requirement of the blower in horsepower. How does your answer change if the blower is 40% efficient? (See note at the end of the list of questions.)

CS 1.16. What is the purpose of the waste-heat boiler? Give reasons why, in practice, the reactor and waste-heat boiler are combined in one unit.

CS 1.17. What are the standard heats of Reactions CS 1.1, CS 1.2, and CS 1.3?

CS 1.18. What is the rate at which steam is fed to the reactor? Determine the temperature of the reactor effluent stream if no steam were fed to the process. What role is played by the steam fed to the reactor?

CS 1.19. What fraction of the hydrogen produced by Reaction CS 1.1 is consumed in Reaction CS 1.2? Would more or less steam be required if Reaction CS 1.2 proceeded to completion? Explain. What would be the required process changes if Reaction CS 1.2 were suppressed completely?

CS 1.20. At what rate is steam generated in the waste-heat boiler?

CS 1.21. Recognizing that increased residence time in a reactor usually means a higher conversion, why might the length of the reactor be only 3 cm? (*Hint:* Consider the possibility of unwanted side reactions.) What problems in heat transfer are presented by such a small reactor?

CS 1.22. Assuming ambient air and stored methanol to be at 25°C, how much heat must be supplied to the vaporizer? Assuming that a portion of the steam generated in the waste-heat boiler could be used for this purpose, estimate the required flow rate.

CS 1.23. What is the required flow rate of cooling water to the exchanger between the waste-heat boiler and the absorber?

CS 1.24. How much heat must be removed by the two heat exchangers cooling the recycled absorber liquid? Why is there a need to remove this heat?

CS 1.25. The liquid entering the reboiler, the vapor entering the condenser, the liquid leaving the condenser, and the vapor and liquid from the reboiler may be considered saturated. How much heat must be added to the distillation column through the reboiler?

CS 1.26. Can the available cooling water be used to condense the overhead stream from the distillation column? Explain.

Additional Problems for Study

CS 1.27. Estimate the total cost of raw materials and compare these with the current selling price of 37% formaldehyde solution. A currently available rough guide to the cost of chemicals is at the website http://www.icis.com/chemicals/channel-info-chemicals-a-z/.

CS 1.28. Establish the source of commercial methanol. A useful reference is the *Kirk-Othmer Encyclopedia of Chemical Technology*.

CS 1.29. Estimate the cost of utilities required to operate the process.

CS 1.30. Suggest alternative arrangements for connecting energy-consuming operations with energy-producing operations, with the objective of reducing the cost of operating the plant.

Note on Problem CS 1.15. The solution to this problem requires thermodynamics beyond the scope of this text. To calculate the minimum energy requirement, assume that the compression is adiabatic and reversible, and that $C_p/C_v = 1.4$.

CS 1-6

~~CHAPTER 12 – FIRST EDITION~~

CS 1.1

~~12~~.1

<EQ>

$$\left(8\times10^{6}\ \frac{\text{met t}}{\text{yr}}\right)\left(\frac{1\ \text{kg}}{0.001\ \text{met t}}\right)\left(\frac{1\ \text{yr}}{365\ \text{d}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right) = \boxed{9.13\times10^{5}\ \frac{\text{kg}}{\text{h}}}$$

CS 1.2

See p. ~~I-12.25~~ CS 1-25

~~12~~.3

$$P = \left(36\times10^{3}\ \frac{\text{met t}}{\text{yr}}\right)\left(\frac{1\ \text{yr}}{350\ \text{d}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right) = 4.286\ \frac{\text{met t}}{\text{h}} \Rightarrow 4286\ \frac{\text{kg}}{\text{h}}$$

formaldehyde in $P = 0.37P = 1585.8$ kg/hr $\Rightarrow 52.9\ \frac{\text{kmol}}{\text{h}}$

methanol in $P = 0.01\,P = 42.9$ kg/hr $\Rightarrow 1.3\ \frac{\text{kmol}}{\text{h}}$

F_M = methanol feed rate $= (52.9 + 1.3)\ \frac{\text{kmol}}{\text{h}} = 54.2\ \frac{\text{kmol}}{\text{h}}$

$$\Rightarrow \boxed{1734.4\ \frac{\text{kg}}{\text{h}}}$$

~~12~~.4

$$\%\ \text{conversion} = \frac{(54.2 - 1.3)}{54.2}\times 100\% = \boxed{97.6\ \%}$$

~~12~~.5

F_{MR} = methanol feed rate to reactor

$$0.7\,F_{MR} = 52.9\ \frac{\text{kmol}}{\text{h}}$$

$$F_{MR} = 75.6\ \frac{\text{kmol}}{\text{h}}$$

R_M = methanol recycle rate

$$F_M + R_M = F_{MR} \Rightarrow R_M = \boxed{21.4\ \frac{\text{kmol}}{\text{h}}} = 685\ \frac{\text{kg}}{\text{h}}$$

~~12~~.6

$$\frac{42\ \text{kmol}\ \ CH_3OH}{58\ \text{kmol}\ \ \text{air}} \Rightarrow \boxed{42\ \text{mole}\ \%\ CH_3OH} \Rightarrow 42\ \text{vol}\ \%\ CH_3OH$$

∴ outside explosion limits

~~I-12.6~~

12.7

F_A = air feed rate

~~(a)~~

$$\frac{F_{m_R}}{F_A} = \frac{42 \text{ kmol } CH_3OH}{58 \text{ kmol air}} \Rightarrow \boxed{F_A = 104.4 \frac{\text{kmol air}}{\text{h}}}$$

~~(b)~~

$$V_A = F_A RT/P \quad \frac{(104.4 \frac{\text{kmol}}{\text{h}})(0.082 \frac{\text{m}^3\,\text{atm}}{\text{kmol}\cdot\text{K}})(273\text{ K})}{} = 2337 \text{ m}^3/\text{hr}$$

/ a &

or

$$V_A = \boxed{38.95 \text{ m}^3/\text{min}}$$

12.8

$$\frac{F_{m_R}}{F_A} = \frac{p_m}{p_A} \Rightarrow p_m = 0.42\,P = (0.42)(760 \overset{\#}{|} \text{mm} \overset{\#}{|} \text{Hg}) = 319.5 \overset{\#}{|} \text{mm} \overset{\#}{|} \text{Hg}$$

Since gas from vaporizer is saturated $p_m = p_m^*$

$\Downarrow$ Table 6.1-1, p. 235 of text

$$\log p_m^* = 7.87863 - \frac{1473.11}{T + 230} = 2.504$$

$$\Downarrow$$

$$T = \boxed{44.1°C}$$

12.9

Absorber exit gas saturated with H_2O

$$\Downarrow$$

$$p_{H_2O} = p^*_{H_2O} = 0.5069 \text{ lbf/in}^2$$

$$\Downarrow$$

$$y_{H_2O} = 0.5069/14.7 = 0.0345$$

By specification, $y_{HCHO} = 0.0002$ (200 ppm by vol.)

