

Problem 4.1A

A steel tank having a capacity of 25 m³ holds carbon dioxide at 30°C and 1.6 atm. Calculate the weight, in grams, of the carbon dioxide.

Solution

$$T = 30^\circ\text{C} = 30 + 273.15 = 303\text{K}$$

$$p = 1.6 \text{ atm}$$

$$V = 25 \text{ m}^3$$

$$\text{Use } pV = nRT$$

The gas constant has to be chosen to be consistent with the units of pressure, temperature, and volume. Use standard conditions to calculate R

$$R = \frac{1.00 \text{ atm} \left| \frac{22.415 \text{ m}^3}{\text{kg mol}} \right|}{273.15 \text{ K}} = 0.08206 \frac{(\text{atm})(\text{m}^3)}{(\text{kg mol})(\text{k})}$$

$$n = \frac{(p)(V)}{(R)(T)} = \frac{(1.6)(25)}{(0.08206)(303)} = 1.608 \text{ kg mol or } 1,608 \text{ g mol}$$

$$\text{Weight of carbon dioxide} = \frac{1,608 \text{ g mol}}{\left| \frac{44 \text{ g CO}_2}{\text{g mol CO}_2} \right|} = 70.7 \times 10^3 \text{ g CO}_2$$

Alternate Solution:

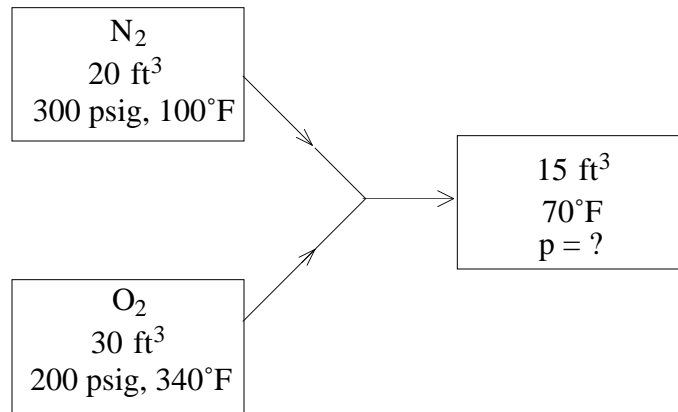
Use $V = 22.415 \text{ m}^3/\text{kg mol}$ at $T = 273\text{K}$ and $p = 1 \text{ atm abs}$.

$$\text{and } \left(\frac{p_2}{p_1} \right) \left(\frac{V_2}{V_1} \right) = \left(\frac{n_2}{n_1} \right) \left(\frac{T_2}{T_1} \right)$$

$$\frac{25 \text{ m}^3}{\left| \frac{1.6 \text{ atm abs}}{1 \text{ atm abs}} \right|} \left| \frac{273 \text{ K}}{303 \text{ K}} \right| \left| \frac{1 \text{ kg mol}}{22.415 \text{ m}^3} \right| \left| \frac{44 \text{ kg CO}_2}{1 \text{ kg mol CO}_2} \right| \left| \frac{1000 \text{ g}}{1 \text{ kg}} \right| = 70.7 \times 10^3 \text{ g CO}_2$$

Problem 4.1B

20 ft³ of nitrogen at 300 psig and 100°F and 30 ft³ of oxygen at 200 psig and 340°F are injected into a 15 ft³ vessel. The vessel is then cooled to 70°F. Find the partial pressure of each component in the 15 ft³ vessel. Assume that the ideal gas law applies.

Solution

The problem can be solved by determining the number of moles of oxygen and nitrogen and solving for the total pressure at the final conditions. Then the partial pressures are calculated using the mole fractions.

Nitrogen

$$V = 20 \text{ ft}^3$$

$$p = 300 \text{ psig} = 314.7 \text{ psia}$$

$$T = 100^\circ\text{F} = 560^\circ\text{R}$$

$$n_{\text{N}_2} = \frac{pV}{RT} = \frac{(314.7)(20)}{(10.73)(560)} = 1.05 \text{ lb mol}$$

Oxygen

$$V = 30 \text{ ft}^3$$

$$p = 200 \text{ psig} = 214.7 \text{ psia}$$

$$T = 340^\circ\text{F} = 800^\circ\text{R}$$

$$n_{\text{O}_2} = \frac{(214.7)(30)}{(10.73)(800)} = 0.75 \text{ lb mol}$$

$$n_{\text{T}} = n_{\text{N}_2} + n_{\text{O}_2} = 1.80 \text{ lb mol}$$

$$\text{Final pressure } p_{\text{T}} = \frac{n_{\text{T}}RT}{V} = \frac{(1.80)(10.73)(530)}{15} = 682 \text{ psia}$$

	<i>moles</i>	<i>mole fr</i> (y_i)	$p_i = p_{\text{T}}(y_i)$
O ₂	0.75	0.42	286
N ₂	<u>1.05</u>	<u>0.58</u>	<u>396</u>
	1.80	1.00	682 psia

Problem 4.1C

A steel container has a volume of 200 m³. It is filled with nitrogen at 22°C and atmospheric pressure. If the container valve is opened and the container heated to 200°C, calculate the fraction of the nitrogen which leaves the container.

Solution

The solution involves determining the number of moles of nitrogen in the tank at the final given temperature and pressure (T_2 and p_2), and at the initial conditions, and subtracting.

$$T_1 = 22^\circ\text{C} = 295\text{K}$$

$$p_1 = 1 \text{ atm}$$

$$V_1 = 200 \text{ m}^3$$

$$n_1 = \frac{p_1 V_1}{RT_1}$$

$$n_1 = \frac{(1)(200)}{(0.08206)(295)} \\ = 8.26 \text{ kg mol}$$

$$T_2 = 200^\circ\text{C} = 473\text{K}$$

$$p_2 = 1 \text{ atm}$$

$$V_2 = 200 \text{ m}^3$$

$$n_2 = \frac{p_2 V_2}{RT_2}$$

$$n_2 = \frac{(1)(200)}{(0.08206)(473)} \\ = 5.15 \text{ kg mol}$$

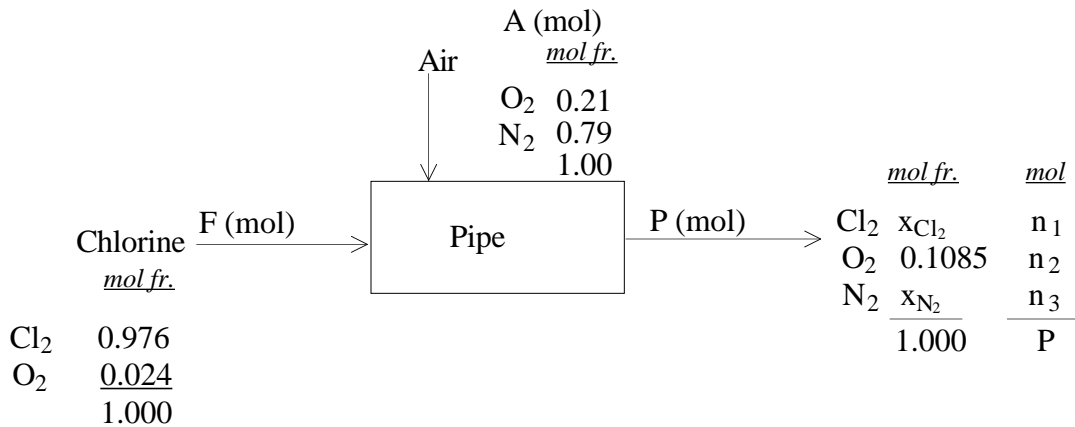
$$\text{The fraction of N}_2 \text{ leaving} = \frac{8.26 - 5.15}{5.15} = \mathbf{0.60}$$

Problem 4.1D

Chlorine gas containing 2.4 percent O₂ is flowing through an earthenware pipe. The gas flow rate is measured by introducing air into it at the rate of 115 m³/min. Further down the line, after mixing is complete, the gas is found to contain 10.85 percent O₂. How many m³ of the initial gas were flowing per minute through the pipe?

Solution

The problem is similar to other nonreacting material balance problems. It is convenient to imagine the pipeline between the point of injection of air to the point of sampling as a mixer. The process may be considered to be a steady state process without reaction.



Step 5 We could use $F = 100$ mol as the basis instead of the given flowrate. All flow rates can be then be converted to the basis of 1 minute at the end of the problem. However, it is easier to use the given flow rate in m^3 assuming that the temperature and pressure are the same for all streams so that moles are proportional to m^3 in each stream.

$$A = 115 \text{ m}^3$$

Step 6 Let x_{Cl_2} and x_{N_2} be the respective mole fractions in P. The unknowns are: F, P, x_{Cl_2} , and x_{N_2} (or n_1 and n_3).

Step 7 The balances are: Cl₂, O₂, N₂, and $\sum x_i = 1$ (or $\sum n_i = P$) so the problem has a unique solution.

Step 8	Total	$F + 115 = P$	(1)
	Oxygen Balance	$0.024F + 0.21(115) = 0.1085 P$	(2)
	Chlorine Balance	$0.976F = x_{\text{Cl}_2}(P)$	(3)
	Nitrogen Balance	$0.79(115) = x_{\text{N}_2}P$	(4)
	$\sum x_i = 1.000$	$0.1085 + x_{\text{Cl}_2} + x_{\text{N}_2} = 1.000$	(5)

Steps 8 and 9

Only 4 of the balances are independent. Substitute the total balance for one component balance and solve (1) and (2) together to get

$$P = 253 \text{ m}^3 \text{ at } T \text{ and } p$$

$$V_{\text{in}} = \mathbf{138 \text{ m}^3} \text{ at } T \text{ and } p$$

Step 10 Use $\sum x_i$ as a check

from (4) $x_{\text{N}_2}^{\text{P}} = 0.79(115)/253 = 0.359$

from (3)&(1) $x_{\text{Cl}_2}^{\text{P}} = (0.976)(138)/253 = 0.532$

from (5) $0.359 + 0.532 + 0.1085 = 1.00$

Problem 4.1E

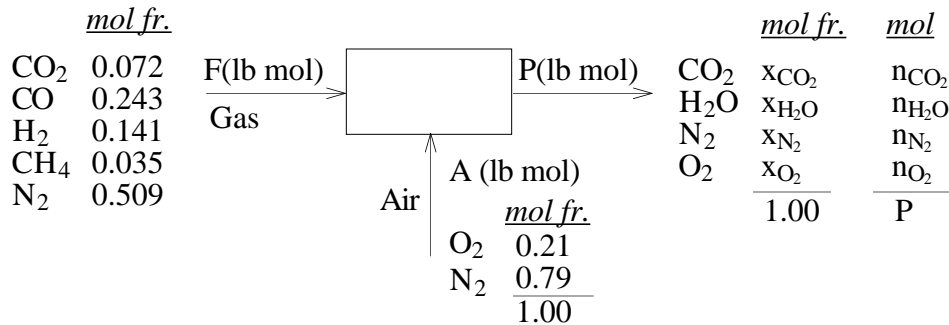
A synthetic gas generated from coal has the following composition: CO₂, 7.2%; CO, 24.3%; H₂, 14.1%; CH₄, 3.5%; N₂, 50.9%.

- (a) Calculate the cubic feet of air necessary for complete combustion per cubic foot of synthetic gas at the same conditions.
- (b) If 38% excess air were used for combustion, what volume of flue gas at 750°F and 738 mm Hg would be produced per cubic foot of synthetic gas at standard conditions?
- (c) Calculate the flue gas analysis for (a) and (b).

Solution

The problem is just a material balance problem with volumes of inlet and outlet gases specified instead of moles. We could select ft³ or moles as a basis.

