Chapter 3

New Problems and new solutions are listed as new immediately after the solution number. These new problems are: 3A7, 3A10, 3A11, 3C3, 3C4, 3D4, 3D8, 3G2.

3.A7. Simultaneous solution is likely when one of the key variables can be found only from the energy balances. For example, if only 1 of x_D, x_B, D, B, $FR_{A\,dist}$ are given energy balances will be required. This is case for most of the simulation problems and for a few design problems. In some simulation problems the internal equations have to be solved also.

3.B1. a. x_D, x_B, opt feed, Q_{Reb}

x_D, x_B, opt feed, Q_C

x_D, x_B, opt feed, S (open steam), sat'd vapor steam

All of above with fractional recoveries set instead of x_D, x_B

D, x_B, opt feed, L/D

b. N, N_F, col diameter, frac. recoveries both comp.

N, N_F, col diameter, FR_A dist, L_o/D

N, N_F, col diameter, FR_A dist, Q_R

N, N_F, col diameter, FR_A dist, Q_C

N, N_F, col diameter, x_D, Q_C $\left(\text{or } x_B\right)$

N, N_F, col diameter, S (sat'd steam), sat'd vapor steam, $x_D\left(\text{or } x_B\right)$

Many other situations are possible [e.g., 2 feeds, side streams, intermediate condensers or reboilers etc.]

3.C1. See solution to problem 3-D2.

3.C2. See solution to problem 3-D3.

3.C3. *New Problem in 3rd Edition.* $F_{mix} = F_1 + F_2 = D + B$

$F_{mix}z_{mix} = F_1z_1 + F_2z_2 = Dx_D + Bx_B$ (Mole frac. MVC)
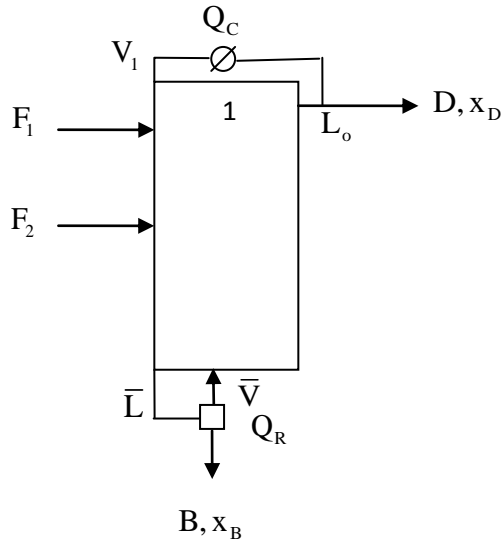
$$z_{mix} = \frac{F_1z_1 + F_2z_2}{F_{mix}}$$

Now solve like 1 Feed Column $\left(F_{mix} \ \& \ z_{mix}\right)$. From Eq. (3-3),

$$D = \frac{z_{mix} - x_B}{x_D - x_B}F_{mix} \text{ kmol/h.}$$

$$B = F_{mix} - D \text{ kmol/h.}$$

3.C4. *New Problem in 3rd Edition.* See solution to 3D4, Part b.

3.D1.

$$F_1 + F_2 = B + D \qquad\qquad x_B = 0.0001\ (0.01\%)$$

$$F_1 z_1 + F_2 z_2 = B x_B + D\ x_D \qquad\qquad x_D = 0.85$$

$$\text{Solve } D = \left(\frac{z_{avg} - x_B}{x_D - x_B}\right) F_{total}$$

$$F_{total} = F_1 + F_2 = 1500 \text{ kg/h}$$

$$z_{avg} = \frac{F_1 z_1 + F_2 z_2}{F_{total}} = \frac{(1000)(.60) + 500(0.10)}{1500} = 0.43333$$

$$D = \frac{0.43333 - 0.0001}{0.85 - 0.0001}(1500) = 764.62 \text{ kg/h}$$

$$B = F_{total} - D = 1500 - 764.62 = 735.38\ \frac{kg}{h}$$

Mass balance calculation is valid for parts a & b for problem 3G1.

a) $\dfrac{L_o}{D} = 3$, Eq $(3\text{-}14)$ $\quad Q_C = (1 + L_0/D)D(h_D - H_1)$

h_D is a saturated liquid at $x_D = 0.85$ wt. frac. From Fig. 2-4, $h_D =\sim 45$ kcal/kg