Mole fraction noncondensibles $= y_{NC} = 1 - y_{H_2O} - y_{HCHO} = 0.9653$

E_A = exit gas flow rate $= F_{NC}/y_{NC}$

(continued)

~~12~~.9 (cont'd)

F_{NC} cannot be determined until after the amount of O_2 consumed and H_2 produced in the reactor have been determined in (18). **Solution** (see p 495): $\boxed{\begin{array}{l} 3.52 \text{ kmol } H_2O/h \\ 0.0204 \text{ kmol HCHO}/h \end{array}}$

~~12~~.10

F_W = water feed rate to absorber

water balance around absorber:

$$F_W + \left(\begin{array}{c} H_2O \text{ in} \\ \text{product gas} \end{array}\right) = \left(\begin{array}{c} \text{water in} \\ \text{off-gas} \end{array}\right) + \left(\begin{array}{c} H_2O \text{ in} \\ \text{product sol'n} \end{array}\right)$$

H_2O in product gas and off-gas cannot be determined until after a complete material balance around reactor has been completed. (Problem 18.) CS 1.18?

Solution (see p. 495): $\boxed{53.0 \text{ kmol } H_2O/h}$

~~12~~.11

Since the exit liquid is saturated, it will not absorb more CH_3OH and/or HCOH without a lowering of solution temperature and/or an increase in system pressure.

~~12~~.12

Liquid Stream (wt%) $\xrightarrow{\text{Fig.12-1}}$ Vapor Stream (wt%)

	Liquid Stream (wt%)	Vapor Stream (wt%)
HCHO	37	33
CH_3OH	1	2
H_2O	62	65

CS 1.2

$\Downarrow$ Fig. ~~12-2~~

Equilibrium temperature = $\boxed{98°C}$

~~12~~.13

(a) $\boxed{\text{No.}}$ These data can be used for systems that contain HCHO, H_2O, and CH_3OH only.

(b) Must know composition of product gas from reactor. This calculation will have to wait until the composition is determined. [Solution (see p. 496): $\boxed{T_{dp} = 76°C}$]

(c) Same as (b). [Solution: Raoult's law is invalid.]

~~1~~2.14

Utility Consumption Units

Steam:

(a) to heat methanol/air mixture
(b) to heat liquid from absorber
(c) to operate reboiler

Water:

(a) to cool gases from reactor
(b) to cool absorber recycle streams
(c) to operate distillate condenser

~~Electricity~~ (major units):

(a) blower
(b) methanol and water feed pumps
(c) pumps for absorber recycle streams
(d) methanol recycle pump

~~12~~.15

a. $$\frac{\Delta P}{\rho} + \frac{g}{g_c}\Delta z + \frac{\Delta \bar{V}^2}{2g_c} + F = \frac{W_s}{m}$$ (Eq. 7.7-2 p. 318 of text)

$\Delta z = 0$

$h = 76 \text{ cm } H_2O \Rightarrow \Delta P = \rho_f \frac{g}{g_c} h = (1000 \frac{kg}{m^3})(\frac{9.81 \text{ N}}{kg})(0.76 \text{ m})$

$= 7456 \text{ N/m}^2$

$m = (104.4 \text{ kg-moles/hr})(29.0 \text{ kg/kg-mole}) = 3028 \text{ kg air/hr}$

(continued)

~~12~~.15 (cont'd)

$$\rho = \frac{(14.7\ \text{lb}_f/\text{in}^2)(29\ \text{lb}_m/\text{lb-mole})}{\left(10.73\ \frac{\text{lb}_f/\text{in}^2\ \text{ft}^3}{\text{lb}_m\text{mole}\ {}^\circ\text{R}}\right)(540\,{}^\circ\text{R})} = 0.0736\ \text{lb}_m/\text{ft}^3$$

$$\frac{\Delta P}{\rho} = \frac{156\ \text{lb}_f/\text{ft}^2}{0.0736\ \text{lb}_m/\text{ft}^3} = 2120\ \frac{\text{ft}\cdot\text{lb}_f}{\text{lb}_m}$$

$$\Delta \bar{v}^2 \approx 0 \qquad (\text{small } \Delta P)$$

$$W_s = \frac{\Delta P}{\rho} = \left(2120\ \frac{\text{ft}\cdot\text{lb}_f}{\text{lb}_m}\right)\left(104.4\ \frac{\text{kmol}}{\text{h}}\right)\left(\frac{1\ \text{lb-mole}}{0.454\ \text{kmol}}\right)\left(\frac{29\ \text{lb}_m}{\text{lb-mole}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right)\left(\frac{1\ \text{hp}}{550\ \frac{\text{ft}\cdot\text{lb}_f}{\text{s}}}\right) = 7.1\ \text{hp}$$

$$W_p = W_s/0.4 = \boxed{17.9\ \text{hp}}$$

~~12~~.16

a. Recover thermal energy released by chemical reaction.

b. Reduce equipment costs, better temperature control, length of catalyst bed makes separate reactor impractical.