Steps 1, 2, 3, and 4 This is a steady state problem with reaction.



Part (a)

Calculate the required air first.

Step 5 Basis 100 mol F

Step 4

<u>Component</u>	<u>mol</u>	<u>Reaction</u>	<u>mol reqd O₂</u>
CO ₂	7.2		
CO	24.3	CO + 1/2 O ₂ → CO ₂	12.15
H ₂	14.1	H ₂ + 1/2 O ₂ → H ₂ O	7.15
CH ₄	3.5	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	7.0
N ₂	<u>50.9</u>		
	100.0		26.3
		Accompanying N ₂ : 26.3 (79/21)	<u>98.9</u>
		Total	125.2

$$a. \quad \frac{A}{F} = \frac{125.2 \text{ mol air}}{100 \text{ mol feed}} = 1.25 \frac{\text{mol air}}{\text{mol feed}} = \frac{1.25 \text{ ft}^3 \text{ air}}{1.00 \text{ ft}^3 \text{ feed}}$$

(both at same conditions)

Since the temperature and pressure are the same for both streams, the mole ratio and the volume ratio are the same.

Next, let us make a material balance for the case in which the air supplied is 38% in excess. Keep the same basis.

$$A = 125.2 (1.38) = 172.7 \text{ mol}$$

Part (b)

Step 6 Unknowns: P, and x_{CO_2} , $x_{\text{H}_2\text{O}}$, x_{N_2} , x_{O_2} (or n_{CO_2} , $n_{\text{H}_2\text{O}}$, n_{N_2} , n_{O_2})

Steps 7, and 8 The element balances are:

$$\text{Carbon balance:} \quad 7.2 + 24.3 + 3.5 = P x_{\text{CO}_2} = n_{\text{CO}_2} \quad (1)$$

$$\text{Hydrogen balance:} \quad 14.1(2) + 3.5(4) = 2 P x_{\text{H}_2\text{O}} = 2 n_{\text{H}_2\text{O}} \quad (2)$$

$$\text{Oxygen balance:} \quad 7.2(2) + 24.3 + 0.21 (172.7)(2) = 2 P x_{\text{CO}_2} + P x_{\text{H}_2\text{O}} + 2 P x_{\text{O}_2} \quad (3)$$

$$\text{Nitrogen balance(N}_2\text{):} \quad 50.9 + 0.79 (172.7) = P x_{\text{N}_2} = n_{\text{N}_2} \quad (4)$$

$$\text{Also:} \quad x_{\text{H}_2\text{O}} + x_{\text{CO}_2} + x_{\text{N}_2} + x_{\text{O}_2} = 1 \quad (5)$$

$$\text{or} \quad n_{\text{H}_2\text{O}} + n_{\text{CO}_2} + n_{\text{N}_2} + n_{\text{O}_2} = P$$

Step 9

From the above equations we get

<u>Component</u>	<u>mol</u>
CO ₂	35
H ₂ O	21.1
O ₂	10.1
N ₂	<u>187.3</u>
Total	253

Vol. of P @ 750°F, 738 mm Hg

$$T = 750^\circ\text{F} = 1210^\circ\text{R}$$

$$p = 738 \text{ mm Hg}$$

$$V_P = \frac{253 \text{ lb mol}}{1 \text{ lb mol}} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| \frac{1210^\circ\text{R}}{492^\circ\text{R}} \left| \frac{760 \text{ mm Hg}}{738 \text{ mm Hg}} \right| = 2.30 \times 10^5 \text{ ft}^3$$

$$V_F = \frac{100 \text{ lb mol}}{1 \text{ lb mol}} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| = 3.59 \times 10^4 \text{ ft}^3$$

$$\frac{V_P}{V_F} = \frac{2.30 \times 10^5}{3.59 \times 10^4} = 6.41 \frac{\text{ft}^3 \text{ flue gas}}{\text{ft}^3 \text{ air at SC}} \text{ at T and p}$$

Part (c) Flue gas analysis.

a. The water and carbon dioxide are the same as in part b, and there is no O₂ in the flue gas.

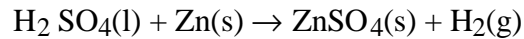
	<u>mol</u>	<u>mol fr</u>
CO ₂	35	0.23
H ₂ O	21.1	0.14
N ₂	<u>98.9</u>	<u>0.63</u>
	155	1.00

b.

	<u>mol</u>	<u>mol fr</u>
CO ₂	35	0.14
H ₂ O	21.1	0.08
N ₂	187	0.74
O ₂	<u>10.1</u>	<u>0.04</u>
	253	1.00

Problem 4.1F

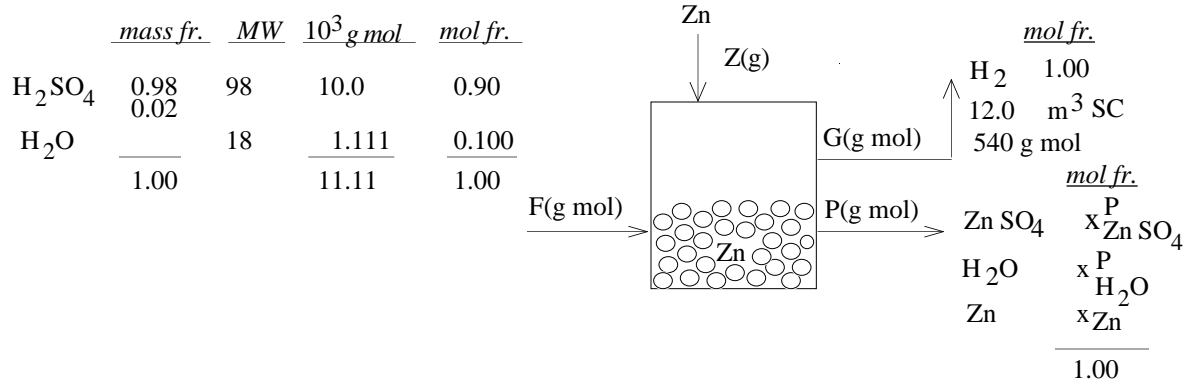
An old way of producing hydrogen gas in the laboratory was by the reaction of sulfuric acid with zinc metal



How many grams of sulfuric acid solution (98%) must act on an excess of zinc to produce 12.0 m³/hr of hydrogen at standard conditions. Assume all the acid used completely reacts.

Solution

Steps 1, 2, 3, and 4 You first must determine the number of moles of hydrogen produced, and then calculate the acid required via stoichiometry. This is a steady state process with reaction except for the Zn (which can be assumed to exit the vessel).



Step 5 Basis 1 hr (12.0 m³ at SC in G)

$$\begin{aligned} \text{moles of hydrogen} &= n = \frac{pV}{RT} \\ \text{vol of hydrogen} = V &= \frac{12.0 \text{ m}^3}{1 \text{ m}^3} \left| \frac{1000 \text{ L}}{1 \text{ m}^3} \right. = 1.20 \times 10^4 \text{ L} \\ n &= \frac{(1 \text{ atm})(1.20 \times 10^4)}{(0.08206)(273)} = 5.36 \times 10^2 \text{ g mol} \end{aligned}$$

Step 6 Unknowns are: F, P, $x_{\text{ZnSO}_4}^P$, $x_{\text{H}_2\text{O}}^P$, and x_{Zn}^P . The only unknown we want to solve for is F.

Steps 7 and 8 Balances: We can make H, S, O, and Zn element balances (they may not all be independent) plus $\sum x_i = 1$. The easiest balance to make to get F is an H₂SO₄ compound balance, but other reasonable balances can be used.

$$\begin{array}{ccccccc} \underline{In} & & \underline{Out} & & \underline{Generation} & & \underline{Consumption} & & \underline{Accum.} \\ 0.90F & - & 0 & + & 536 & - & 0 & = & 0 \end{array}$$

$$F = 596 \text{ g mol H}_2\text{SO}_4$$

$$\frac{596 \text{ g mol H}_2\text{SO}_4 \text{ soln}}{11.11 \times 10^{-3} \text{ g mol 98\% soln}} \left| \frac{10.0 \text{ g soln}}{11.11 \times 10^{-3} \text{ g mol 98\% soln}} \right. = 5.37 \times 10^4 \text{ g 98\% soln}$$

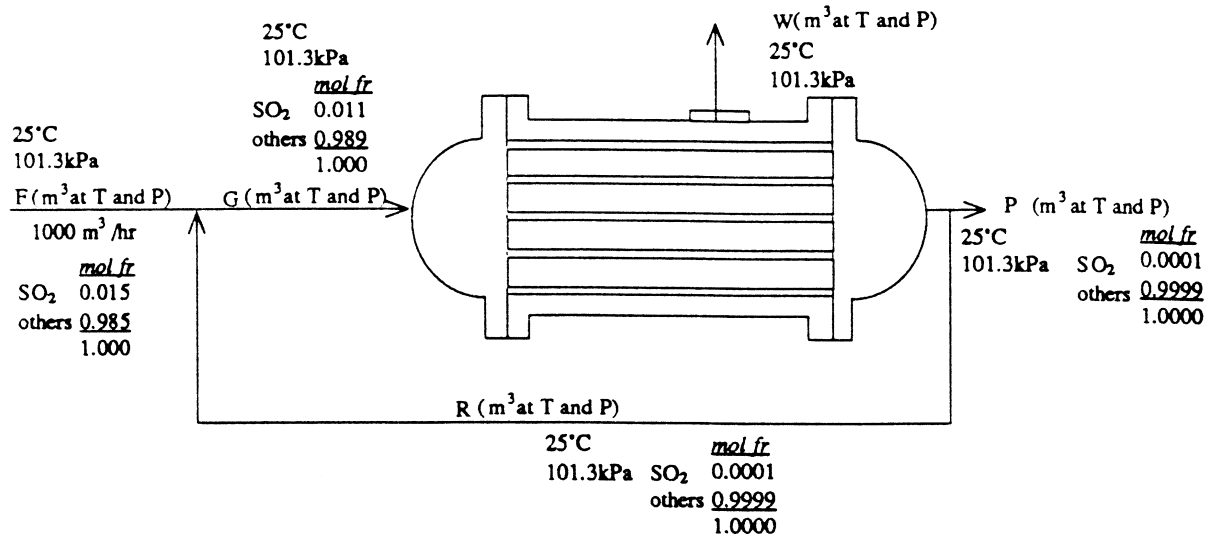
Problem 4.1G

Polymeric membranes are proposed to be used to reduce the SO₂ concentration in the waste gas of a sulfuric acid plant from 1.5% to 0.01%. Hollows fibers (made of polymeric membrane) fill the separations unit. The waste gas containing 1.5% SO₂ is the fresh feed in the amount of 1000 m³ hr at 25°C and 1 atm (101.3 kPa). To meet the product gas specifications, part of the product stream has to be recycled to reduce the concentration of SO₂ entering the separator itself to 1.10% SO₂ in G, the process feed. The process is isothermal at 25°C and isobaric at 1 atm.

- Determine the recycle stream flow rate R in m³/hr.
- Determine the waste stream flowrate W in m³/hr.

Solution

Steps 1, 2, 3, and 4 This is a steady state process with reaction and recycle. All the known data have been placed in the figure. No reaction occurs.



Step 5 Basis: $F = 1000 \text{ m}^3$ at 25°C and 101.3kPa (same basis as 1 hr)

Step 6 Ignore the exit stream from the reactor. Then G , P , W , and R are unknowns and their compositions are known.

Since the temperature and pressure are constant throughout, volume balances can be used (mole fraction is the same as volume fraction). The balances could be made in moles and then converted to the basis of 1000 m^3 .

