temperature and mole fractions are not even close to values in Table 2-1. Explain why not.

A12. Why is there a difference between degrees of freedom for equilibrium and degrees of freedom for complete design? Example: binary flash. Gibbs phase rule, $F = C - P + 2 = 2$; entire design $F = 6$.

A13. Is a binary flash distillation system fully specified if we specify F, T_1, p_1, z, T_{drum}, and V even though V is an extensive variable? If it is, explain how Gibbs phase rule is satisfied.

A14. Table 2-4 is at a pressure of 1.0 kg/cm^2 (actually kgf/cm^2), which was formerly a fairly common pressure unit. What is the pressure in bar and in atm?

B. *Generation of Alternatives*

B1. Think of all the ways a binary flash distillation problem can be specified. For example, we have usually specified F, z, T_{drum}, p_{drum} in addition to T_1 and p_1. If T_1 and p_1 are constant, what other combinations of variables can be used? (I have over 20.) Then consider how you would solve the resulting problems.

B2. An existing flash drum is available. The vertical drum has a demister and is 4 ft in diameter and 12 ft tall. The feed is 30.0 mol% methanol and 70.0 mol% water. A vapor product that is 58.0 mol% methanol is desired. We have a feed rate of 25,000 lbmol/h. Operation is at 1.0 atm pressure. Since this feed rate is too high for the existing drum, what can be done to produce a vapor of the desired composition? Design processes using both the existing plus new equipment (if needed). You should devise at least three alternatives. Data are given in Problem 2.D1.

C. *Derivations*

C1. Determine the effect of pressure on the temperature, separation and diameter of a flash drum.

C2. Analytically solve the Rachford-Rice equation for V/F for a binary system.

C3. Assume that vapor pressure can be calculated from the Antoine equation and that Raoult's law can be used to calculate K values. For a binary flash system, solve for the drum pressure if drum temperature and V/F are given.

C4. Prove that the operating and $y = x$ lines for binary flash distillation intersect at $y = x = z$.

C5. Choosing to use V/F to develop the Rachford-Rice equation is conventional but arbitrary. We could also use L/F, the fraction remaining liquid, as the trial variable. Develop the Rachford-Rice equation as f(L/F).

C6. In flash distillation a liquid mixture is partially vaporized. We could also take a vapor mixture and partially condense it. Draw a schematic diagram of partial condensation equipment. Derive the equations for this process. Are they different from flash distillation? If so, how?

C7. Plot Eq. (2-40a) versus V/F for Example 2-2 to illustrate that convergence is not as linear as the Rachford-Rice equation.

C8. For a vapor-liquid-liquid flash distillation, derive Eqs. (2-59) and (2-60) and the equations that allow calculation of all the mole fractions once V/F and $L_{liquid-1}/F$ are known.

D. *Problems*

**Answers to problems with an asterisk are at the back of the book.*

D1.* We are separating a mixture of methanol and water in a flash drum at 1.0 atm pressure. Equilibrium data are listed in Table 2-7.

TABLE 2-7. *Vapor-liquid equilibrium data for methanol water (p = 1 atm) (mol%)*

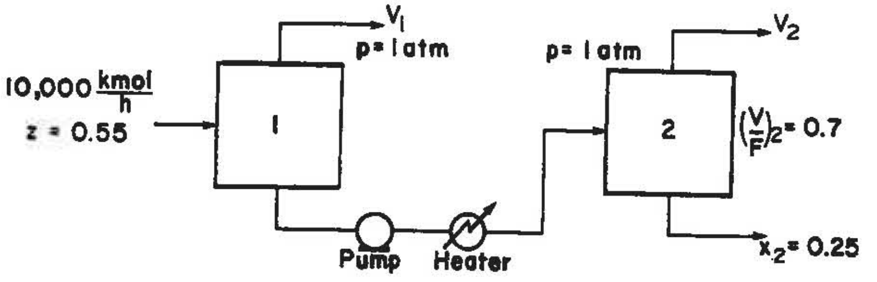
Methanol Liquid	*Methanol Vapor*	*Temp., °C*
0	0	100
2.0	13.4	96.4
4.0	23.0	93.5
6.0	30.4	91.2
8.0	36.5	89.3
10.0	41.8	87.7
15.0	51.7	84.4
20.0	57.9	81.7
30.0	66.5	78.0
40.0	72.9	75.3
50.0	77.9	73.1
60.0	82.5	71.2
70.0	87.0	69.3
80.0	91.5	67.6
90.0	95.8	66.0
95.0	97.9	65.0
100.0	100.0	64.5