~~12~~.17

a. $CH_3OH \longrightarrow HCHO + H_2$

$$\Delta H^\circ_{rxn} = \Sigma(\nu_i \Delta H^\circ_f)_{prod} - \Sigma(\nu_i \Delta H^\circ_f)_{reac}$$

$$(\Delta H^\circ_f)_{H_2} = 0$$

$$(\Delta H^\circ_f)_{HCHO} = -115.90\ \text{kJ/mol}$$

$$(\Delta H^\circ_f)_{CH_3OH} = -201.2\ \text{kJ/mol}$$

$$\boxed{\Delta H^\circ_{rxn} = 85.3\ \text{kJ/mol}}$$

(continued)

2.17 (cont'd)

b. $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

$$\Delta H^{\circ}_{rxn} = (\Delta H^{\circ}_f)_{H_2O} = \boxed{-241.83\ kJ/mol}$$

c.

$$CH_3OH + \frac{1}{2}O_2 \rightarrow HCHO + H_2O$$

$$\Delta H^{\circ}_{rxn} = (-115.90 - 241.83 + 201.2)\ kJ/mol \quad \boxed{-156.53\ \frac{kJ}{mol}}$$

2.18

a. x = kmol/h of H_2 reacting by 12-2

Component	Reactor Feed ($\frac{kmol}{h}$)	Reactor Product ($\frac{kmol}{h}$)
$HCHO$	0	52.9
CH_3OH	75.6	$75.6 - 52.9 =$ 22.7
N_2	$(0.79)(104.4) =$ 82.5	82.5
O_2	21.9	$21.9 - 0.5x$
H_2	0	$52.9 - x$
H_2O	F_S	$F_S + x$
total	$F_S + 180.0$	$232.9 + F_S - 0.5x$

from given data $\quad \dfrac{52.9 - x}{232.9 + F_S - 0.5x} = 0.05$

Energy balance around reactor is required to give second equation relating F_S and x.

For the reactor, energy balance reduces to

$$\Delta H = Q = 0 \quad \text{(reactor is adiabatic)}$$

ΔH will be evaluated from the following hypothetical process:

(continued)

~~12~~.18 (cont'd)

$$\begin{tikzcd}
\text{Reactants } 145°\text{C} \arrow[d, "\Delta H_1"] & & \text{Products } 600°\text{C} \\
\text{Reactants } 25°\text{C} \arrow[rr, "\Delta H_2 \text{ (rxn 12-1)}", "\Delta H_3 \text{ (rxn 12-2)}"'] & & \text{Products } 25°\text{C} \arrow[u, "\Delta H_4"']
\end{tikzcd}$$

$$\Delta H = \Delta H_1 + \Delta H_2 + \Delta H_3 + \Delta H_4$$

Heat capacity data (J/mol·°C) − T in °C

HCHO: $C_p = 34.28 + 4.268\times10^{-2}T - 8.694\times10^{-9}T^3$

CH_3OH: $C_p = 42.93 + 8.301\times10^{-2}T - 1.87\times10^{-5}T^2 - 8.03\times10^{-9}T^3$

N_2: $C_p = 29.00 + 0.2199\times10^{-2}T + 0.5723\times10^{-5}T^2 - 2.871\times10^{-9}T^3$

O_2: $C_p = 29.10 + 1.158\times10^{-2}T - 0.6076\times10^{-5}T^2 + 1.311\times10^{-9}T^3$

H_2: $C_p = 28.84 + 0.00765\times10^{-2}T + 0.3288\times10^{-5}T^2 - 0.8698\times10^{-9}T^3$

H_2O: $C_p = 33.46 + 0.6880\times10^{-2}T + 0.7604\times10^{-5}T^2 - 3.593\times10^{-9}T^3$

$$\hat{H} = aT + b\frac{T^2}{2} + c\frac{T^3}{3} + d\frac{T^4}{4}$$

Component	25°C	145°C	600°C
	$\hat{H}$ (J/mol) ×10^{-3}		
HCHO	0.870	5.418	27.967
CH_3OH	1.099	7.078	39.093
N_2	0.726	4.234	18.115
O_2	0.731	4.335	19.149
H_2	0.721	4.186	17.526
H_2O	0.839	4.931	21.745

(continued)

CS 1-13

12.18 (cont'd)

~~I-12.13~~

<LH>

Component	Reactor Feed (kmol/h)	$\Delta\hat{H}_{1,i}$	$\Delta H_{1,i}$ (kJ/h)	Reactor Product (kmol/h)	$\Delta\hat{H}_{4,i}$	$\Delta H_{4,i}$ (kJ/h)
$HCHO$	0	-4.548×10^3	0	52.9	2.710×10^4	1.433×10^6
CH_3OH	75.6	-5.979×10^3	-4.520×10^5	22.7	3.799×10^4	8.625×10^5
N_2	82.5	-3.508×10^3	-2.894×10^5	82.5	1.739×10^4	1.435×10^6
O_2	21.9	-3.604×10^3	-0.789×10^5	$21.9-0.5\chi$	1.842×10^4	$4.034\times10^5-0.921\times10^4\chi$
H_2	0	-3.465×10^3	0	$52.9-\chi$	1.681×10^4	$8.889\times10^5-1.681\times10^4\chi$
H_2O	F_S	-4.092×10^3	$-4.092\times10^3 F_S$	$F_S+\chi$	2.091×10^4	$2.091\times10^4 F_S+2.091\times10^4\chi$
Total	$180+F_S$		$\Delta H_1=-8.203\times10^5-4.092\times10^3 F_S$	$232.9+F_S-0.5\chi$		$\Delta H_4=5.022\times10^6+2.091\times10^4 F_S-5.112\times10^3\chi$

$$\Delta H_2=\left(52.9\ \frac{\text{kmol}}{\text{h}}\right)\left(85.3\ \frac{\text{kJ}}{\text{mol}}\right)\left(1000\ \frac{\text{mol}}{\text{kmol}}\right)=4.512\times10^6\ \text{kJ/h}$$

$$\Delta H_3=\chi\left[\frac{\text{kmol}}{\text{h}}\right]\left(-241.83\ \frac{\text{kJ}}{\text{mol}}\right)\left(1000\ \frac{\text{mol}}{\text{kmol}}\right)=-2.418\times10^5\,\chi$$

$$\Delta H=0=\Delta H_1+\Delta H_2+\Delta H_3+\Delta H_4=8.714\times10^6+1.681\times10^4 F_S-2.469\times10^5\,\chi$$

$$\Downarrow$$

$$\chi=35.29+0.0681\,F_S$$

(continued)