Steps 7, 8, and 9 The system is the overall process. The balances are

$$\text{Total: } 1000 = P + W$$

$$\text{SO}_2: (0.015)(1000) = 0.0001 P + W (1.000)$$

$$\text{Other: } (0.985)(1000) = 0.9999 P \quad (\text{a tie component})$$

SEPARATION BY MEMBRANES

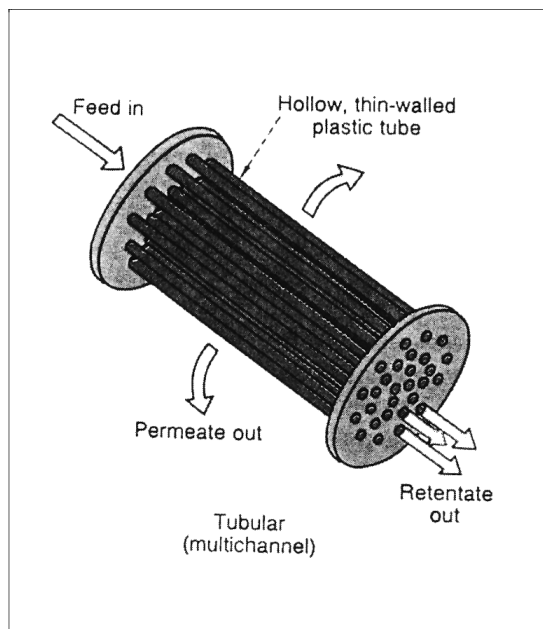


Fig. 17a Tubular membrane separator

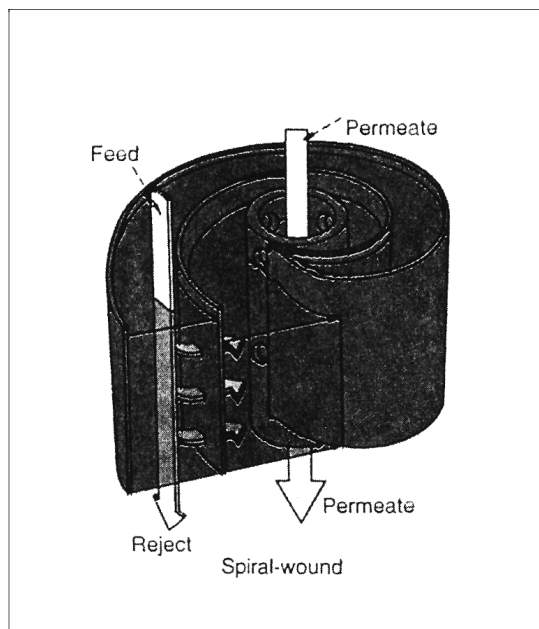


Fig. 17b Spiral wound membrane separator

Membranes are used to separate gaseous mixtures or liquid mixtures. Membrane modules can be tubular, spiral-wound, or plate and frame configurations. Membrane materials are usually proprietary plastic films, ceramic or metal tubes, or gels with hole size, thickness, chemical properties, ion potential, and so on appropriate for the separation. Examples of the kinds of separation that can be accomplished are separation of one gas from a gas mixture, separation of proteins from a solution, dialysis of blood of patients with kidney disease, and separation of electrolytes from non electrolytes.

Two of the balances are independent. Solve any two to get

$$P = 985.1 \text{ m}^3/\text{hr at } 25^\circ\text{C and } 1 \text{ atm}$$

$$\mathbf{W = 14.9 \text{ m}^3/\text{hr at } 25^\circ\text{C and } 1 \text{ atm}}$$

To get R we make a balance on the mixing point where F and R combine to make G

$$\text{Total: } 1000 + R = G$$

$$\text{SO}_2: 0.015(1.000) + 0.0001R = 0.011G$$

$$\text{Other: } (0.985)(1000) + 0.9999R = 0.989G$$

(Two of the balances are independent). Solve the first two to get

$$\mathbf{R = 364 \text{ m}^3/\text{hr at } 25^\circ\text{C and } 1 \text{ atm}}$$

$$G = 1364 \text{ m}^3/\text{hr at } 25^\circ\text{C and } 1 \text{ atm}$$

Step 10 Check

$$0.15(1000) \stackrel{?}{=} 0.001(985.1) + 14.9$$

$$15 = 15 \text{ OK.}$$

Problem 4.1H

In a sulfuric acid plant, sulfur is burned in the presence of excess oxygen to produce sulfur dioxide which in turn is further reacted in the next step with oxygen in a converter to produce sulfur trioxide.

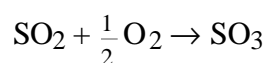
In the plant SO_2 along with 10% excess air is fed into the converter which operates at 1500°C and 1 atm. The per pass conversion of SO_2 is 75% and overall conversion is 100%. If $10^6 \text{ m}^3/\text{hr}$ of SO_3 at 1100°C and 1 atm is fed to the converter, calculate the:

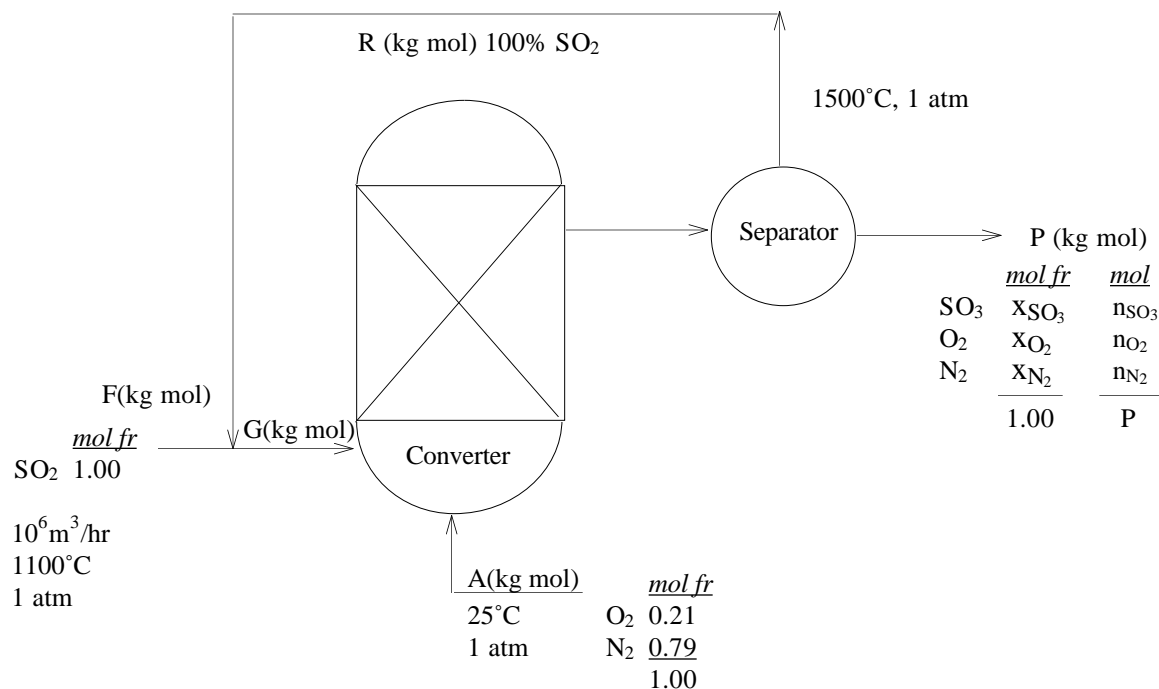
- flow rate of the product stream P in m^3/hr at 1500°C and 1 atm and its composition in mole percent;
- flow rate of the recycle stream R in m^3/hr at 1500°C and 1 atm.

Solution

This is a steady state problem with reaction and recycle.

Steps 1, 2, and 3





Step 5 Basis: $F = 10^6 \text{ m}^3$ at 1100°C and 101.3kPa (equivalent to 1 hr)

Step 4 We will make the balance in moles (m^3 could also be used if A and F are adjusted to 1 atm and 1500°C).

$$n = \frac{pV}{RT} = \frac{101.3(10^6)}{8.314(1100 + 273)} = 8874 \text{ kg mol SO}_2$$

Next, calculate the value of A, the entering air.

Required O ₂ :		$\frac{\text{kg mol}}{3} = 4,437$
Excess O ₂ :		$0.1(4,437) = \underline{444}$
Total		4,881
N ₂ :	$4881 \left(\frac{0.79}{0.21} \right) =$	18,360

Step 6 The system is the overall process. The unknowns are P , n_{SO_3} , n_{O_2} , and n_{N_2} (or P , x_{SO_3} , x_{O_2} , x_{N_2})

Step 7 The balances are: S, O, N, and $\sum n_i = P$ (or $\sum x_i = 1$)

Steps 8 and 9 For the overall process the element balances are (units are kg mol):

S:	$8,874 = P(x_{SO_3}) = n_{SO_3}$
N ₂ :	$18,360 = P(x_{N_2}) = n_{N_2}$
O:	$8,874(2) + 4,881(2) = 8,874(3) + n_{O_2}(2)$

$$n_{\text{SO}_3} = 8,874 \quad n_{\text{N}_2} = 18,360 \quad n_{\text{O}_2} = 444$$

Thus $P = 8,874 + 18,360 + 444 = 27,618$ kg mol or 27,620 kg mol

a. Apply $pV = nRT$

$$V = \frac{(27,620)(8.314)(1500 + 273)}{101.3} = \mathbf{4.02 \times 10^6 \text{ m}^3/\text{hr at } 1500^\circ\text{C and } 1 \text{ atm}}$$

At the mixing point of F and R we get G: $F + R = G$

b. Make the system the reactor plus the separator to avoid having to calculate information about the converter outlet stream. Use an SO_2 balance in kg mol.

$$\frac{\text{In}}{(1.00)(8874+R)} - \frac{\text{Out}}{R(1.00)} + \frac{\text{Gen.}}{0} - \frac{\text{Consum.}}{0.75(8874+R)} = \frac{\text{Accum.}}{0}$$

$R = 2958$ kg mol which corresponds $\mathbf{0.43 \times 10^6 \text{ m}^3/\text{hr at } 1500^\circ\text{C and } 1 \text{ atm}}$

Problem 4.2A

Seven pounds of N_2 at $120^\circ F$ are stored in a cylinder having a volume of 0.75 ft^3 . Calculate the pressure in atmospheres in the cylinder

- (a) assuming N_2 to be an ideal gas
- (b) assuming the pressure of N_2 can be predicted by van der Waal's equation
- (c) using the compressibility factor method
- (d) using the Redlich-Kwong equation of state.