H_1 is saturated vapor at $x_D = y_1 = 0.85,\quad H_1 \sim 310$ kcal/kg

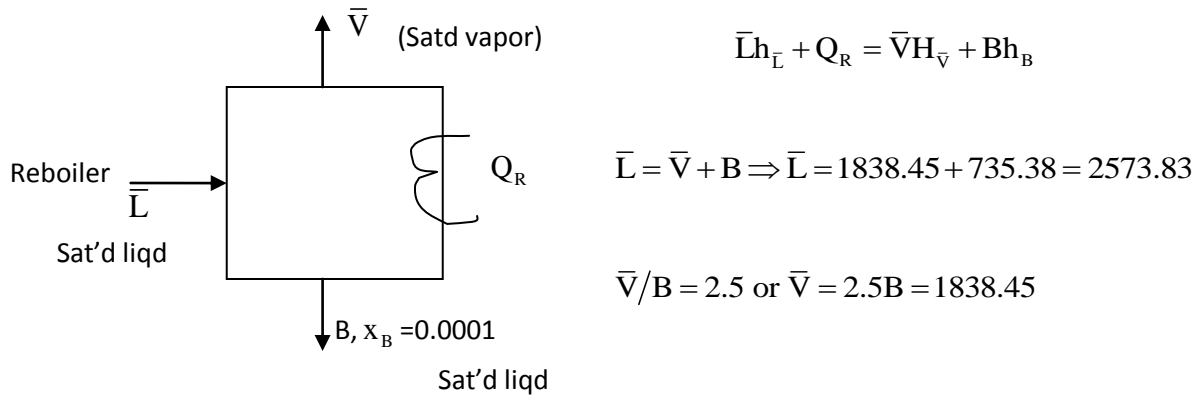$$Q_C = (1+3)(764.62)(45 - 310) = -810,497 \text{ kcal/hour}$$

EB around column. $\qquad F_1 h_{F_1} + F_2 h_{F_2} + Q_{col} + Q_C + Q_R = D h_D + B h_B$

$h_{F_1}\left(81°C,\ 60 \text{ wt\% ethanol}\right) \sim 190 \text{kcal}/\text{kg}$; $h_{F_2}\left(20°C,\ 10 \text{ wt\% ethanol}\right) \sim 10 \text{kcal}/\text{kg}$

h_B (sat'd liquid – leaves equil contact, ~ 0 wt% ethanol) ~ 100 kcal/kg, $Q_{col} = 0$ (adiabatic)

$$Q_R = (764.62)(45) + (735.38)(100) - 1000(190) - 500(10) - (-810,497) = 657,259 \text{ kcal/kg}$$

(b) $\overline{V}/B = 2.5$ mass.

$\bar{V}$ (Satd vapor)

Reboiler

$\bar{L}$

Sat'd liqd

Q_R

B, $x_B = 0.0001$

Sat'd liqd

$$\bar{L}h_{\bar{L}} + Q_R = \bar{V}H_{\bar{V}} + Bh_B$$

$$\bar{L} = \bar{V} + B \Rightarrow \bar{L} = 1838.45 + 735.38 = 2573.83$$

$$\bar{V}/B = 2.5 \text{ or } \bar{V} = 2.5B = 1838.45$$

Approximately $x_B \sim y_{\bar{V}} \sim x_{\bar{L}}$. Thus $h_{\bar{L}} = h_B = 100$. $H_{\bar{V}} \approx 640 \, \text{kcal/kg}$

$$Q_R = (1838.45)(640) + (735.38)(100) - (2573.83)(100) = 992,763 \text{ kcal / h}$$

EB. $\quad Q_C = D h_D \nearrow + Bh_B - Q_{col} - F_1 h_{F_1} - F_2 h_{F_2} - Q_R$

$$Q_C = 34407.9 + 7353.8 - 190,000 - 5000 - 992,763 = -1,146,001 \text{ kcal/h}$$

3.D2. *Column:* mass bal: $F + S = D + B$ (1)

MVC: $Fz + Sy_S = Dx_D + Bx_B$ (2)

Note: $y_S = 0$

energy bal: $Fh_f + SH_s + Q_C = Dh_D + Bh_B$ (3)

Condenser: mass bal. : $V_1 = L_o + D$ (4)

energy bal.: $V_1 H_1 + Q_C = (L_o + D)h_D$ (5)

Solve Eqs. (1) and (2) to get:

$$D = \frac{Fz - Fx_B - Sx_B}{x_D - x_B} = \frac{100(.3) - 100(.05) - 100(.05)}{.6 - .05} = 36.4$$