12.18 (cont'd)

Since product gas from reactor is 5 mole % H_2

$$\frac{52.9-x}{232.9+F_s-0.5x} = \frac{52.9-35.29-0.0681F_s}{232.9+F_s-0.5(35.29)-0.5(0.0681)F_s} = 0.05$$

$$\Downarrow$$

$$\boxed{F_s = 58.8 \text{ kmol/h}}$$

$$x = 39.3 \text{ kmol/h}$$

(b) No steam fed to reactor $\Rightarrow F_s = 0$

From material balance and H_2 observation

$$\frac{52.9-x}{232.9-0.5x} = 0.05 \Rightarrow x = 42.31 \text{ kmol/h}$$

An energy balance on reactor is required to determine its operating temperature. The hypothetical process path used in problem 12.18a will also be used in this problem. ΔH_4 can be determined from the equation

$$\Delta H_4 = \Sigma m_i \, \Delta\hat{H}_{4,i}$$

where

$$\Delta\hat{H}_{4,i} = a_i T + \frac{b_i}{2}T^2 + \frac{c_i}{3}T^3 + \frac{d_i}{4}T^4 - \hat{H}_i(25°C)$$

$$\begin{aligned}\Delta H_4 = {} & 52.9\left[34.28T + \frac{4.268}{2}\times10^{-2}T^2 + 0T^3 - \frac{8.694}{4}\times10^{-9}T^4 - 870\right] \\ & + 22.7\left[42.93T + \frac{8.301}{2}\times10^{-2}T^2 - \frac{1.87}{3}\times10^{-5}T^3 - \frac{8.03}{4}\times10^{-9}T^4 - 1099\right] \\ & + 82.5\left[29.00T + \frac{0.2199}{2}\times10^{-2}T^2 + \frac{0.5723}{3}\times10^{-5}T^3 - \frac{2.871}{4}\times10^{-9}T^4 - 726\right] \\ & + 0.745\left[29.10T + \frac{1.158}{2}\times10^{-2}T^2 - \frac{0.6076}{3}\times10^{-5}T^3 + \frac{1.311}{4}\times10^{-9}T^4 - 731\right] \\ & + 10.59\left[28.84T + \frac{0.00765}{2}\times10^{-2}T^2 + \frac{0.3288}{3}\times10^{-5}T^3 - \frac{0.8698}{4}\times10^{-9}T^4 - 721\right] \\ & + 42.31\left[33.46T + \frac{0.6880}{2}\times10^{-2}T^2 + \frac{0.7604}{3}\times10^{-5}T^3 - \frac{3.593}{4}\times10^{-9}T^4 - 839\right]\end{aligned}$$

$$\Delta H_4 = 6.923\times10^{3}T + 2.312T^2 + 1.332\times10^{-4}T^3 - 2.222\times10^{-7}T^4 - 1.745\times10^5$$

$\Delta H_1 = 8.203\times10^5$; $\Delta H_2 = 4.512\times10^6$; $\Delta H_3 = -1.023\times10^7$ (continued)

~~1~~2.18 (contd)

$$\Delta H = 6.923\times10^{3}T + 2.312T^{2} + 1.334\times10^{-4}T^{3} - 2.222\times10^{-7}T^{4} - 6.713\times10^{6}$$

All values of ΔH are in kJ/h. The value of T for which $\Delta H = 0$ corresponds to the reactor operating temperature. To determine T the Newton convergence procedure will be used. (See Appendix A.2) Let

$$f(T) = 6923T + 2.312T^{2} + 1.334\times10^{-4}T^{3} - 2.222\times10^{-7}T^{4} - 6.713\times10^{6}$$

and

$$f'(T) = 6923 + 4.624T + 4.002\times10^{-4}T^{2} - 8.888\times10^{-7}T^{3}$$

To begin calculations evaluate T neglecting second-order terms and above: i.e., $T_0 = 6.713\times10^{6}/6923 = 970°C$

T_k(°C)	$f(T)$	$f'(T)$	⇒ $T_{k+1} = T_k - f(T)/f'(T)$
970	2.103×10^{6}	1.097×10^{4}	778.4
778.4	5.806×10^{4}	1.035×10^{4}	772.8
772.8	1.826×10^{2}	1.033×10^{4}	772.8

Successive estimates of T indicate $\boxed{T \approx 773°C}$

Adding steam helps control the reactor temperature. (See solution to ~~12.21~~ Problem CS 1.21)

Now return to problems requiring information from this problem.

~~1~~2.9 cont'd.

F_{NC} = flow rate of non-condensables in product stream from reactor = flow rate of non-condensables in product gas stream from absorber

= 98.35 kmol/h

$$E_A = F_{NC}/y_{NC} = 98.35\ \text{kmol/h}\ /0.9653 = 101.9\ \frac{\text{kmol}}{\text{h}}$$

H_2O in $E_A = y_{H_2O}E_A = 3.52$ kmol/h

$HCHO$ in $E_A = y_{HCHO}E_A = 0.0204$ kmol/h

~~1~~2.10 cont'd.

$$F_W = 3.52\ \text{kmol/h} + 147.6\ \text{kmol/h} - (58.8+39.3)\ \text{kmol/h}$$

$$= \boxed{53.0\ \text{kmol/h}}$$

~~12~~. 13~~(b)~~ cont'd

Product gas:

Component	flow rate	mole fraction	partial pressure
$HCHO^*$	52.9 kmol/h	0.1994	2.86 psi
CH_3OH^*	22.7 "	0.0834	1.23 "
N_2	82.5 "	0.3033	4.46 "
O_2	2.25 "	0.0083	0.12 "
H_2	13.6 "	0.0500	0.74 "
H_2O^*	98.1 "	0.3606	5.30 "
	272.05		

* condensable components

$$\Sigma (p_i)_{condensable} = 9.48\ psi = \Sigma x_i p_i^*$$

Use vapor pressure from Gallant for CH_3OH ital ~~Hyd. Proc.~~, ~~45~~ 44 (10), 171 (October, 1966) and for HCHO Hyd. Proc., 47 (5), 151 (May, 1968). Steam tables will be used to obtain vapor pressures for water.