Solution

$$\left. \begin{array}{l} V = 0.75 \text{ ft}^3 \\ T = 120^\circ F = 580^\circ R \\ n = \frac{7 \text{ lb } N_2}{28 \text{ lb } N_2} \left| \frac{1 \text{ lb mol}}{28 \text{ lb } N_2} \right. = 0.25 \text{ lb mol } N_2 \end{array} \right\} \text{Basis}$$

$$R = 10.73 \text{ (psia)(ft}^3\text{)/(lb mol)(}^\circ R\text{)}$$

- a. Using the ideal gas relation $pV = nRT$

$$p = \frac{(0.25)(10.73)(580)}{0.75} \left(\frac{1 \text{ atm}}{14.7 \text{ psia}} \right) = \mathbf{141 \text{ atm (2074 psia)}}$$

- b. Using van der Waals, equation

$$\left(p + \frac{n^2 a}{V^2} \right) (V - nb) = nRT$$

From the text for nitrogen $a = 1.347 \times 10^6 \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2$ and $b = 38.6 \left(\frac{\text{cm}^3}{\text{g mol}} \right)$

$$a = 1.347 \times \frac{\left(\frac{\text{cm}^3}{\text{g mol}} \right)^2}{1 \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2} \left| \frac{3.776 \times 10^{-3} \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2}{1 \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2} \right. = 5086 \left(\frac{\text{ft}^3}{\text{g mol}} \right)^2$$

$$b = \frac{38.6 \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2}{1 \left(\frac{\text{ft}^3}{\text{g mol}} \right)^2} \left| \frac{1.60 \times 10^{-2} \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2}{1 \left(\frac{\text{ft}^3}{\text{g mol}} \right)^2} \right. = 0.6176 \left(\frac{\text{ft}^3}{\text{g mol}} \right)^2$$

Then

$$\left(p + \frac{(0.25)^2 5086}{(0.75)^2} \right) [0.75 - 0.25 (0.6176)] = 0.25 (10.73) \quad (580)$$

$$(p + 565.1) [0.596] = 1556$$

$$\mathbf{p = 20.46 \text{ psi (139 atm)}}$$

c. Using the compressibility factor

$$pV = znRT$$

From Appendix D in the text the critical properties for nitrogen are

$$p_c = 33.5 \text{ atm and } T_c = 126.2\text{K (227}^\circ\text{R)}$$

$$\hat{V}'_c = \frac{RT_c}{p_c} = \frac{(0.7302)(227)}{(33.5)} = 4.95 \text{ ft}^3/\text{lb mol}$$

$$T_r = \frac{T}{T_c} = \frac{580^\circ\text{R}}{227^\circ\text{R}} = 2.56$$

$$\hat{V}'_r = \frac{\hat{V}}{\hat{V}'_c} = \frac{0.75 \text{ ft}^3/0.25 \text{ lb mol}}{4.95 \text{ ft}^3/\text{lb mol}} = 0.61$$

On one of the compressibility charts having the right domain determine the intersection of the $\hat{V}'_r = 0.61$ and the $T_r = 2.56$ lines. Some approximation may be required. From this point you can read z on the vertical and p_r on the horizontal axis:

$$z = 1.05 \quad p_r = 4.5$$

$$p = \frac{znRT}{\hat{V}} = \frac{(1.05)(0.25)(10.73)(580)}{(0.75)} = 2178 \text{ psia (148 atm)}$$

or use p_r :

$$p_r = p/p_c$$

$$p = (p_r)(p_c) = 4.5 (33.5) = 151 \text{ atm}$$

These answers are close enough in view of the accuracy of the original data.

d. Using the Redlich Kwong Equation of State

$$\left[p + \frac{a}{T^{1/2} \hat{V} (\hat{V} + b)} \right] (\hat{V} - b) = RT$$

$$\text{where } a = 0.4278 \frac{R^2 T_c^{2.5}}{p_c} \text{ and } b = 0.0867 \frac{RT_c}{p_c}$$

$$a = 0.4278 \frac{(0.7302)^2 (227)^{2.5}}{(33.5)} = 5286 (\text{°R})^{0.5} (\text{atm}) (\text{ft}^3/\text{lb mol})^2$$

$$b = 0.0867 \frac{(0.7302) (227)}{(33.5)} = 0.429 \text{ ft}^3/\text{lb mol}$$

Substitute these values into the equation

$$\left[p + \frac{5286}{(580)^{1/2} 3 (3 + 0.429)} \right] (3 - 0.429) = (0.7302) (580)$$

$$(p + 20.96) (2.571) = 4235$$

$$p = 144 \text{ atm}$$

The pressures determined by three methods are comparable although not exactly same.

Problem 4.2B

A gas analyzes 60% methane and 40% ethylene by volume. It is desired to store 12.3 kg of this gas mixture in a cylinder having a capacity of $5.14 \times 10^{-2} \text{ m}^3$ at a maximum temperature of 45°C . Calculate the pressure inside the cylinder by

- assuming that the mixture obeys the ideal gas laws;
- using the compressibility factor determined by the pseudo critical point method.

Solution

Basis: 12.3 kg

a. *Ideal Gas Law* $pV = nRT$

$$\text{av mol wt} = \sum y_i MW_i = 0.60 (16) + 0.40 (28) = 20.8 \frac{\text{kg}}{\text{kg mol}}$$

$$n = \frac{12.3 \text{ kg}}{20.8 \text{ kg mixture}} \left| \frac{1 \text{ kg mol mixture}}{20.8 \text{ kg mixture}} \right| = 0.591 \text{ kg mol}$$

$$T = 45^\circ\text{C} = 318\text{K} \quad V = 5.14 \times 10^{-2} \text{ m}^3 \quad R = 8.314 (\text{kPa}) (\text{m}^3)/(\text{kg mol})(\text{K})$$

$$p = \frac{nRT}{V} = \frac{0.591 (8.314)(318)}{5.14 \times 10^{-2}} = 30,400 \text{ kPa}$$

b. *Pseudocritical method*

$$p'_c = \sum_i p_{ci} y_i \qquad T'_c = \sum_i T_{ci} y_i \qquad V'_c = \sum_i V'_{ci} y_i$$

Methane

$$T_c = 190.7\text{K}$$

$$p_c = 45.8 \text{ atm (4640 kPa)}$$

$$V'_c = \frac{RT_c}{p_c} = 0.342 \frac{\text{m}^3}{\text{kg mol}}$$

Ethylene

$$T_c = 283.1 \text{ K}$$

$$p_c = 50.5 \text{ atm (5116 kPa)}$$

$$V'_c = \frac{RT_c}{p_c} = 0.460 \frac{\text{m}^3}{\text{kg mol}}$$

$$T'_c = 0.60 (190.7) + 0.40 (283.1) = 227.7\text{K} \qquad p'_c = 0.60 (4640) + 0.40 (5116) = 4830 \text{ kPa}$$

$$V'_c = 0.60 (0.342) + 0.40 (0.460) = 0.389 \frac{\text{m}^3}{\text{kg mol}}$$

$$T'_r = \frac{T}{T'_c} = \frac{318\text{K}}{227.7\text{K}} = 1.40$$

$$V'_r = \frac{\widehat{V}}{\widehat{V}'_c} = \frac{5.14 \times 10^{-2} \text{ m}^3/0.591 \text{ kg mol}}{0.389 \text{ m}^3/\text{kg mol}} = 0.22$$

Using T'_r and V'_r , we get $p_r = 5.3$ (approximately) so that $p = p_r p'_c = (5.3)(4830) = 26,000 \text{ kPa}$

Problem 4.3A

Calculate the vapor pressure of benzene at 50°C using the Antoine Equation. Also estimate the normal boiling point of benzene (the vapor pressure at 1 atm), and compare it with the experimental value (taken from a handbook).

Solution

$$\text{Antoine Equation} \quad \ln(p^*) = A - \frac{B}{C + T}$$

From Appendix G in the text the coefficients are

$$\begin{array}{ll} \text{Benzene:} & A = 15.9008 \quad T = \text{K} \\ & B = 2788.51 \quad p^* = \text{mmHg} \\ & C = -52.36 \end{array}$$

- a. Vapor Pressure of benzene at 50°C

$$\ln(p^*) = 15.9008 - \frac{2788.51}{-52.36 + (50 + 273)}$$

$$p^* = \mathbf{270 \text{ mmHg abs}}$$

- b. At the boiling point the vapor pressure is 1 atm (760 mmHg abs.)

$$\ln(760) = 15.9008 - \frac{2788.51}{-52.36 + T}$$

$$\text{Solving, } T = \mathbf{353.3\text{K}}$$

From Appendix D in the text the normal boiling point of benzene is **353.26K**. The two values agree well.

Problem 4.3B

Prepare a Cox chart for ethyl acetate. The vapor pressure of ethyl acetate is 200 mmHg abs. at 42°C and 5.0 atm at 126.0°C. By using the chart estimate the

- boiling point of ethyl acetate at 760 mmHg and compare with the experimental value (77.1°C).
- vapor pressure of ethyl acetate at its critical temperature of 523.1K. Compare with the experimental value of 37.8 atm.

Solution

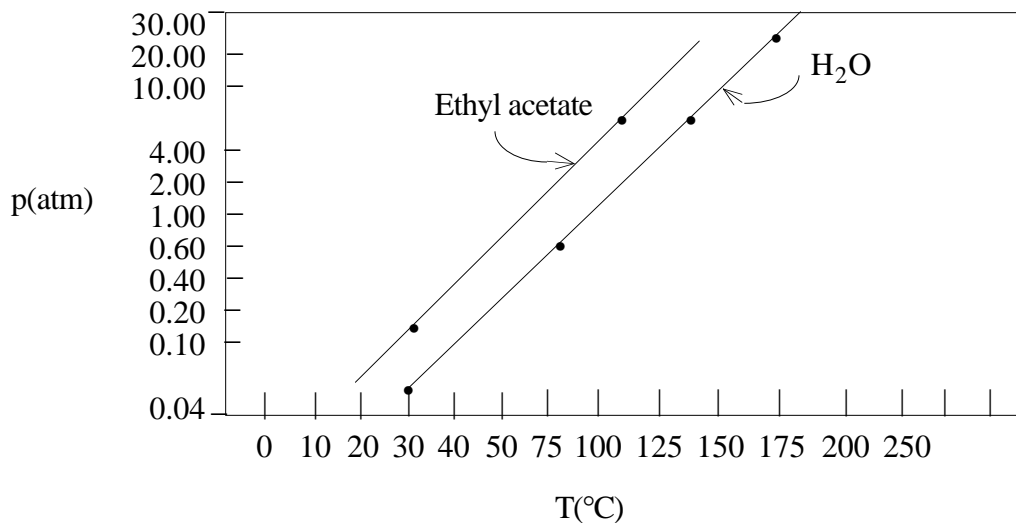
To construct the temperature scale the following data for the vapor pressure of water are used:

T(°C):	30.0	50.0	100.0	150.0	200.0	250.0
p(atm):	0.042	0.122	1.00	4.70	15.36	39.22

The procedure is as follows:

1. First, select a logarithmic vertical scale and place even values of the vapor pressure on the vertical scale to cover the desired pressure range.
2. Then draw a straight line representing the vapor pressure of water at any suitable angle so that you cover the range of temperatures and pressures needed for the problem.
3. To locate each integer value of the water temperature (such as 30, 50, 100, etc.) on the horizontal scale, note the corresponding vapor pressure on the vertical axis, and move horizontally to the line. Then drop vertically down to the temperature axis and mark the axis with the selected temperature (the spacing will not be at even intervals). Repeat to get a series of temperatures.
4. Finally, put the two points given for ethyl acetate on the chart and draw a line between them for ethyl acetate.

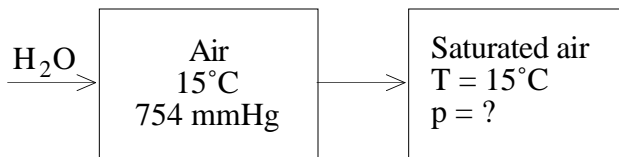
Cox Chart



The normal boiling point is estimated to be between 75°C and 80°C (a bigger chart would produce a more accurate result), and at the critical point (250°C), the estimated vapor pressure is about 50 atm.

Problem 4.4A

If sufficient water is placed in a vessel containing a dry gas at 15°C and 100.5 kPa to thoroughly saturate it, what will be the absolute pressure in the vessel after saturation? The temperature and volume of the vessel remain constant.

Solution

Once the air is saturated with water vapor, the water (if the water vapor is in equilibrium with liquid water) exerts a pressure equal to its vapor pressure at 15°C.