Source: Perry et al. (1963), p. 13-5.

a. Feed is 60.0 mol% methanol, and 40.0% of the feed is vaporized. What are the vapor and liquid mole fractions and flow rates? Feed rate is 100 kmol/h.
b. Repeat part a for a feed rate of 1500.0 kmol/h.
c. If the feed is 30.0 mol% methanol and we desire a liquid product that is 20.0 mol% methanol, what V/F must be used? For a feed rate of 1000.0 lbmol/h, find product flow rates and compositions.
d. We are operating the flash drum so that the liquid mole fraction is 45.0 mol% methanol. L = 1500.0 kmol/h, and V/F = 0.2. What must the flow rate and composition of the feed be?
e. Find the dimensions of a vertical flash drum for Problem 2.D1c.
Data: $\rho_w = 1.00$ g/cm^3, $\rho_{m,L} = 0.7914$ g/cm^3, $MW_w = 18.01$, $MW_m = 32.04$. Assume vapors are ideal gas.
f. If z = 0.4, p = 1.0 atm, and $T_{drum} = 77$°C, find V/F, x_m, and y_m.
g. If F = 50.0 mol/h, z = 0.8, p = 1.0 atm, and $y_m = 0.892$ mole fraction methanol, find V, L, and x_m.

D2.* Two flash distillation chambers are hooked together as shown in the diagram. Both are at 1.0 atm pressure. The feed to the first drum is a binary mixture of methanol and water that is 55.0 mol% methanol. Feed flow rate is 10,000 kmol/h. The second flash drum operates with $(V/F)_2 = 0.7$ and the liquid product composition is 25.0 mol% methanol. Equilibrium data are given in Table 2-7.

a. What is the fraction vaporized in the first flash drum?
b. What are y_1, y_2, x_1, T_1, and T_2?



D3. A flash drum operating at 700.0 kPa is separating binary mixtures of ethane and n-butane.

a. The following partial equilibrium results were generated using Eq. (2-28). Complete the table and use these equilibrium results to answer the remaining parts of this problem.

x ethane	*T °C*	*y ethane*
0	63.19	0
0.025	56.18	0.1610
0.05		
0.10		
0.15		
0.20		
0.25		
0.30		
1.0	–37.47	1.0

b. If the feed is $z_E = 0.20$ mole fraction ethane, p = 700 kPa, and V/F can assume any value from 0 to 1.0; what are the highest and lowest possible ethane vapor mole fractions? What are the highest and lowest possible ethane liquid mole fractions? What are the highest and lowest temperatures of the flash drum?

c. If the feed is $z_E = 0.30$ mole fraction ethane, p = 700 kPa, and V/F =0.4, what are the outlet vapor and liquid mole fractions and the drum temperature?

d. If the feed is $z_E = 0.30$ mole fraction ethane, p = 700 kPa, and $x_E = 0.2$, what value of V/F was used and what is the outlet vapor mole fraction ethane?

e. If the feed is $z_E = 0.18$ mole fraction ethane, p = 700 kPa, and $T_{drum} = 45°C$, what are the values of V/F, x_E, and y_E?

D4. We have a mixture that is 20 mol% propane, 35 mol% n-butane, and 45 mol% n-hexane. If a flash drum operates at 400 kPa, what is the highest temperature at which the flash drum can operate and still have vapor and liquid present? Use the DePriester chart for equilibrium.

D5. We have a feed that is a binary mixture of methanol and water (55.0 mol% methanol) that is sent to a system of two flash drums hooked together. The vapor from the first drum is cooled, which partially condenses the vapor, and then is fed to the second flash drum. Both drums operate at a pressure of 1.0 atm and are adiabatic. The feed rate to the first drum is 1000 kmol/h. We desire a liquid product from the first drum that is 30.0 mol% methanol ($x_1 = 0.30$). The second drum operates at a fraction vaporized of $(V/F)_2 = 0.25$. The equilibrium data are in Table 2-7.

a. Sketch the process labeling the different streams.

b. Find the following for the first drum: vapor mole fraction y_1, fraction vaporized $(V/F)_1$, and vapor flow rate V_1.

c. Find the following for the second drum: vapor mole fraction y_2, liquid mole fraction x_2, and vapor flow rate V_2.