~~Component~~	$p_i^*(75°C)$	x_i	$p_i^*(80°C)$	x_i
HCHO	292 psi	0.0098	310	0.0092
CH_3OH	21.0 psi	0.0586	22.8	0.0539
H_2O	5.6 psi	0.9464	6.9	0.7681
		1.0148		$\Sigma x_i = 0.8312$

	$p_i^*(76°C)$	x_i
HCHO	295	0.0097
CH_3OH	21.1	0.0583
H_2O	5.9	0.8983
		0.966

$\boxed{T_{dew\ point} \approx 76°C.}$ Since observed dew point is 100 °C, Raoult's law is invalid in this case.

~~12~~.19

(a) H_2 produced by ~~12.1~~ CS 1.1 = 52.9 kmol/h.

H_2 consumed in ~~12.2~~ = 39.3 kmol/h CS 1.2

$$\boxed{\text{fraction of } H_2 \text{ consumed} = 39.3/52.9 = 0.74}$$

(b) If no H_2 is in the product stream from the reactor, then ξ = 52.9 kmol/h and $\boxed{\dot{F}_5 = 258.6 \text{ kmol/h}}$

(From last equation on p. 494)

(c) If reaction CS 1.2 is suppressed, the reaction process becomes endothermic and heat must be supplied to the reactor.

~~12~~.20

In waste-heat boiler product gases are cooled from 600 °C to 145 °C. From an energy balance on the boiler

$$\Delta H_{\substack{prod\\gases}} = \dot{m}_{steam}(-\Delta\hat{H}_{vap}) = \sum \dot{n}_i[\hat{H}_i(145°C) - \hat{H}_i(600°C)]$$

Component(i)	$\dot{n}_i$(kmol/h)	(from page 493) $[\hat{H}_i(145°C) - \hat{H}_i(600°C)]$ (kJ/kmol)
HCHO	52.9	-2.255×10^4
CH_3OH	22.7	-3.200×10^4
N_2	82.5	-1.388×10^4
O_2	2.25	-1.481×10^4
H_2	13.6	-1.334×10^4
H_2O	98.1	-1.681×10^4

$$\Delta H_{\substack{prod\\gases}} = -4.928 \times 10^6 \text{ kJ/h} = \dot{m}_{steam}(-\Delta\hat{H}_v(3.1 \text{ bars}))$$

$$\Downarrow \Delta\hat{H}_v = 2160 \text{ kJ/kg}$$

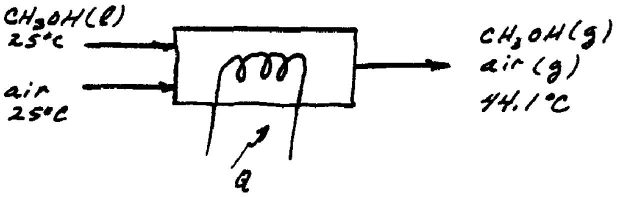
$$\dot{m}_s = \boxed{2280 \text{ kg/h}} \Rightarrow 127 \text{ kmol/h}$$

~~12~~.21

~~(a)~~ Additional reactor length could lead to extensive side reactions or further reaction of formaldehyde. Without capability of heat removal from the catalyst, further reaction of H_2 could result in a very high temperature of the catalyst.

~~(b)~~ The length of the catalyst bed makes removal of heat from the reactor impossible. The addition of steam as a diluent prevents the destruction of the catalyst due to an excessive temperature rise.

~~1~~2.22



~~(a)~~ Assume that recycled CH_3OH has cooled to ambient conditions and, therefore, that the methanol enters the vaporizer at 25°C.

An energy balance on vaporizer gives

$$Q = F_{MR}\left[C_{Pm(l)}(64.7°C - 25°C) + \Delta\hat{H}_v(@64.7°C) + \int_{64.7°C}^{44.1°C} C_{Pm(g)}\,dT\right] + F_A \int_{25°C}^{44.1°C} C_{P_A}\,dT$$

Since temperature ranges are narrow, higher-order terms in heat capacity equations will be neglected.

$$\Delta\hat{H}_v(@64.7°C) = 35.27 \text{ kJ/mol}$$

$$Q = 75.6\,\frac{\text{kmol}}{\text{h}}\left[82.59\,\frac{\text{kJ}}{\text{kmol}\cdot°C}(64.7°C - 25°C) + 35270\,\frac{\text{kJ}}{\text{kmol}} + 42.93\,\frac{\text{kJ}}{\text{kmol}\cdot°C}(44.1°C - 64.7°C)\right]$$

$$+ \left(104.4\,\frac{\text{kmol}}{\text{h}}\right)\left(28.94\,\frac{\text{kJ}}{\text{kmol}\cdot°C}\right)(44.1°C - 25°C)$$

(continued)

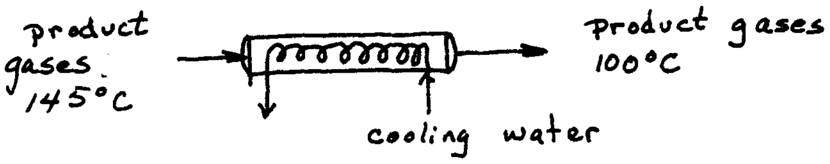
~~2~~.22 cont'd

$$\boxed{Q = 2.90 \times 10^6 \text{ kJ/h}}$$

~~(b)~~ $Q = -\dot{m}_s (\Delta \hat{H}_v)_{steam} \Longrightarrow \dot{m}_s = Q / -(\Delta \hat{H}_v)_{steam}$

$$\dot{m}_s = (2.90 \times 10^6 \text{ kJ/h}) / (2160 \text{ kJ/kg}) = \boxed{1340 \frac{\text{kg}}{\text{h}}} = 74.4 \frac{\text{kmol}}{\text{h}}$$