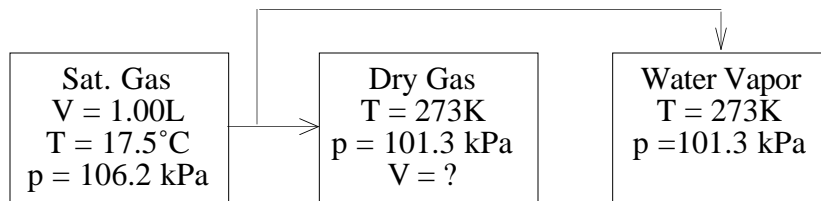
Basis: Dry gas at 15°C and 100.5 kPa

The vapor pressure of H₂O at 15°C = 1.7 kPa. Since the temperature and volume remain constant

$$p_T = p_{\text{air}} + p_{\text{H}_2\text{O}} = 100.5 + 1.7 = \mathbf{102.2 \text{ kPa}}$$

Problem 4.4B

A gas saturated with water vapor in a tank has a volume of 1.00L at 17.5°C and a pressure of 106.2 kPa. What is the volume of dry gas under standard conditions? How many grams of water vapor are present in the gas?

Solution

At the initial conditions the total pressure is the sum of gas pressure and vapor pressure of the water. The first step in the solution involves determining the pressure of the dry gas assuming constant temperature and volume. Look up: $p_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}^*$ (at 17.5°C) = 2.00 kPa

$$p_T = 106.2 \text{ kPa} = p_{\text{H}_2\text{O}}^* + p_{\text{gas}} = 2.00 + p_{\text{gas}} \quad p_{\text{gas}} = 104.2 \text{ kPa}$$

$$\mathbf{a.} \quad \frac{1.00\text{L}}{290.5\text{K}} \left| \frac{273\text{K}}{101.3 \text{ kPa}} \right| \frac{104.2 \text{ kPa}}{101.3 \text{ kPa}} = \mathbf{0.97\text{L at SC}}$$

b. One solution technique is to apply $pV = nRT$ to the water vapor.

$$\frac{1.00\text{L}}{290.5\text{K}} \left| \frac{2.00 \text{ kPa}}{101.3 \text{ kPa}} \right| \frac{1 \text{ atm}}{0.08206 \text{ (L)(atm)}} \left| \frac{1 \text{ (g mol)(K)}}{1 \text{ g mol H}_2\text{O}} \right| \frac{18\text{g H}_2\text{O}}{1 \text{ g mol H}_2\text{O}} = \mathbf{0.015 \text{ g H}_2\text{O}}$$

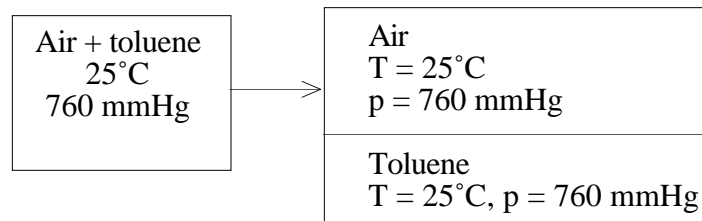
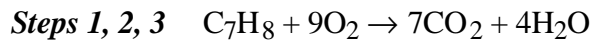
Another approach is to use $pV = nRT$ to calculate the total moles present and multiply the result (0.039 g mol) by the mole fraction water (2.00/106.2).

Problem 4.4C

Dry air at 25°C is saturated with toluene under a total pressure of 760 mmHg abs. Is there adequate air for complete combustion of all the toluene? If so, determine the percent excess air present for combustion.

Solution

The solution involves first determining the number of moles of toluene and the moles of oxygen in a specified volume



Step 5 Basis: 1 g mol C_7H_8

Step 4 From the chemical equation we see 9 mol of O_2 are needed per mol of toluene hence $(9/0.21) = 42.86$ mol of air is needed per mol of toluene. The mole fraction C_7H_8 would be $(1/43.86) = 0.0228$.

Steps 6, 7, 8 and 9 At 25°C, C_7H_8 exerts a vapor pressure of

$$\ln(p^*) = 16.0137 - \frac{3096.52}{-53.67 + (25 + 273.1)}$$

$$p^* = 28.22 \text{ mm Hg abs.}$$

At saturation

$$760 - 28.22 = 731.78 \text{ mm Hg abs.} = p_{\text{air}}$$

$$\frac{p_{\text{air}}}{p_{\text{toluene}}} = \frac{n_{\text{air}}}{n_{\text{toluene}}} = \frac{731.78}{28.22} = 25.93$$

Since the molar ratio of air/toluene required for complete combustion is 42.9, and under the given conditions the air/toluene ratio is only 25.93, the amount of air available is not adequate.

Problem 4.5A

Assume that Raoult's Law holds for the following mixture

	<i>mole%</i>
n-Hexane	20
Benzene	50
Toluene	30

- a. What is the dew point pressure of the mixture if it is at 150°F?
- b. What is the dew point temperature of the mixture if it is at 85 psia?
- c. What is the bubble point temperature of the mixture if it is at 70 psig? The barometer reads 780 mmHg.
- d. What is the bubble point pressure if the mixture is 150°F?

Solution

- a.** The dew point pressure is the pressure of which the vapor first starts to condense at 150°F. The mixture is assumed to be all vapor and the condensate composition is determined by

$$1 = p_T \sum_{i=1}^n \frac{y_i}{p_i^*} \quad \text{or} \quad \frac{1}{p_T} = \sum_{i=1}^n \frac{y_i}{p_i^*}$$

Assume an ideal solution exists and use the Antoine Equation to determine p_i^* for the pure components

$$\ln(p^*) = A - \frac{B}{C + T} \quad T = 150^\circ\text{F} = 338.6\text{K}$$

	A	B	C	p_i^*	y_i	y_i/p_i^*
n-Hexane	15.8366	2697.55	-48.78	684.67	0.20	2.921×10^{-4}
Benzene	15.9008	2788.51	-52.36	472.93	0.50	1.057×10^{-3}
Toluene	16.0137	3096.52	-53.67	171.75	0.30	1.747×10^{-3}
						3.096×10^{-3}

$$\frac{1}{p_T} = \sum \frac{y_i}{p_i^*} = 3.096 \times 10^{-3}$$

$$p_T = 333 \text{ mmHg}$$

- b.** The dew point temperature is the temperature at which the vapor first condenses when the vapor and liquid are in equilibrium. For an ideal solution at 85 psia (4395 mmHg) the relation to use is

$$\frac{1}{p_T} = \sum \frac{y_i}{p_i^*}$$

$$p^* = \exp \left[A - \frac{B}{C + T} \right]$$

$$\frac{1}{4394.6} = \left[\frac{0.2}{e \left(15.8366 - \frac{2697.55}{-48.78 + T} \right)} + \frac{0.5}{e \left(15.9008 - \frac{2788.51}{-52.36 + T} \right)} + \frac{0.3}{e \left(16.0137 - \frac{3096.52}{-53.67 + T} \right)} \right]$$

Solve for T by trial and error (or on a computer) to get

$$\begin{array}{ll}
 T = 500\text{K} & p_T = 13105 \text{ mmHg} \\
 T = 425\text{K} & p_T = 3842 \text{ mmHg} \\
 T = 435\text{K} & p_T = 4321 \text{ mmHg}
 \end{array}
 \qquad
 \mathbf{T \sim 435\text{K}}$$

c. The bubble point temperature at a given pressure is the temperature at which the liquid mixture vapor pressure equals the total pressure. The mixture is assumed to be all liquid and the vapor composition is assumed to be in equilibrium with the liquid. The relation used under these assumptions for an ideal liquid is

$$p_T = \sum P_i^* x_i$$

$$\frac{70 \text{ psi}}{14.696 \text{ psia}} \left| \frac{760.0 \text{ mmHg}}{14.696 \text{ psia}} \right. = 3619 \text{ mmHg}$$

$$p_T = 3619 + 780 = 4399 \text{ mmHg abs.}$$

$$4399 = \left[0.20 e^{\left(15.8366 - \frac{2697.55}{-48.78 + T} \right)} + 0.5 e^{\left(15.9008 - \frac{2788.51}{-52.36 + T} \right)} + 0.3 e^{\left(16.0137 - \frac{3096.52}{-53.67 + T} \right)} \right]$$

Solve for T by trial and error (or on a computer) to get

$$\begin{array}{ll}
 T = 400\text{K} & p = 2372 \text{ mmHg} \\
 T = 425\text{K} & p = 4070 \text{ mmHg} \\
 T = 430\text{K} & p = 4496 \text{ mmHg}
 \end{array}
 \qquad
 \mathbf{T = 429\text{K}}$$

d. The bubble point pressure at 150°F (338.6K) is the pressure at which the liquid first starts to vaporize when the vapor and liquid are in equilibrium

For an ideal liquid

$$p_T = \sum P_i^* x_i$$

	A	B	C	P_i^*	x_i	$P_i^* x_i$
n-Hexane	15.8366	2697.55	-48.78	684.67	0.20	136.93
Benzene	15.9008	2788.51	-52.36	472.93	0.50	236.47
Toluene	16.0137	3096.52	-53.67	171.75	0.30	51.53
						424.9

$$\mathbf{p_T = 425 \text{ mmHg}}$$

Problem 4.5B

A natural gas has the following analysis at 400 kPa

	<u>Mole%</u>
Propane	78.0
Butane	12.0
Pentane	10.0

Its temperature must be kept above what value to prevent condensation? If it were cooled, what would be the composition of the liquid that first condenses out of the gas?

Solution

Basis: 1.00 mol gas at 400 kPa.

Assume ideal vapor and liquid at the dew point. $x_i = y_i/K_i$ $\sum x_i = 1$ $K_i = p_i^* / p_T$
 $\sum (y_i / K_i) = 1$ or $p_T \sum (y_i / p_i^*) = 1$ for an ideal solution.

Procedure

Assume a temperature and obtain values for p_i^* from the Antoine equation or, a handbook. Calculate $(\sum y_i / p_i^*) p_T$ to see if the sum equals 1.0. If not, repeat to bracket the value 1.

1st iteration, let T = 310K

	p_i^* (kPa)	y_i / p_i^*	$p_T \sum (y_i / p_i^*)$
C ₃	1269	6.147×10^{-4}	
C ₄	343.4	3.494×10^{-4}	$400(1.999 \times 10^{-3}) = 0.768$
C ₅	104.7	9.551×10^{-4}	
		$\sum = 1.919 \times 10^{-3} (\text{kPa})^{-1}$	

2nd iteration, let T = 290K

	p_i^*	y_i / p_i^*	$p_T \sum (y_i / p_i^*)$
C ₃	765	1.020×10^{-3}	
C ₄	186.5	6.434×10^{-3}	$400 (3.644 \times 10^{-3}) = 1.457$
C ₅	50.5	1.980×10^{-3}	
		$\sum = 3.644 \times 10^{-3} (\text{kPa})^{-1}$	

3rd iteration T = 300K

	p_i^*	y_i / p_i^*	$p_T \sum (y_i / p_i^*)$
C ₃	993.5	7.851×10^{-4}	$400 (2.610 \times 10^{-3}) = 1.04$
C ₄	255.9	4.689×10^{-4}	close enough
C ₅	73.76	1.356×10^{-3}	
		$\sum = 2.610 \times 10^{-3} (\text{kPa})^{-1}$	$T \cong 300\text{K}$

At the dew point temperature, the liquid which first condenses has the composition

$$x_i = y_i P_T / p_i^*$$

$$\frac{y_i P_T}{p_i^*}$$

$$x_{C_3} = \frac{(0.78)(400 \text{ kPa})}{993.5 \text{ kPa}} = 0.314$$

$$x_{C_4} = \frac{(0.12)(400 \text{ kPa})}{255.9 \text{ kPa}} = 0.188$$

$$x_{C_5} = \frac{(0.10)(400 \text{ kPa})}{73.76 \text{ kPa}} = 0.542$$

$$\sum x_i = 1.04$$

Problem 4.6A

A gas mixture contains 0.0083 g mol of water vapor per g mol of dry CH_4 at a temperature of 27°C and a total pressure of 200 kPa. Calculate the:

- percent relative saturation of the mixture.
- percent saturation of the mixture
- temperature to which the mixture must be heated at 200 kPa in order that the relative saturation will be 0.20.