D6. One form of the Antoine equation is $\log_{10}(VP) = A - B/(T + C)$ where VP is in mm Hg and T is in °C. For 1-octanol, A = 6.8379, B = 1310.62, C = 136.05.

a. At 1.5 atm and 100°C, what is vapor pressure of 1-octanol in mm Hg?

b. Assuming Raoult's law is valid, what is the K value of 1-octanol at 1.5 atm and 100°C?

D7. Your plant feeds 100 kmol/h of a mixture that is 46.0 mol% ethanol and 54.0 mol % water to a flash drum. Your boss thinks that results will be better with two flash drums (same configuration as in Problem 2.D2.) with $V_1 = 30.0$ kmol/h and $V_2 = 30.0$ kmol/h.

a. Find L_1, L_2, and x_2.

b. Compare x_2 to the liquid mole fraction from a single flash drum with V/F = 0.60.

D8.* You want to flash a mixture with a drum pressure of 2.0 atm and a drum temperature of 25°C. The feed is 2000.0 kmol/h. The feed is 5.0 mol% methane, 10.0 mol% propane, and the rest n-hexane. Find the fraction vaporized, vapor mole fractions, liquid mole fractions, and vapor and liquid flow rates. Use DePriester charts.

D9.* We wish to flash distil an ethanol-water mixture that is 30.0 wt% ethanol and has a feed flow of 1000.0 kg/h. Feed is at 200°C. The flash drum operates at a pressure of 1.0 kg/cm². Find T_{drum}, weight fraction of liquid and vapor products, and liquid and vapor flow rates.

Data:

$C_{PL,EtOH} = 37.96$ at 100°C, kcal/(kmol°C)

$C_{PL,W} = 18.0$, kcal/(kmol°C)

$C_{PV,EtOH} = 14.66 + 3.758 \times 10^{-2}T - 2.091 \times 10^{-5}T^2 + 4.74 \times 10^{-9}T^3$

$C_{PV,W} = 7.88 + 0.32 \times 10^{-2}T - 0.04833 \times 10^{-5}T^2$

Both C_{PV} values are in kcal/(kmol°C), with T in °C.

$\rho_{EtOH} = 0.789$ g/mL, $\rho_W = 1.0$ g/mL, $MW_{EtOH} = 46.07$, $MW_W = 18.016$, $\lambda_{EtOH} = 9.22$ kcal/mol at 351.7 K, and $\lambda_W = 9.7171$ kcal/mol at 373.16 K.

Enthalpy composition diagram at p = 1 kg/cm² is in Figure 2-4. Note: Be careful with units.

D10. We have a mixture that is 35.0 mol% n-butane with unknown amounts of propane and n-hexane. We are able to operate a flash drum at 400 kPa and 70°C with $x_{C6} = 0.7$. Find the mole fraction of n-hexane in the feed, z_{C6}, and the value of V/F.

D11. An equilibrium mixture of ethylene and propylene is at 2500.0 kPa and 25°C. Find the vapor and liquid mole fractions of ethylene. Note: This is not a guess-and-check problem.

D12. Find h_{total} and D for a horizontal flash drum for Problem 2.D1c. Use $h_{total}/D = 4$.

D13. We flash distil a mixture that is 36% ethane (C2) and 64% n-butane (C4). The flash drum operates as an equilibrium stage. We measure the outlet concentrations of ethane as $x_{C2} = 0.088$ and $y_{C2} = 0.546$. Find x_{C4}, y_{C4}, T_{drum}, p_{drum}, and V/F. Note: This is not trial and error.

D14. A flash drum is separating a mixture that is 12.0 mol% methane (C1), 48.0 mol% n-butane (C4), and 40.0 mol% n-pentane (C5). Feed rate is 122.0 kmol/h. The feed is partially liquid and partially vapor at a pressure of 5.0 bar and temperature of 50.4°C. The flash drum is at 3.0 bar and T = 36°C. Find V/F, the K values, and vapor and liquid mole fractions.

D15.* We have a flash drum separating 50.0 kmol/h of a mixture of ethane, isobutane, and n-butane. The ratio of isobutane to n-butane is held constant at 0.8 (that is, $z_{iC4}/z_{nC4} = 0.8$). The mole fractions of all three components in the feed can change. The flash drum operates at a pressure of 100 kPa and a temperature of 20°C. If the drum is operating at V/F = 0.4, what must the mole fractions of all three components in the feed be?