~~2~~.23



Let $F_{P,i}$ = flow rate of i in product gases

Energy balance: $Q = (\Delta H)_{\substack{prod\\gases}} = \sum F_{P,i} [\hat{H}_i(100°C) - \hat{H}_i(145°C)]$

(Relative to 0°C — see p. 487)

Component	$F_{P,i}$ (kmol/h)	$\hat{H}_i$ (kJ/kmol at 145°C)	$\hat{H}_i$ (kJ/kmol at 100°C)
$HCHO$	52.9	5418	3641
CH_3OH	22.7	7078	4702
N_2	82.5	4234	2911
O_2	2.25	4335	2966
H_2	13.6	4186	2885
H_2O	98.1	4931	3383

$$\Downarrow$$

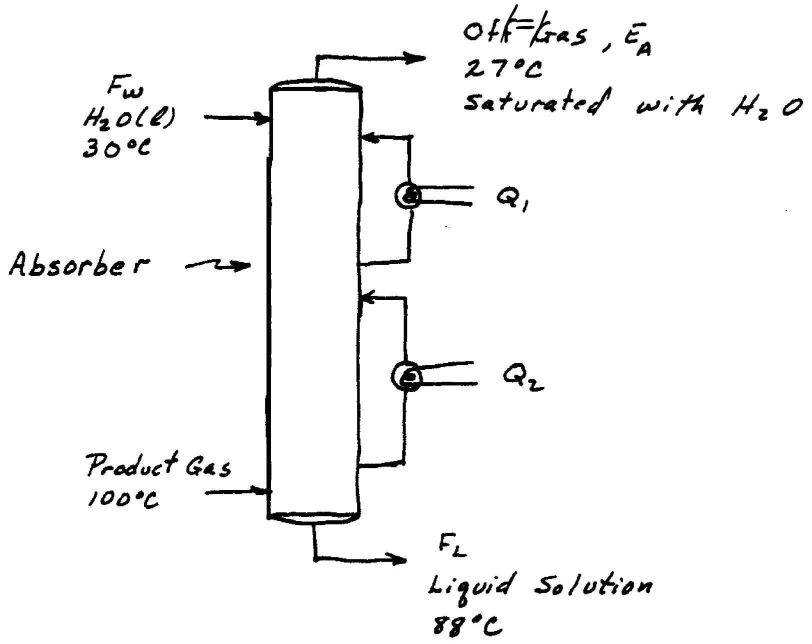
$$Q = -3.77 \times 10^5 \text{ kJ/h} = [\dot{m} C_p (T_{in} - T_{out})]_{H_2O}$$

$\Downarrow$ $T_{in} - T_{out} = -15°C$

$C_p = 75.3$ kJ/kmol·°C

$$\dot{m}_{H_2O} = 333 \text{ kmol/h} = \boxed{6000 \text{ kg } H_2O/\text{h}}$$

~~1~~2.24



An energy balance on the absorber gives

$$F_W \hat{H}_{H_2O(\ell),30^\circ C} + \sum F_{P_i} \hat{H}_{P_i} + Q_1 + Q_2 = E_{A,i} \hat{H}_{OG,i} + F_L \hat{H}_L$$

$\hat{H}_{OG,i}$ will be evaluated at 25°C since these values have been determined.

Enthalpies for water will be evaluated with reference to liquid water at 0°C. Enthalpies for other components will be with reference to these components as gases at 25°C.

~~gases at 25°C.~~

$$F_W \hat{H}_{H_2O(\ell),30^\circ C} = \left(53.0 \frac{kcal}{h}\right)\left(125.7 \frac{kJ}{kg}\right)\left(\frac{18\,kg}{kmol}\right) = 119{,}918\ kJ/h$$

(from page 500)

Component(i)	F_{P_i}(kmol/h)	$\hat{H}_{P_i}$ (kJ/kmol)	$F_{P_i}\hat{H}_i$ (kJ/h)
HCHO	52.9	3641	1.93×10^5
CH_3OH	22.7	4702	1.07×10^5
N_2	82.5	2911	2.40×10^5
O_2	2.25	2966	6.67×10^3
H_2	13.6	2885	3.92×10^4
H_2O	98.1	3383+(2501.6)(18)	~~4.75×10^6~~

$$\Sigma F_{P_i} \hat{H}_i = 5.34 \times 10^6$$

(continued)

~~1~~2.24 (cont'd)

(from page 493)

Component(i)	$E_{A,i}$ (kmol/h)	$\hat{H}_{OG,i}$ (kJ/kmol)	$E_{A,i}\hat{H}_{OG,i}$ (kJ/h)
HCHO	0.0204	0.870×10^3	0.0178×10^5
CH_3OH	0	1.099×10^3	0
N_2	82.5	0.726×10^3	59.85×10^3
O_2	2.25	0.731×10^3	1.64×10^3
H_2	13.6	0.721×10^3	9.81×10^3
H_2O	3.52	$839+(2501.6)(18)$	1.515×10^5

$$\sum E_{A,i}\hat{H}_{OG,i} = 2.328 \times 10^5$$

The composition of F_L can be determined from a component balance on the absorber

Component(i)	$F_{L,i} = F_{P,i} + F_{W,i} - E_{A,i}$
HCHO	52.9 kmol/h
CH_3OH	22.7 "
N_2	0
O_2	0
H_2	0
H_2O	147.6

$$F_L = \sum F_{L,i} = 223.2 \text{ kmol/h}$$

The enthalpy of the product solution will be determined using the following hypothetical process path:

$$\begin{tikzcd}
\begin{matrix}\text{HCHO}(g)\\ 0^\circ\text{C}\end{matrix} \arrow[r, "\Delta H_1"] & \begin{matrix}\text{HCHO}(g)\\ 25^\circ\text{C}\end{matrix} \arrow[dr, "\Delta H_4"] & & \\
& & \begin{matrix}\text{HCHO (sol'n)}\\ 25^\circ\text{C}\end{matrix} \arrow[dr, "\Delta H_6"] & \\
\begin{matrix}H_2O(l)\\ 0^\circ\text{C}\end{matrix} \arrow[r, "\Delta H_2"] & \begin{matrix}H_2O(l)\\ 25^\circ\text{C}\end{matrix} \arrow[ur, dash] & & \begin{matrix}\text{Product}\\ 25^\circ\text{C}\end{matrix} \arrow[dd, "\Delta H_7"] \\
\begin{matrix}CH_3OH(g)\\ 0^\circ\text{C}\end{matrix} \arrow[r, "\Delta H_3"] & \begin{matrix}CH_3OH(g)\\ 25^\circ\text{C}\end{matrix} \arrow[r, "\Delta H_5"] & \begin{matrix}CH_3OH(l)\\ 25^\circ\text{C}\end{matrix} \arrow[ur, dash] & \\
& & & \begin{matrix}\text{Product Solution}\\ 68^\circ\text{C}\end{matrix}
\end{tikzcd}$$