Solution

Basis: 1 lb mol CH_4

$$P_{\text{H}_2\text{O}}^* (27^\circ\text{C}) = 3.536 \text{ kPa}$$

$$P_{\text{total}} = 200 \text{ kPa}$$

$$P_{\text{H}_2\text{O}} = P_{\text{total}} y_{\text{H}_2\text{O}}$$

$$\text{a. Percent relative saturation} = \frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2\text{O}}^*} (100)$$

$$y_{\text{H}_2\text{O}} = \frac{0.0083}{1 + 0.0083} = 0.0082$$

$$P_{\text{H}_2\text{O}} = (200 \text{ kPa}) (0.0082) = 1.64 \text{ kPa}$$

$$\frac{1.64}{3.536} (100) = \mathbf{46.4\%}$$

$$\text{b. Percent saturation} = (\text{rel. saturation}) \left(\frac{P_{\text{T}} - P_{\text{i}}^*}{P_{\text{T}} - P_{\text{i}}} \right) 100$$

$$= (0.464) \left(\frac{200 - 3.54}{200 - 1.64} \right) 100 = \mathbf{46.0\%}$$

Note that the percent saturation is always less than the percent relative saturation.

c. In the heating at constant pressure, the mole fraction of the water vapor does not change so $P_{\text{H}_2\text{O}} = 1.64 \text{ kPa}$.

$$\frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2\text{O}}^*} = 0.20 \quad \text{or} \quad \frac{1.64}{P_{\text{H}_2\text{O}}^*} = 0.20$$

The vapor pressure has to be calculated to get the temperature.

$$P_{\text{H}_2\text{O}}^* = \frac{1.64}{0.20} = 8.2 \text{ kPa and from stream table} \quad \mathbf{T = 315\text{K} (42^\circ\text{C})}$$

Problem 4.6B

A gas at 200°F and 30 in Hg abs. has a molal humidity of 0.10. Calculate:

- the percentage humidity
- the relative humidity
- the dew point of the gas (°F)

Solution

$$p_{\text{H}_2\text{O}}^*(\text{at } 200^\circ\text{F}) = 11.525 \text{ psia}$$

$$p_{\text{T}} = 30 \text{ in Hg} = 1.003 \text{ atm} = 14.74 \text{ psia}$$

$$\text{molal humidity} = \frac{n_{\text{vapor}}}{n_{\text{vapor free gas}}} = \frac{p_{\text{vapor}}}{p_{\text{vapor gas}}}$$

$$\left. \begin{array}{l} \frac{p_{\text{H}_2\text{O}}}{p_{\text{gas}}} = 0.10 \\ p_{\text{T}} = p_{\text{H}_2\text{O}} + p_{\text{gas}} \end{array} \right\} \begin{array}{l} p_{\text{H}_2\text{O}} = 1.34 \text{ psia} \\ p_{\text{gas}} = 13.4 \text{ psia} \end{array}$$

$$\text{a. Percentage humidity} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*} \left(\frac{p_{\text{T}} - p_{\text{H}_2\text{O}}}{p_{\text{T}} - p_{\text{H}_2\text{O}}^*} \right) 100 = \mathbf{2.79\%}$$

$$\text{b. Relative humidity} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*} (100) = \mathbf{11.6\%}$$

c. The dew point of the gas can be determined from the steam tables. It is the temperature of which the partial pressure is equal to the vapor pressure of vapor (cooling at constant total pressure)

$$p_{\text{H}_2\text{O}} = 1.34 \text{ psia} = p^*$$

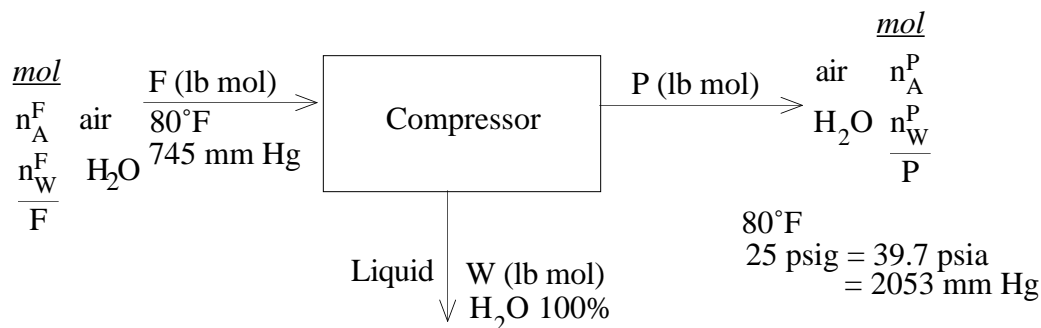
The corresponding T is **T = 112°F**

Problem 4.7A

Air saturated with water vapor at 80°F and 745.0 mm Hg abs. is passed through an air compressor and then stored in a tank at 25.0 psig and 80°F. What percentage of the water originally in the air was removed during the processing?

Solution

This problem can be treated as a steady state problem without reaction, or as an unsteady state problem. We will carry out the solution as a steady state problem. Recall that the water vapor condenses on compression so that the compressed gas is still saturated.

Steps 1, 2, 3, and 4

Step 5 Several basis can be considered: $F = 100$ lb mol, $P = 100$ lb mol, $W = 100$ lb mol, $F = 745$ lb mol, and so on, but we will take a tie component as a convenient basis

Basis: $F = 1.00$ lb mol

Step 4 Calculate the gas compositions.

F	P
p_W^* at 80°F is 0.5067 psia (26.2 mm Hg abs.)	$p_W^* = 26.2$ mm Hg
p_A in F = 745 - 26.2 = 718.8 mm Hg	p_A in P = 2053 - 26.2 = 2027 mm Hg
$\frac{n_A^F}{n_T^F} = \frac{p_A^F}{p_T^F} = \frac{718.8}{745}$	$\frac{n_A^P}{n_T^P} = \frac{p_A^P}{p_T^P} = \frac{2027}{2053}$

Steps 6, 7, 8 and 9

We can make two component balances and one total balance ($F = P + W$) of which two are independent. Two unknowns exist: W and P .

$$\text{Total balance (lb mol)} \\ 1.00 = P + W$$

$$\text{Air balance (lb mol)} \\ 1.00 \left(\frac{718.8}{745} \right) = P \left(\frac{2027}{2053} \right) \text{ so that } P = 0.977 \text{ lb mol}$$

$$W = 1.00 - 0.977 = 0.023 \text{ lb mol}$$

$$100 (0.023/0.0364) = 63\%$$

GAS COMPRESSORS (TURBO COMPRESSORS)

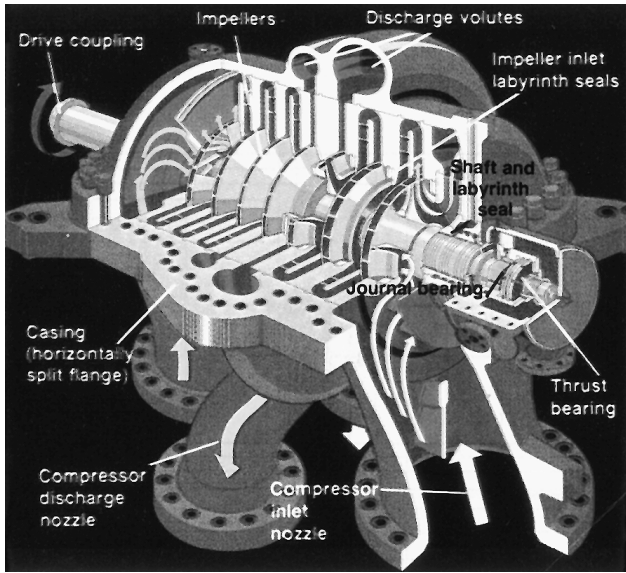


Fig. 18a Centrifugal compressor, quarter section open

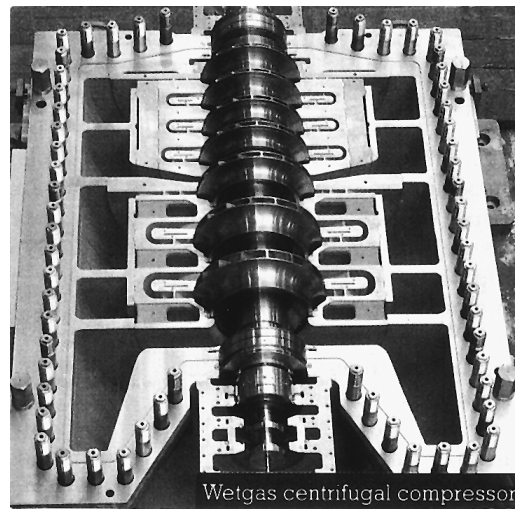


Fig. 18b One half section of a wet gas centrifugal compressor (courtesy of SultzerturboSystems)

Compressors take in gas at one pressure and release it at a higher pressure. Some axial flow compressors have adjustable guide vanes such as occur in units for natural gas liquification. A minimum flow exists below which the compressor operation becomes unstable (surges) and back flow can occur as well as mechanical damage. A different type of compressor found in common use is the reciprocating compressor which uses pistons to compress gases to higher pressures than can be achieved with axial flow units, but can only handle smaller volumes of gas. Both types of compressors can be used in stages to achieve higher pressures than provided by a single unit. The approximate range of functioning of compressors is in Fig. 18c.

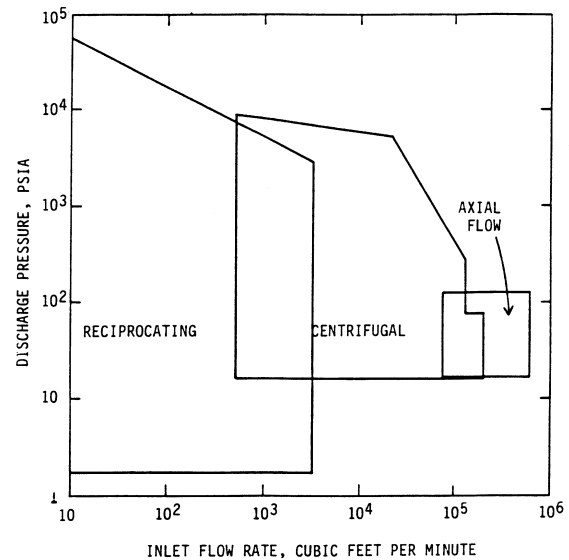


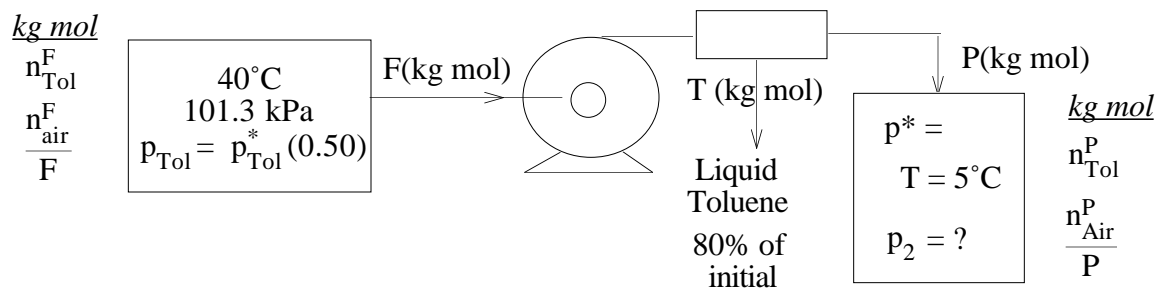
Fig. 18c Range of operation of compressors

Problem 4.7B

Toluene is evaporated into dry air. The resulting mixture at 40°C and a pressure of 101.3 kPa has a percentage saturation of 50%. It is desired to condense 80% of the toluene in the mixture by a process of cooling and compressing. If the temperature is reduced to 5°C, determine the pressure to which gas must be compressed.