D16. A feed that is 50.0 mol% methane, 10.0 mol% n-butane, 15.0 mol% n-pentane, and 25.0 mol% n-hexane is flash distilled. F = 150.0 kmol/h. Drum pressure = 250.0 kPa, drum temperature = 10°C. Use the DePriester charts. Find V/F, x_i, y_i, V, and L.

D17. We are separating a mixture of acetone (MVC) from ethanol by flash distillation at p = 1 atm. Equilibrium data are listed in Problem 4.D7. Solve graphically.

a. 1000.0 kmol/day of a feed that is 70.0 mol% acetone is flash distilled. If 40% of the feed is vaporized, find the flow rates and mole fractions of the vapor and liquid products.

b. Repeat part a for a feed rate of 5000.0 kmol/day.

c. If feed is 30.0 mol% acetone, what are the lowest possible liquid mole fraction and the highest possible vapor mole fraction?

d. If we want to obtain a liquid product that is 40.0 mol% acetone while flashing 60% of the feed, what must the mole fraction of the feed be?

D18.* 10.0 kmol/h of a feed that is 10.0 mol% propane, 30.0 mol% n-butane, and 60.0 mol% n-hexane is flash distilled at a drum pressure of 200.0 kPa. We desire a liquid that is 85.0 mol% n-hexane. Use DePriester charts. Find T_{drum} and V/F. Continue until your answer is within 0.5°C of the correct answer. Note: This is a single trial and error, *not* a simultaneous mass and energy balance convergence problem.

D19.* A flash drum operating at 300.0 kPa is separating a mixture that is 40.0 mol% isobutane, 25.0 mol% n-pentane, and 35.0 mol% n-hexane. We wish a 90% recovery of n-hexane in the liquid. F = 1000.0 kmol/h. Find T_{drum}, x_j, y_j, V/F.

D20. 200.0 kmol/h of a feed that is 10.0 mol% ethanol and 90.0 mol% water is separated in a pair of flash drums. The vapor from drum 1 is partially condensed and fed to drum 2 ($F_2 = V_1$). If $y_2 = 0.45$ and $V_2/F_2 = 0.6$, find V_1, L_1, V_2, L_2, x_1, y_1, and x_2. Both drums are at 1.0 atm.

D21. We wish to flash distil a feed that is 55.0 mol% ethane and 45.0 mol% n-pentane. The drum operates $p_{drum} = 700.0$ kPa and $T_{drum} = 30$°C. Feed flow rate is 100,000 kg/h.

a. Find V/F, V, L, liquid mole fraction, and vapor mole fraction.

b. Find the dimensions in metric units required for a vertical flash drum. Assume the vapor is an ideal gas to calculate vapor densities. Use DePriester chart for VLE. Be careful of units. Arbitrarily pick $h_{total}/D = 4$. $MW_{ethane} = 30.07$, $MW_{pentane} = 72.15$. Liquid densities are $\rho_E = 0.54$ g/ml (estimated), $\rho_P = 0.63$ g/ml.

D22. 50.0 kmol/h of a vapor feed that is 70.0 mol% methanol and 30.0 mol% water is partially condensed in a heat exchanger and then fed to a flash drum operating at a pressure of 1.0 atm. 20.0 kmol/h of liquid product is collected.

a. Find mole fractions of methanol in the liquid and in the vapor.

b. Find the temperature of the drum.

D23.

a. Design a new vertical flash drum for Example 2-4 but with a feed of 1500.0 kmol/h.

b. If a vertical flash drum 4.0 feet in diameter has been built, what size additional vertical flash drum is needed if the drums will be operated in parallel to separate 1500.0 kmol/h?

D24. We plan to separate a mixture of propane and n-hexane at 300.0 kPa.

a. Using the data in the DePriester charts, plot y propane versus x propane for this mixture at this pressure.

b. If the feed is 30.0 mol% propane, and 40.0 mol% of the feed is vaporized, what are the liquid and vapor mole fractions, and what is the drum temperature? Solve graphically.

c. What is the drum temperature in part b?

d. If y = 0.8 and the feed is 0.6 (both mole fraction propane), what is the value of V/F?

e. Use the Rachford-Rice equation to check the answers obtained in parts b and c.

D25. We wish to flash distil a mixture of methane and n-butane in a flash drum operating at 50°C. The feed is 20.0 mol% methane and 80.0 mol% n-butane. Feed rate is 100.0 kmol/h. Feed is at a pressure and temperature such that in the drum V/F = 0.40. Use the DePriester charts.

a. Find the drum pressure.

b. Find the methane mole fraction in the liquid and the vapor.