(continued)

~~12~~-24 cont'd

$$\Delta H_1 = \left(52.9\ \frac{\text{kmol}}{\text{h}}\right)\left(870\ \frac{\text{kJ}}{\text{kmol}}\right) = 4.602\times10^4\ \frac{\text{kJ}}{\text{h}}$$

$$\Delta H_2 = \left(147.6\ \frac{\text{kmol}}{\text{h}}\right)\left(104.8\ \frac{\text{kJ}}{\text{kg}}\right)\left(18\ \frac{\text{kg}}{\text{kmol}}\right) = 2.784\times10^5\ \frac{\text{kJ}}{\text{h}}$$

$$\Delta H_3 = \left(22.7\ \frac{\text{kmol}}{\text{h}}\right)\left(1099\ \text{kJ/kmol}\right) = 2.495\times10^4\ \text{kJ/h}$$

$$\Delta H_4 = \left(52.9\ \frac{\text{kmol}}{\text{h}}\right)\left(-15\ \text{kcal/mol}\right)\left(\frac{1\ \text{kJ}}{0.23901\ \text{kcal}}\right)\left(\frac{1000\ \text{mol}}{\text{kmol}}\right)$$

$$= -3.320\times10^6\ \text{kJ/h}$$

$$\Delta H_5 = \left(22.7\ \frac{\text{kmol}}{\text{h}}\right)\left(-35.27\ \frac{\text{kJ}}{\text{mol}}\right)\left(\frac{1000\ \text{mol}}{\text{kmol}}\right) = -8.006\times10^5\ \frac{\text{kJ}}{\text{h}}$$

↑ assumes $\Delta\hat{H}_v(T_b) \approx \Delta\hat{H}_v(25°\text{C})$

$$\Delta H_6 \approx 0$$

$$\Delta H_7 = \left(4286\ \frac{\text{kg}}{\text{h}}\right)\left(0.8\ \frac{\text{cal}}{\text{g}\cdot°\text{C}}\right)\left(\frac{1000\ \text{g}}{\text{kg}}\right)\left(\frac{1\ \text{kJ}}{0.23901\ \text{kcal}}\right)(88-25)°\text{C}$$

$$= 9.038\times10^5\ \text{kJ/h}$$

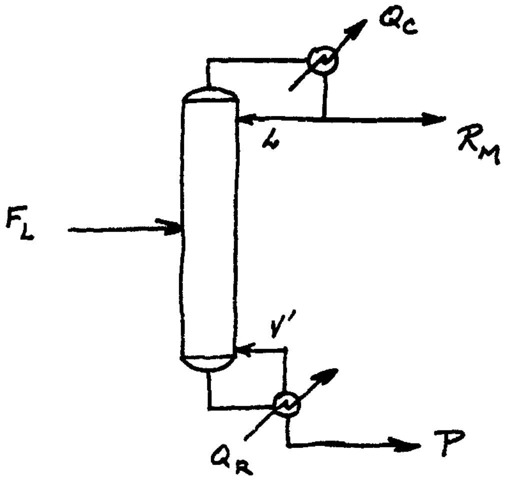
$$\Delta H = -2.867\times10^6\ \text{kJ/h} = F_L\hat{H}_L$$

For the absorber $Q_1 + Q_2 = \boxed{-8.10\times10^6\ \text{kJ/h}}$

↑ from first eqn. p. ⓢ501

b. Heat must be removed because of the exotherm associated with the dissolution of HCHO and the condensation of H_2O.

~~12~~-25



(continued)

~~11.25~~ (cont'd)

Enthalpies will be calculated on the same basis used in Problem ~~24~~ CS 1.24 ⊙

$F_L \hat{H}_L = -2.867 \times 10^6$ kJ/h

$R_m = 21.4$ kmol/h {Note check on CH_3OH balance}

$P = F_L - R_m = 202$ kmol/h {Check on specified Product Flow rate}

From specified reflux ratio $= 2.5 = L/R_m$

$L = 2.5 R_m = 53.5$ kmol/h

$V = L + R_m = 74.9$ kmol/h

The condenser is operating at 64.7°C, the normal boiling point of CH_3OH, because its pressure is 1 atm.

$$Q_c = V \Delta \hat{H}_v (64.7°C) = \left(74.9 \frac{\text{kmol}}{\text{h}}\right)\left(-35.77 \frac{\text{kJ}}{\text{mol}}\right)\left(\frac{1000 \text{ mol}}{\text{kmol}}\right)$$

$$= -2.679 \times 10^6 \text{ kJ/h}$$

for CH_3OH:

$\hat{H}(v, 64.7°C) = 2.950 \times 10^3$ kJ/kmol

$\hat{H}_{Rm} = (2.950 \times 10^3 - 35.77 \times 10^3)$ kJ/kmol $= -3.282 \times 10^4 \frac{\text{kJ}}{\text{kmol}}$

$R_m \hat{H}_{Rm} = -2.458 \times 10^6$ kJ/h

From Problem ~~12.12~~ CS 1.12, the reboiler temperature is 98°C. The enthalpy of the product solution will be calculated as follows:

$$P\hat{H}_P = P_{HCHO}\left(\hat{H}_{HCHO}(25°C) + \Delta \hat{H}_s\right) + P_{H_2O}\hat{H}_{H_2O}(25°C)$$

$$+ P_{CH_3OH}\hat{H}_{CH_3OH(l)}(25°C) + P C_{P_P}(98°C - 25°C)$$

(continued)