Note: Not Eq. (3-3). Solve Eqs. (4) and (5) to get:

$$Q_C = D(1 + L/D)(h_D - H_1)$$

Substitute Q_C into Eq. (3):

$$\frac{L}{D} = \frac{Dh_D + (F + S - D)h_B - Fh_F - SH_S}{D(h_D - H_1)} - 1$$

From Figure 2-4: $h_F = 8$, $h_D = 65$, $h_B = 92$, $H_S = 638$, $H_1 = 608$ kcal/kg.

$$L/D = \frac{36.4(65) + 163.6(92) - 100(8) - 100(638)}{36.4(65 - 408)} - 1 = 2.77$$

3.D3. External balances: $F + C = B + D$ (1)

$Fz + Cx_C = Bx_B + Dy_D$ (2)

$Q_R + Fh_F + Ch_C = Bh_B + DH_D$ (3)

$F = 2000$, $C = 1000$, $z = .4$, $x_C = 1.0$, $x_B = .05$, $y_D = .80$, $h_F(-20°C) = 30.7$,

$h_C(\text{sat'd liquid}) = 50$, $h_B(\text{sat'd liquid}) = 92$, $H_D(\text{sat'd vapor}) = 327$ kcal/kg

Around reboiler:
$$\bar{L} = \bar{V} + B$$
$$\bar{L}x_N = \bar{V}y_{Reb} + Bx_B$$
$$\bar{L}h_N + Q_R = \bar{V}H_{reb} + Bh_B$$

For a total reboiler: $x_N = x_B$, $y_N = x_N = x_B$, $h_N = h_B = 92$

M.B.: $(\bar{V} + B)h_N + Q_R = \bar{V}H_{reb} + Bh_B$

or $\quad \bar{V} = \dfrac{Q_R}{H_{reb} - h_N}$ since $h_B = h_N$

$H_{Reb} = 617$ (saturated vapor at $y_{N+1} = 0.05$)

Solve Eqs. (1) and (2) for B: $\quad B = \dfrac{Fz + Cx_C - Fy_D - Cy_D}{x_B - y_D}$

Thus $\quad B = \dfrac{800 + 1000 - 1600 - 800}{(.05 - .8)} = 800$ and $D = 2200$

From Eq. (3), $\quad Q_R = Bh_B + DH_D - Fh_F - Ch_C$

$$Q_R = (800)(92) + (2200)(327) - (2000)(-30.75) - (1000)(50) = 804{,}500 \text{ cal/h}$$

$$\bar{V} = \frac{Q_R}{H_{reb} - h_N} = \frac{804500}{617 - 92} = 1532.4 \text{ kg/h}$$

3.D4. *New Problem in 3rd Edition.* $\quad F = B + D$

MVC $Fz = Bx_B + Dy_D$

But given recoveries. Thus, use:

$\qquad Fz_{F,M}$ (Frac Rec Methanol in distillate) $= Dy_{D,M}$

and $\qquad\qquad Fz_{F,W}$ (Frac Rec water in bottom) $= Bx_{B,W}$

$z_{F,M} = 0.3$, $\quad z_{F,W} = 1 - z_{F,M} = 0.7$

$y_{D,M}$ unknown, $x_{B,W}$ unknown.

Methanol $29.7 = 100(0.3)(.99) = Dy_{D,M}$

If 99% methanol recovered in distillate, 1% is in bottoms $\quad 0.3 = 100(0.3)(0.01) = Bx_{B,M}$

Water $\quad 68.6 = 100(0.7)(0.98) = Bx_{B,W} \Rightarrow$ 2% water in distillate

$1.4 = 100(0.7)(0.02) = Dy_{D,W}$

Since $\sum x_i = 1$ and $\sum y_i = 1$, $\sum(Dy_{D,i}) = D$, and $\sum(Bx_{B,i}) = B$