D26. We are feeding 100.0 kmol/h of a 45.0 mol% propane, 55.0 mol% n-pentane feed to a flash distillation system. We measure the outlet vapor and liquid mole fractions leaving the flash drum, which is an equilibrium stage, and obtain, $y_{propane} = 0.8$, $x_{propane} = 0.2162$.

Find (a) L and V. (b) $x_{pentane}$ and $y_{pentane}$. (c) T_{drum} and p_{drum}.
Use the DePriester charts. Note: This is not trial and error.

D27. For the Antoine equation in the form

$$\log_{10}(VP) = A - \frac{B}{T+C}$$

with VP in mm Hg and T in °C, the constants for n-pentane are A = 6.853, B = 1064.8, C = 233.01. n-hexane constants are A = 6.876, B = 1171.17, C = 224.41 (Speight, 2005).

a. Predict the vapor pressure at 0°C for pure n-pentane.

b. Predict the boiling point of pure n-pentane at 3.0 atm pressure.

c. Predict the boiling pressure if pure n-pentane is boiling at 0°C.

d. At a pressure of 500.0 mm Hg and temperature of 30°C, predict the K values for n-pentane and n-hexane using Raoult's law.

e. If T = 30°C and p = 500.0 mm Hg, determine the mole fractions in the liquid and vapor phases of an equilibrium mixture of n-pentane and n-hexane.

f. One mole of a mixture that is 75.0 mol% n-pentane and 25.0 mol% n-hexane is placed in a closed chamber. The pressure is adjusted to 500.0 mm Hg, and the temperature to 30°C. The vapor and liquid mole fraction were found in part e. How many moles of liquid and moles of vapor are there at equilibrium?

g. If 1.0 mol/min of a mixture that is 75.0 mol% n-pentane and 25.0 mol% n-hexane is fed continuously to an equilibrium flash chamber operating at 30°C and 500.0 mm Hg, find the flow rates of the liquid and vapor products.

D28. Repeat Example 2-4, but with F = 3000.0 lbmol/h, and use a horizontal flash drum with holding time = 55.0 min and surge time = 85.0 min. Calculate D, h, and h/D.

D29. Design a horizontal flash drum to separate 15,000 kg/h of a feed with the following mass fractions: methane 0.21, propane 0.39, n-butane 0.24, i-butane 0.11, and n-pentane 0.05. The feed is at 0°C and a pressure just high enough that it is all liquid. The drum pressure is 4.0 atm and the drum is adiabatic (heat duty = 0).

a. Find the minimum feed pressure (to within a whole number of atmospheres) that keeps the feed a liquid. Report this pressure and the VLE correlation used, and use this as the feed pressure for the flash calculation.

b. Find L, V (in kg/h and in kmol/h), y_i, x_i (in mole fractions), and T_{drum} (in °C).

c. If a horizontal drum is used, find D_{min}. If the holding time is 9 minutes and the ratio of the drum length to diameter is h/D = 6, find the surge time that can be accommodated.

Note: The easiest way to solve this problem is to use Aspen Plus for part a (trial and error) and then obtain the solution for part b. Although Aspen Plus does not do the drum sizing, it does calculate the physical properties needed for drum sizing. Obtain these values and do the drum sizing with a hand calculation.

D30. Data for the equilibrium of water and n-butanol at 1.0 atm is given in Table 8-2. Plot y_w versus x_w. A feed of 100.0 kmol/h that is 20.0 mol% water is fed to flash chamber A in the figure that follows. The vapor from flash chamber A is 40.0 mol% water. This vapor is then partially condensed and fed to flash chamber B. In flash chamber B, 40% of the vapor from chamber A is condensed.

a. What are the flow rates L_A and V_A, and what is the value of x_A?

b. What are the flow rates L_B and V_B, and what are the values of x_B and y_B?

c. Suppose we changed the operation of chamber B so that enough vapor was condensed to give a liquid mole fraction of x_B = 0.20 mole fraction water. If x_B = 0.20, what are y_B, L_B, and V_B? We could now easily recycle this liquid to the feed (also 20% water) and produce only $V_{B,new}$ and $L_{A,new}$ as products. Calculate these new flow rates when L_B with mole fraction 0.2 is recycled.