Solution

Steps 1, 2, and 3, This is a steady state process without reaction.



Step 4 Use the Antoine Equation for toluene to get p^* for toluene

$$A = 16.0137$$

$$B = 3096.52$$

$$C = -53.67$$

$$\ln(p^*) = A - \frac{B}{C + T}$$

$$\text{at } T = 40^\circ\text{C}$$

$$p_T^* = 58.71 \text{ mm Hg abs.}$$

$$\text{at } T = 5^\circ\text{C}$$

$$p_T^* = 9.118 \text{ mm Hg abs.}$$

$$p_{\text{Total}} = 101.3 \text{ kPa} = 760 \text{ mm Hg. At } 40^\circ\text{C}$$

$$p_{\text{Tol}} = 0.50 p_{\text{Tol}}^* = 0.50 (58.71) = 29.36 \text{ mm Hg}$$

Step 5 Basis: $F = 100 \text{ kg mol}$

Step 4 The toluene condensed is

$$T = 0.80(100) (0.0386) = 3.088 \text{ kg mol}$$

Calculate the composition of the inlet gas.

$$\frac{n_{\text{Tol}}^F}{n_{\text{Tot}}^F} = \frac{p_{\text{Tol}}^F}{p_{\text{Tot}}^F} = \frac{29.36}{760} = 0.0386$$

Step 6 Unknown are: n_{Air}^P , n_{Tol}^P , P

Steps 7, 8, and 9

An overall balance, an air balance, and a toluene balance can be written; only two are independent. But $n_A^P + n_{Tol}^P = P$ is the third equation needed.

$$\text{Air balance (kg mol):} \quad 100 (1 - 0.0386) = n_{Air}^P$$

$$\text{Toluene balance (kg mol):} \quad 100 (0.0386) = 3.088 + n_{Tol}^P$$

Note that because of condensation, the toluene in P is saturated, and amounts to 20% of the original toluene, or 0.77 kg mol. The partial pressure of the saturated toluene in P is 9.118 mm Hg abs.

$$\frac{p_{Tol}}{p_{Tot}} = \frac{p_{Tol}^*}{p_{Tot}} = \frac{n_{Tol}}{n_{Tot}} = \frac{0.77}{0.77 + 96.14} = \frac{0.77}{96.91}$$

$$p_{Tot} = 9.118 \left(\frac{96.91}{0.77} \right) = \mathbf{1150 \text{ mm Hg abs. (153 kPa)}}$$

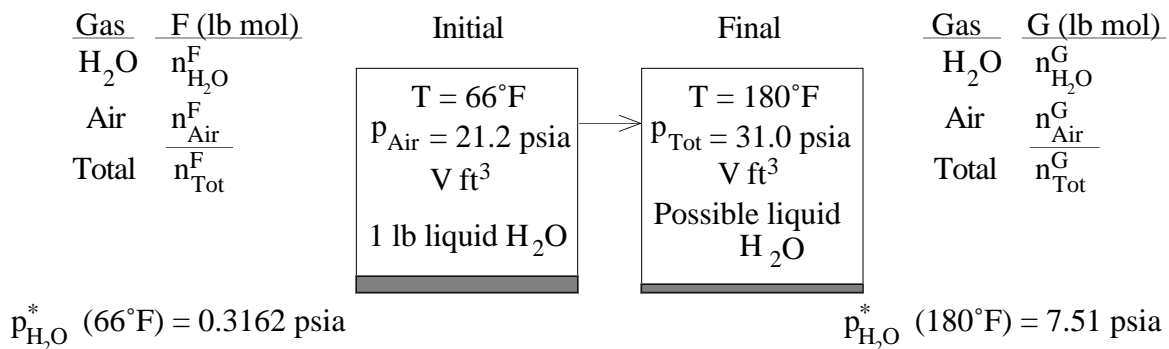
Problem 4.7C

A constant-volume vessel contains dry air at 66°F and 21.2 psia. One pound of liquid water is introduced into the vessel. The vessel is then heated to a constant temperature of 180°F. After equilibrium is reached, the pressure in the vessel is 31.0 psia. The vapor pressure of water at 180°F is 7.51 psia.

- Did all of the water evaporate?
- Compute the volume of the vessel in cubic feet.
- Compute the humidity of the air in the vessel at the final conditions in pounds of water per pound of air.

Solution

Steps 1, 2, and 3 Assume the liquid water occupies a negligible volume in the vessel. The system is the vessel.



Step 5 Basis: Initial gas at conditions shown in the Figure.

Steps 6, 7, 8, and 9

First we have to determine if all the water is vaporized or not in the vessel. We can calculate the partial pressure of the air in the vessel at 180°F by applying the ideal gas law to both the initial and final conditions, and using as the material balance the equality of the initial and final moles of air, $n_{\text{Air}}^{\text{F}} = n_{\text{Air}}^{\text{G}}$.

$$\frac{p_{\text{Air}}^{\text{F}} V}{p_{\text{Air}}^{\text{G}} V} = \frac{n_{\text{Air}}^{\text{F}} R T^{\text{F}}}{n_{\text{Air}}^{\text{G}} R T^{\text{G}}}$$

$$\text{or } p_{\text{Air}}^{\text{G}} = p_{\text{Air}}^{\text{F}} \left(\frac{T^{\text{G}}}{T^{\text{F}}} \right) = 21.2 \left(\frac{180 + 460}{66 + 460} \right) = 26.9 \text{ psia}$$

Thus, the pressure of the water vapor in the air at the final conditions is

$$p_{\text{H}_2\text{O}}^{\text{G}} = 31.1 - 26.9 = 4.2 \text{ psia}$$

Because $4.2 < 7.51 \text{ psia}$, the air at the final state is not saturated.

- a.** All the water vaporizes
b. We can calculate the volume of the vessel from the final given conditions plus the value of the partial pressure of the water vapor in the final state

$$V_{\text{H}_2\text{O}} = \frac{n_{\text{H}_2\text{O}}^{\text{G}} RT^{\text{G}}}{P_{\text{H}_2\text{O}}^{\text{G}}} = \frac{(\frac{1}{18})(0.73)(640)}{4.2} = \mathbf{90.8 \text{ ft}^3}$$

The volume of the water vapor at its partial pressure is the same as the volume of the vessel.

- c.** The humidity is

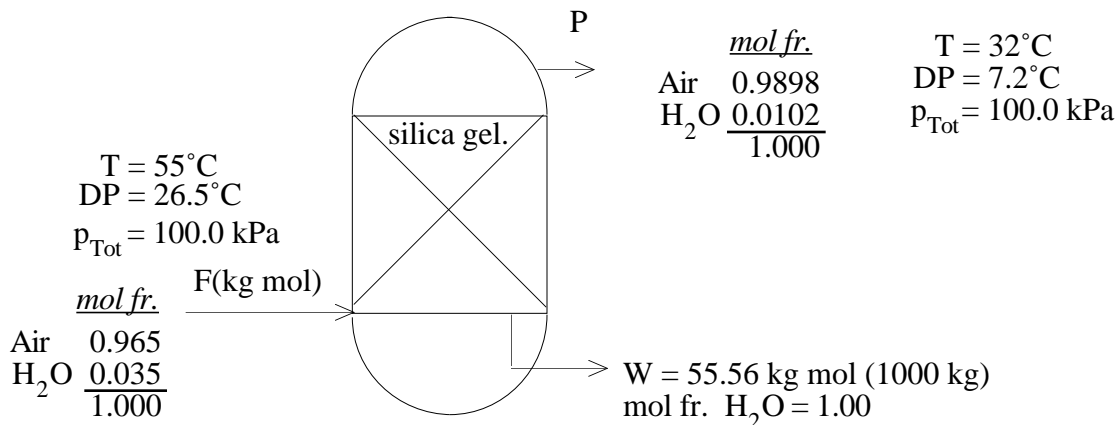
$$\frac{4.2 \text{ lb mol H}_2\text{O}}{26.9 \text{ lb mol air}} \left| \frac{18 \text{ lb H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| \frac{1 \text{ lb mol air}}{29 \text{ lb air}} = 0.097 \frac{\text{lb H}_2\text{O}}{\text{lb air}}$$

Problem 4.7D

A silica gel drier removes 1000 kg of water per hour. Air is supplied at a temperature of 55°C and a dew point of 26.5°C. The air leaves the drier at a temperature of 32°C and a dew point of 7.2°C. The pressure in the system is constant at 100.0 kPa. Calculate the volume of the wet air (at the initial conditions) which is supplied per hour.

Solution

Steps 1, 2, 3 and 4 Some of the data in the figure have been calculated in Step 4 below. The process is a steady state one without reaction. Because gas are involved, the calculations will be in moles. The systems is the drier.



Step 5 Basis: 1 hour

Step 4 $p_{\text{H}_2\text{O}}^* (26.5^\circ\text{C}) = 3.50 \text{ kPa}$

$p_{\text{H}_2\text{O}}^* (7.2^\circ\text{C}) = 1.02 \text{ kPa}$

Calculate the stream compositions first.

Inlet air

$p_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}^* (26.5^\circ\text{C}) = 3.50 \text{ kPa}$

$p_{\text{T}} = 100.0 \text{ kPa}$

Outlet air

$p_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}^* (7.2^\circ\text{C}) = 1.02 \text{ kPa}$

$p_{\text{T}} = 100.0 \text{ kPa}$

Step 6 Unknowns are F and P

Step 7 Balances are H₂O and air (or total)

Steps 8 and 9

$$\left. \begin{array}{l} \text{Air: } F(0.965) = P(0.9898) \\ \text{H}_2\text{O: } F(0.035) = P(0.0102) + 55.56 \end{array} \right\} F = 2214 \text{ kg mol}$$

$$V = \frac{nRT}{p} = \frac{(2214)(8.314)(328)}{100.0} = 6.04 \times 10^4 \text{ m}^3/\text{hr}$$

at 55°C and 100 kPa

CHAPTER 4 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 4.1

4.1A In a test on an oil-fired boiler, it is not possible to measure the amount of oil burned, but the air used is determined by inserting a venturi meter in the air line. It is found that 5000 ft³/min of air at 80°F and 10 psig is used. The dry gas analyzes CO₂, 10.7 percent; CO, 0.55 percent; O₂, 4.75 percent; and N₂, 84.0 percent. If the oil is assumed to be all hydrocarbon, calculate the gallons per hour of oil burned. The sp gr of the oil is 0.94.