Thus, $\quad D = Dy_{D,M} + Dy_{D,W} = 29.7 + 1.4 = 31.1$ kmol/h

$B = Bx_{B,M} + Bx_{B,W} = 0.3 + 68.6 = 68.9$ kmol/h

Check: $\quad B + D = 100 = F \qquad$ OK

$$y_{d,M} = \frac{Dy_{D,M}}{D} = 29.7/31.1 = 0.955$$

$$x_{B,M} = Bx_{B,M}/B = 0.3/68.9 = 0.00435$$

a) $D = 31.1$ & $L_0/D = 2$. Thus $L_0 = 62.2$

Reflux liquid is in equilibrium with vapor $y_{D,M} = 0.955$

From equilibrium data (Table 2-7) $x_{M,0} \sim 0.893$ (linear interpolation)

b)   E.B. Partial condenser: $V_1H_1 + Q_c = DH_0 + L_0h_0$

$$V_1 = D + L_0 = 93.3$$

$$V_1y_1 = Dy_0 + L_0x_0 \Rightarrow y_1 = (Dy_0 + L_0x_0)/V_1$$

$$y_{1,M} = (29.7 + (62.2)(0.893))/93.3 = 0.914; \quad y_{1,w} = 1 - y_{1,M} = 0.086$$

$\lambda_M = 35,270\,J/mol\ @\ 64.5°C = 35,270\ kJ/kmol \Rightarrow$ choose MeOH reference 64.5°C.

$\lambda = 40,656\,J/mol\ @\ 100°C = 40,656\ kJ/kmol \Rightarrow$ choose water reference 100°C.

The condenser is at 66.1°C (linear interpolation Table 2-7).

$$H_1 = \lambda_M y_{1,M} + \lambda_w y_{1,w} + y_{1,M}C_{P,V,M}(T_1 - 64.5) + y_{1,w}C_{P,V,w}(T_1 - 100)$$

V_1 is at T_1 in equilibrium with $y_{1,M} = 0.914$. From Table 2-7 $T_1 \sim 67.6°C$

Assuming only constant & linear T term are important in $C_{P,V}$ eqs., $\bar{C}_{P,V} = C_P(T_{avg})$. For

methanol $T_{avg} = \dfrac{67.6 + 64.5}{2} = 66.65°C$. For water, $T_{avg} = \dfrac{67.6 + 100}{2} = 83.8°C$.

$$C_{PV,M} = 42.93 + 0.08301(66.05) = 48.41\frac{J}{mol}\frac{1000\ mol}{(kmol)}\frac{kJ}{1000J} = 48.41\frac{kJ}{kmol°C}$$

$$C_{P,V,w} = 33.46 + 0.00688(83.8) = 34.04\frac{J}{mol°C} = 34.04\frac{kJ}{kmol°C}$$

$$\Delta T_M = 67.6 - 64.5 = 3.1; \quad \Delta T_w = 67.6 - 100 = -32.4$$

Then

$$H_1 = (35270)(0.914) + (40656)(0.086) + (48.41)(3.1)(0.914) + 34.04(-32.4)(0.086)$$

$H_1 = 35775.5\ kJ/kmol$ Note λ terms dominate.

H_D is at $y_D = 0.955\ @\ 66.1°C$

$$H_D = \lambda_M y_{D,M} + \lambda_w y_{D,w} + y_{D,M}C_{P,V,M}(T_D - 64.5) + y_{D,w}C_{P,V,w}(T_D - 100)$$

$$\bar{C}_{P,V,M} = C_{P,V,M}(T_{M,avg}). \quad T_{avg,M} = \frac{66.1 + 64.5}{2} = 65.3$$

$$\bar{C}_{P,V,M} = 42.93 + 0.08301(65.3) = 48.35$$

$$\bar{C}_{P,V,w} = C_{P,V,w}(T_{W,avg}). \quad T_{W,avg} = \frac{100 + 66.1}{2} = 83.05$$

$$\bar{C}_{P,V,w} = 33.46 + 0.00688(83.05) = 34.03$$

$$\Delta T_W = 66.1 - 100 = -33.9$$

$$H_D = 35270(.955) + 40656(0.045) + 48.35(0.955)(1.6) + (34.03)(0.045)(-33.9)$$

$$H_D = 33682.85 \quad + 1829.5 \quad + 73.88 \quad - 51.91 \quad = 35534.3$$

Reflux liquid at 66.1°C and $x_{M,0} = 0.893$, $x_{W,0} = 0.107$

Reference MeOH 64.5°C, water reference 100 °C

$$h_0 = C_{PL,M} x_{M,0} \Delta T_M + C_{PL,W} x_{W,0} \Delta T_W$$

$$\bar{C}_{PL,M} = C_{PL,M}(T_{avg}) = 75.86 + 0.1683(65.3) = 86.85 \frac{kJ}{kmol°C}$$

$$h_0 = (86.85)(0.893)(1.6) + (75.4)(0.107)(-33.9) = -149 \ kJ/kmol$$

$$Q_C = DH_D + L_0 h_0 - V_1 H_1 = 31.1(35534.3) + (62.2)(-149) - (93.3)(35775.5) = -2,242,030 \ kJ/h$$