~~12~~.25 (cont'd)

$$P\hat{H}_p = 52.9\,\frac{\text{kmol}}{\text{h}}\left[870\,\frac{\text{kJ}}{\text{kmol}} - 15\,\frac{\text{kcal}}{\text{mol}}\left(\frac{1\,\text{kJ}}{0.23901\,\text{kcal}}\right)\left(\frac{1000\,\text{mol}}{\text{kmol}}\right)\right]$$

$$+\ 147.6\,\frac{\text{kmol}}{\text{h}}\left(104.8\,\frac{\text{kJ}}{\text{kg}}\right)\left(\frac{18\,\text{kg}}{\text{kmol}}\right)$$

$$+\ 1.3\,\frac{\text{kmol}}{\text{h}}\left[1099\,\frac{\text{kJ}}{\text{kmol}} - \left(35.77\,\frac{\text{kJ}}{\text{mol}}\right)\left(\frac{1000\,\text{mol}}{\text{kmol}}\right)\right]$$

$$+\ \left(4286\,\frac{\text{kg}}{\text{h}}\right)\left(0.8\,\frac{\text{cal}}{\text{g}\,^\circ\text{C}}\right)\left(\frac{1000\,\text{g}}{\text{kg}}\right)\left(\frac{1\,\text{kJ}}{0.23901\,\text{kcal}}\right)\left(98\,^\circ\text{C} - 25\,^\circ\text{C}\right)$$

$$= -1.993\times10^{6}\ \text{kJ/h}$$

$$R_m\hat{H}_{Rm} + P\hat{H}_p - F_L\hat{H}_L - Q_c = Q_R$$

$$\Downarrow$$

$$Q_R = \boxed{2.851\times10^{6}\ \text{kJ/h}}$$

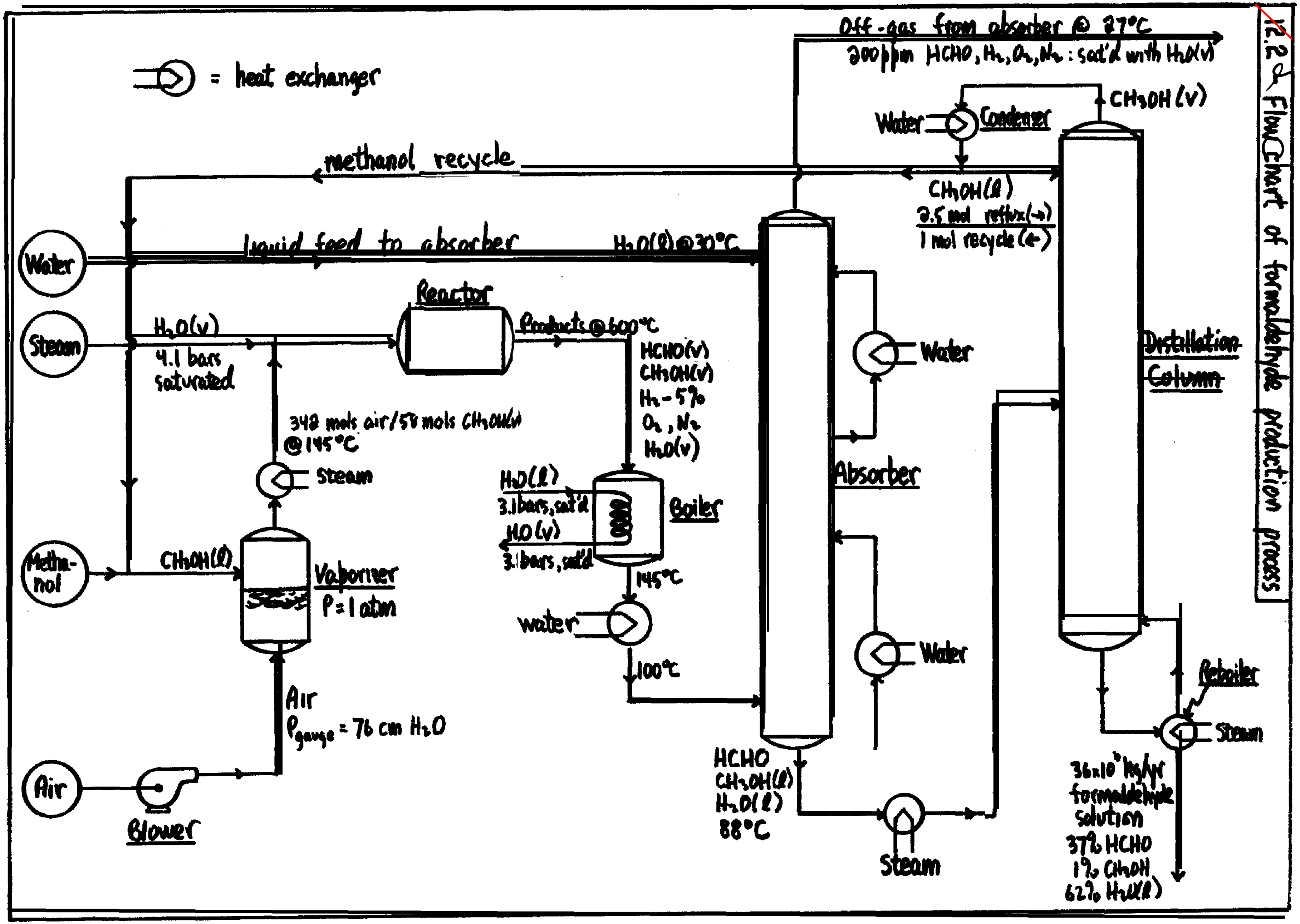
12.26

Cooling water is available at 30°C; therefore, a 15°C rise will mean the exit cooling water will be at 45°C. The driving force for heat transfer at these conditions will be 64.7°C − 45°C ≅ 20°C, which is adequate for the condenser operation. The cooling water can be used.

CS 1-25

CS 1.2

~~I-12,25~~



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