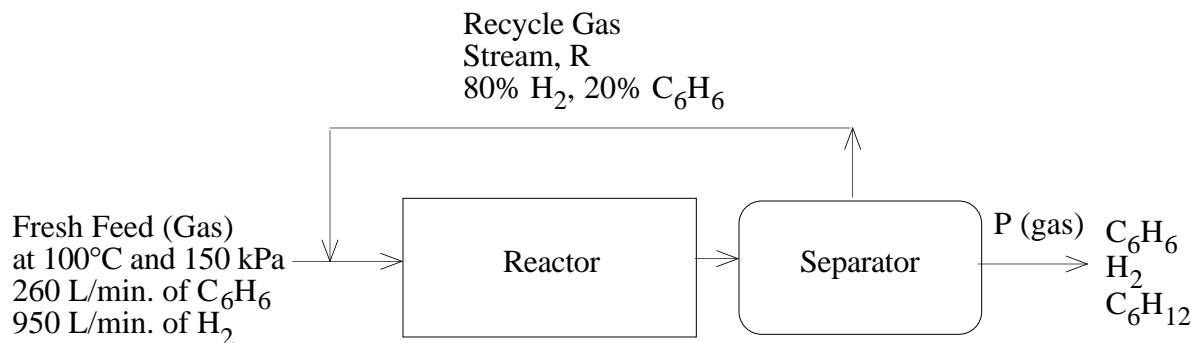
4.1B In the manufacture of dry ice, a fuel is burned to a flue gas which contains 16.2 percent CO₂, 4.8 percent O₂, and the remainder N₂. This flue gas passes through a heat exchanger and then goes to an absorber. The data show that the analysis of the flue gas entering the absorber is 13.1 percent CO₂ with the remainder O₂ and N₂. Apparently something has happened. To check your initial assumption that an air leak has developed in the heat exchanger, you collect the following data with a wet-test meter on the heat exchanger:

Entering flue gas in a 2-min period 47,800 ft³ at 600°F and 740 mm of Hg
 Exit flue gas in a 2-min period 30,000 ft³ at 60°F and 720 mm of Hg

Was your assumption about an air leak a good one, or was perhaps the analysis of the gas in error? Or both?

4.1C. Benzene (C₆H₆) is converted to cyclohexane (C₆H₁₂) by direct reaction with H₂. The fresh feed to the process is 260 L/min of C₆H₆ plus 950 L/min of H₂ at 100°C and 150 kPa. The single pass conversion of H₂ in the reactor is 48% while the overall conversion of H₂ in the process is 75%. The recycle stream contains 80% H₂ and the remainder benzene (no cyclohexane).

- (a) Determine the molar flow rates of H₂, C₆H₆, and C₆H₁₂ in the exiting product.
- (b) Determine the volumetric flow rates of the product stream if it exits at 100 kPa and 200°C.
- (c) Determine the molar flow rate of the recycle stream, and the volumetric flow rate if the recycle stream is at 100°C and 100 kPa.



4.1D. A natural gas at 30°C has the composition of

CH ₄	80%
C ₂ H ₄	10
N ₂	10

If the pressure in the line is 100 kN/m^2 , what are the partial pressures of the three components? If the temperature is raised to 40°C , will the partial pressures change? If so, what will they be?

Section 4.2

- 4.2A Find the molar volume (in $\text{cm}^3/\text{g mol}$) of propane at 375 K and 21 atm . Use the Redlich-Kwong and Peng-Robinson equations, and solve for the molar volume using (1) a nonlinear equation solver, and (2) the compressibility factor method. The acentric factor for propane to use in the Peng-Robinson equation is 0.1487 . Also, check your results with the value found in a data base or a handbook.
- 4.2B What weight of ethane is contained in a gas cylinder of 1.0 ft^3 in volume if the gas is at 100°F and 2000 psig ? Use (1) an equation of state and (2) the compressibility factor method.
- 4.2C Calculate the volume occupied by 2.0 lb air at 735 psia and 392°F .

Section 4.3

- 4.3A Estimate the vapor pressure of aniline at 350°C from the following vapor pressure data (the experimental vapor pressure is 40 atm):

$t(^{\circ}\text{C})$	184.4	212.8	254.8	292.7
$p^*(\text{atm})$	1.00	2.00	5.00	10.00

- (a) Prepare a Cox chart to solve this problem.
 (b) Fit the coefficients in Antoine equation using a nonlinear optimization code or a nonlinear regression code, and predict the value from the Antoine equation.
- 4.3B Estimate the vapor pressure of benzene at 125°C from the vapor pressure data

$T(^{\circ}\text{F})$:	102.6	212
$p^*(\text{psia})$:	3.36	25.5

by preparing a Cox chart.

Section 4.4

- 4.4A Carbon disulfide (CS_2) at 20°C has a vapor pressure of 352 mm Hg . Dry air is bubbled through the CS_2 at 20°C until 4.45 lb of CS_2 are evaporated. What was the volume of the dry air required to evaporate this CS_2 (assuming that the air is saturated) if the air was initially at 20°C and 10 atm and the final pressure on the air- CS vapor mixture is 750 mm Hg ?

- 4.4B A mixture of acetylene (C_2H_2) with an excess of oxygen measured 350 ft^3 at 25°C and 745 mm pressure. After explosion the volume of the dry gaseous product was 300 ft^3 at 60°C and its partial pressure of 745 mm . Calculate the volume of acetylene and of oxygen in the original mixture. Assume that the final gas was saturated and that only enough water was formed to saturate the gas.
- 4.4C An 8.00-liter cylinder contains a gas saturated with water vapor at 25.0°C and a pressure of 102.6 kPa . What is the volume of the gas when dry at standard conditions?
- 4.4D Oxalic acid ($H_2C_2O_4$) is burned with 248 percent excess air, 65 percent of the carbon burning to CO . Calculate the dew point of the flue gas.

Section 4.5

- 4.5A Equilibrium flash vaporization of a liquid mixture of ethane (15 mol), propane (15 mol), n-butane (15 mol), and pentane (15 mol) at 140°F and 200 psia takes place in a vessel. What ratio of liquid to vapor exists when vaporization is complete. K-values are respectively 3.70, 1.38, 0.57, and 0.21.
- 4.5B A vapor composed of 30 percent n-hexane, 30% n-heptane, and 40% n-octane is partially condensed at 100 kPa . Assume that the vapor and liquid are ideal solutions. Calculate the mole fractions of the three components in the vapor at equilibrium if 80 percent of the original vapor condenses.
- 4.5C A solution containing 12 wt percent of dissolved nonvolatile solid is fed to a flash distillation unit. The molecular weight of the solid is 123.0. The effective vapor pressure of the solution is equal to

$$p = p^*x$$

where p = effective vapor pressure of the solution
 x = mole fraction of water
 p^* = vapor pressure of pure water

The pressure in the flash distillation unit is 1.121 psia and the temperature is 100°F . Calculate the pounds of pure water obtained in the vapor stream per 100 lb of feed solution and the weight percent of the dissolved nonvolatile solid leaving in the liquid stream.

- 4.5D Consider a tank of water at 0°C under a pressure of 101.3 kPa at the surface of the water. Would it be possible to maintain ice at the bottom of the water tank at 0°C in equilibrium with the water?

Section 4.6

- 4.6A Toluene is mixed with air at 21°C in such proportions that the partial pressure of the vapor is 1.33 kPa . The total pressure is 99.3 kPa . Calculate the following:
- The relative saturation.
 - The moles of toluene per mole of vapor-free gas.
 - The weight of toluene per unit weight of vapor-free gas.
 - The percent saturation.
 - The percentage of toluene by volume.

- 4.6B A rigid vessel which is 1 ft³ in volume contains 1 lb of N₂ and 1 lb of H₂O at 100F.
- What is the pressure (psia) in the vessel?
 - What is the molal humidity in the vapor phase?
 - What mass fraction of the water is liquid?
- 4.6C Around airports jet aircrafts can become major contributors to pollution, and as aircraft activity increases and public concern brings other sources under control, the relative contribution of aircraft to pollution could go up. Recently, federal-, state-, and local-government pressure has speeded the introduction of new combustors in aircraft. In a test for an aircraft fuel with the average composition C_{1.20}H_{4.40}, the fuel is completely burned with the exact stoichiometric amount of air required. The air is supplied at 24°C and 100 kPa, with a humidity of 80 percent.

For the entering air, compute the following:

- The dew point.
- The molal humidity.
- The relative humidity.

Section 4.7

- 4.7A Leather containing 100 percent of its own weight of water (i.e., if the dry leather is 1 lb, the water is 1 lb) is dried by means of air. The dew point of the entering air is 40°F, and in the exit air it is 55°F. If 2000 lb of leather are forced through the dryer per hour, how many pounds of water are removed per hour? The barometer reads 750 mm Hg.

The following is the solution to the problem. Explain whether the solution is correct or not. If not, what is the solution?

Basis: 750 lb mol wet air in

$$p_{\text{H}_2\text{O}}^* \text{ at } 40^\circ\text{F} = 6.29 \text{ mm Hg}$$

$$p_{\text{H}_2\text{O}}^* \text{ at } 55^\circ\text{F} = 11.05 \text{ mm Hg}$$

$$\text{lb mol dry air in} = 750 - 6.29 = 743.7 \text{ lb mol}$$

$$\text{lb mol dry air out} = 750 - 11.05 = 739 \text{ lb mol}$$

$$\frac{6.29 \text{ lb mol}}{1 \text{ lb mol}} \bigg| \frac{18 \text{ lb}}{1 \text{ lb mol}} = 114 \text{ lb H}_2\text{O}$$

Dry air balance

$$\text{H}_2\text{O}_{\text{out}} = \frac{11.05 \text{ lb mol}}{739} \bigg| \frac{743.7}{739} \bigg| \frac{18 \text{ lb}}{1 \text{ lb mol}} = 200 \text{ lb H}_2\text{O}$$

$$\text{H}_2\text{O}_{\text{absorbed}} = 200 - 114 = 86 \text{ lb H}_2\text{O}$$

<i>Comp.</i>	<i>mol</i>	<i>mol fract</i>	<i>mol fract</i>	<i>M.W.</i>	<i>lb</i>
Dry Air	743.7	0.991	0.991	29	28.7
H ₂ O	<u>6.29</u>	<u>0.009</u>	<u>0.009</u>	18	<u>0.2</u>
Total	750	1.0	1.0		28.9

Basis: 2000 lb leather (1 hr)

$$\frac{2000 \text{ lb leather}}{1 \text{ hr}} \left| \frac{0.50 \text{ lb H}_2\text{O}}{1 \text{ lb leather}} \right| \frac{86 \text{ lb H}_2\text{O removed}}{114 \text{ lb H}_2\text{O in}} = 75.4 \text{ lb / hr}$$

- 4.7B Air at 300K and 100 kPa has a dew point of 289K.
- What is the percent relative humidity?
 - To what pressure must this air be compressed to cause condensation to start (the temperature remains at 300K)?
 - To what temperature must this air be cooled to remove 25 percent of the moisture (the pressure stays constant at 100 kPa)?
 - What would be the percent relative humidity of this air after heating to 340K (at constant pressure)?
 - Did the molal saturation change during the heating indicated in part (d)?
- 4.7C Air saturated with water vapor is at 140°F and a pressure of 29.68 in. Hg.
- To what temperature must the air be cooled to separate 68 percent of the water in it as liquid water (pressure is constant)?
 - To what pressure must the air be compressed to separate 68 percent of the water in it as liquid water (temperature is constant)?
 - If the temperature is reduced to 100°F and the gas is compressed to 25 psia, what percentage of the water separates out as liquid?
- 4.7D Soybean flakes from an extraction process are reduced from 0.96 lb of C_2HCl_3 per pound of dry flakes to 0.05 lb of C_2HCl_3 per pound of dry flakes in a desolventizer by a stream of N_2 which vaporizes the C_2HCl_3 . The entering N_2 contains C_2HCl_3 such that its dew point is 30°C. The N_2 leaves at 90°C with a relative saturation of 60%. The pressure in the desolventizer is 760 mmHg, and 1000 lb/hr of dry flakes pass through the drier.
- Compute the volume of N_2 plus C_2HCl_3 leaving the desolventizer at 90°C and 760 mm Hg in cubic feet per minute.
 - The N_2 leaving the desolventizer is compressed and cooled to 40°C, thus condensing out the C_2HCl_3 picked up in the desolventizer. What must the pressure in the condenser be if the gas is to have a dew point of 30°C at the pressure of the desolventizer?