Overall EB $\quad Fh_F + Q_C + Q_R = DH_D + Bh_B$

or $\quad Q_R = DH_D + Bh_B - Q_C - Fh_F$

h_B is saturated liquid with $x_{B,M} = 0.00435$ and $x_{B,W} = 0.99565$

Interpolating in Table 2.7 $\quad T_{Bot} \approx 99.2°C$

$$h_B = \bar{C}_{PL,M}(0.00435)(99.2 - 64.5) + C_{PL,W}(0.99565)(99.2 - 100)$$

$$T_{avg,M} = \frac{99.2 + 64.5}{2} = 81.86 \quad \text{and} \quad \bar{C}_{PL,M} = 75.86 + 0.1683(81.86) = 89.64$$

$$h_B = 13.53 + (-60.06) = -46.5 \ kJ/kmol$$

Feed is saturated liquid at $z_M = 0.3$, $z_W = 0.7$.

From Table 2-7, $T_F = 78°C$

$$h_F = C_{P,LM}(0.03)(78 - 64.5) + C_{PL,W}(0.7)(78 - 100)$$

$$T_{avg,M} = (78 + 64.5)/2 = 71.25 \quad \text{and} \quad \bar{C}_{P,L,M} = 75.86 + 0.1683(71.25) = 87.85$$

$h_F = -805.4 \ kJ/kmol$ Then

$$Q_R = (31.1)(35534.3) + (68.9)(-46.5) - (-2,242,030) - (100)(-805.4) =$$

$$1,105,116 \quad - 3204 \quad + 2,242,030 \quad + 80,536 \ = 3,424,479 \ kJ/h$$

3.D5. Mass Balances: $F = D + S + B$, $Fz = Dx_D + Sx_S + Bx_B$

Solving simultaneously, B = 76.4 kg/min, D = 13.6 kg/min.

Condenser: $Q_C = V_1(h_0 - H_1)$

$V_1 = L_0 + D = (L/D + 1)D = 4(13.6) = 54.4 \ kg/min$

From Figure 2-4, $h_0 = 7.7 \ kcal/kg$ (x = .9, T = 20°C),

$H_1 = 290 \ kcal/kg$ (y = .9, sat'd vapor).

Thus, Q_C = 54.4 (7.7 − 290) = -15,357 kcal/min

Overall Energy Balance: $Fh_F + Q_R + Q_C = Dh_D + Sh_S + Bh_B$

$$Q_R = Dh_D + Sh_S + Bh_B - Fh_F - Q_C$$

From Figure 2-4,

$$h_S = 61 \ (x_S = .7, \ \text{sat'd Liq'd}); \ h_F = 200(z = .2, \ 93°C),$$

$$h_B = 99 \ \left(x_B = .01, \ \text{sat'd Liq'd}\right), \ h_D = h_o = 7.7$$

Thus,

$$Q_R = (13.6)(7.7) + 10(61) + (76.4)(99) - (100)(200) - (-15357) = 3635.3 \ \text{kcal/min}$$

3.D6.   From Eq. (3-3), $D = F\left(\dfrac{z - x_B}{x_D - x_B}\right) = 2500\left(\dfrac{.4 - .002}{.999 - .002}\right) = 998$ lbmol/h.

Then B = F = 1502.

Condenser: $V = (L_o + D) = (L_o/D)D + D$

$$Q_C = (h_D - H_V)D(L_o/D + 1)$$

With 99.9% nC_5 have essentially pure nC_5. Thus, it is at its boiling point.

$$(h_D - H_V) = -\lambda_{C5} = -11,369 \ \text{Btu/lbmol}.$$

$$Q_C = (-11,369)(998)(4) = -45,385,048 \ \text{Btu/h}$$

Overall: $Q_R = Dh_D + Bh_B - Fh_F - Q_C$

Distillate is at boiling point of pure $nC_5 \ \left(K_{C5} = 1.0 \text{ on DePriester Chart}\right) = 35°C$. Bottoms

is at boiling point of $nC_6 \ \left(K_{C6} = 1.0\right) = 67°C$.

Converting to °F: 35°C = 95°F, 67°C = 152.6°F, 30°C = 86°F.

Note feed is obviously a subcooled liquid. Arbitrarily, pick a liquid at 0°F as reference. (This will not affect the result and other values can be used.)

$$C_{P_F} = x_{C5}C_{P_{LC5}} + z_{C6}C_{PLC6}$$

$$C_{P_F} = (.4)(39.7) + (.6)(51.7) = 46.9 \ \text{Btu/lbmol °F}$$

$$h_F = C_{P_F}(T_F - 0) = (46.9)(86°) = 4033.4 \ \text{Btu/lbmol}$$

Distillate is almost pure nC_5. Liquid at 95°F

$$h_D = C_{P_{LC5}}(T_{Dist} - 0) = (39.7)(95) = 3771.5 \ \text{Btu/lbmol}$$

Bottoms is almost pure liquid nC_6 at 152.6°F.

$$hC_{pLC6}(T_{bot} - 0) = (51.7)(152.6) = 7889.4 \ \text{Btu/lbmol}$$

$$Q_R = (998)(3771.5) + (1502)(7889.4) - 2500(4033.4) - (45,385,048) = 50,861,491 \ \text{Btu/h}$$

3.D7.   Eq. (3-3), $D = F\left(\dfrac{z - x_B}{x_D - x_B}\right) = 1000\left(\dfrac{0.7 - 0.001}{0.999 - 0.001}\right) = 700.4$ kmol/h

$$B = F - D = 299.6 \ \text{kmol/h}$$

Condenser: $L_o = (L_o/D)D = (2.8)(700.4) = 1961.1$ kmol/h

Only this reflux is condensed since product is a vapor.

$Q_C = L_o(-\lambda)$ where λ is for essentially pure n-pentane.

$$Q_C = \left(-1966.1\frac{\text{kmol}}{\text{h}}\right)\left(11,369\frac{\text{Btu}}{\text{lbmol}}\right)\left(\frac{2.20462 \ \text{lbmol}}{1 \ \text{kmol}}\right)$$

$$Q_C = -49,154,204.85\frac{\text{Btu}}{\text{h}}\left|\frac{1 \ \text{J}}{9.486 \times 10^{-4} \ \text{Btu}}\right| = 5.18176 \times 10^{10} \ \frac{\text{J}}{\text{h}}$$

From overall balance $Q_R = DH_D + Bh_B - Fh_F - Q_C$

Distillate is vapor at b.p. of pure n-pentane (35°C from DePriester chart, $K_{C5} = 1.0$)

Bottoms is boiling n-hexane (67°C)

Conversions: 35°C = 95°F   - distillate & Feed and 67°C = 152.6°F - bottoms

As <u>reference,</u> arbitrarily choose liquid at 0°F.

Feed is subcooled liquid.

$$C_{PF} = z_{C5}C_{PLC5} + z_{C6}C_{PLC6} = (0.7)(39.7) + (0.3)(51.7) = 43.3 \, \text{Btu/lbmol°F}$$

$$h_F = C_{PF}(T_F - 0) = (43.3)(95 - 0) = 4113.5 \, \text{Btu/lbmol}$$

Distillate $H_D = \lambda_{C5} + C_{PLC5}(T_{dist} - 0)$

$$H_D = 11,369 + (39.7)(95 - 0) = 15,140.5 \, \text{Btu/lbmol}$$

Bottoms is pure C_6 @ $152.6°F$

$$h_B = C_{PLC6}(T_{bot} - 0) = 51.7(152.6 - 0) = 7889.4 \, \text{Btu/lbmol}$$

$$Q_R = \left[\left(700.4 \frac{\text{kmol}}{\text{h}} \right) \left(15,140.5 \frac{\text{Btu}}{\text{lbmol}} \right) + \left(299.6 \frac{\text{kmol}}{\text{h}} \right) \left(7889.4 \frac{\text{Btu}}{\text{lbmol}} \right) \right.$$

$$\left. - \left(1000 \frac{\text{kmol}}{\text{h}} \right) \left(4113.5 \frac{\text{Btu}}{\text{lbmol}} \right) \right] \left[\frac{2.20462 \, \text{lbmol}}{\text{kmol}} \right] - \left(-49,154,204.85 \frac{\text{Btu}}{\text{h}} \right)$$

$$Q_R = 68,675,167.9 \frac{\text{Btu}}{\text{h}} \left| \frac{1 \, \text{J}}{9.486 \times 10^{-4} \text{Btu}} \right| = 7.240 \times 10^{10} \, \text{J/h}$$

3.D8. *New Problem in 3rd Edition.*
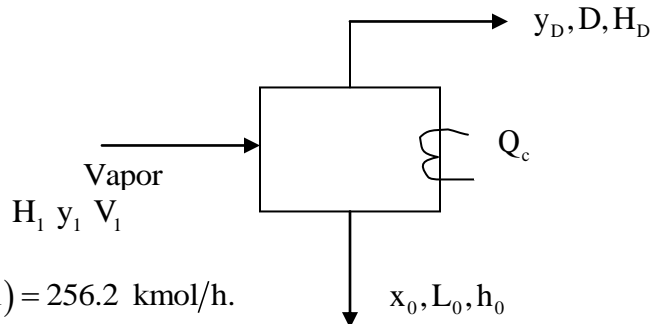
$F = 300$, $z_E = .3$, $z_w = .7$

98% rec. E in distillate, 81% rec water in bot.

$$D = \text{Dist.} = .98(90) + (1 - .81)(300)(.7) = 128.1 \, \text{kmol/h}$$

$$y_{DE} = \frac{(.98)(90)}{128.1} = 0.6885$$

$$B = \text{Bottoms} = (.02)(90) + (.81)(210) = 171.9 \, \text{kmol/h}$$

y_D, D, H_D

b. Partial Condenser.

Vapor

$H_1 \, y_1 \, V_1$

Q_c

x_0, L_0, h_0

$\dfrac{L_0}{D} = 2$, $L_0 = 2D = 2(128.1) = 256.2 \, \text{kmol/h}$.

x_0 in equilibrium with y_0, thus from equation data $x_0 = 0.575$.

Entering vapor y_1 (from graph) $= 0.61$

$$V_1 = L_0 + D = 256.2 + 128.1 = 384.3 \text{ kmol/h}.$$

c. E.B. on PC. $V_1 H_1 + Q_c = DH_{dist} + L_0 h_0$. Can use Figure 2-4 by converting mole fracs to mass fracs. Basis 1 kmole.

Distillate $.6885 \text{ mol E } (MW = 46) = 31.671 \text{ kgE}$

$$.3115 \text{ mole W } (MW = 18) = \frac{5.607 \text{ kgW}}{37.28 \text{ kg total}}$$

Mass frac. E $= 31.671/37.28 = 0.8496$

Vapor V_1 $0.61 \text{ mole E } (46) = 28.06 \text{ kgE}$

$$.39 \text{ mole W } (18) = \frac{7.02 \text{ kgW}}{35.08 \text{ kg total}}$$

Mass frac E $= 28.06/35.08 = 0.7999$

Liquid reflux L_0 $0.575 \text{ mole E } (46) = 26.45 \text{ kgE}$

$$0.425 \text{ mole W } (18) = \frac{7.65 \text{ kgE}}{34.1 \text{ total}}$$

Mass frac E $= 26.45/34.1 = 0.7757$

From Figure 2-4, $H_{dist} \sim 310 \text{ kcal/kg}$, $H_1 \sim 330 \text{kcal/kg}$, $h_0 \sim 65 \text{ kcal/kg}$

$$Q_c = DH_{dist} + L_0 h_0 - V_1 H_1 = 128.1 \frac{\text{kmol}}{\text{hr}} \left| \frac{37.28 \text{ kg}}{\text{kg}} \right| 310 \frac{\text{kcal}}{\text{kg}} + 256.2 | 34.1 | 65$$

$$- 364.3 \left| \frac{35.08 \text{ kg}}{\text{kmol}} \right| 330 = -2,400,517 \text{ kcal/hr}$$

Overall EB. $Fh_F + Q_R + Q_c = DH_{dist} + Bh_B$

Know $Q_c = -2,400,517 \text{ kcal/h}$

and $DH_{dist} = 1,480,426 \text{ kcal/h}.$

To find Fh_F and Bh_B, need to convert mole frac to wt frac.

Basis 1 kmol

Feed $30 \text{ mole \% E: } .3 \text{ mole} (46) = 13.8$

$$70\% \text{ W : } .7(18) = \frac{12.6}{\text{total 26.4 kg/kmol}}$$

Mass frac E $= 13.8/26.4 = 0.5227$

Bottoms $0.01047 \text{ mole } (46) = .48162$

$$0.98953 \text{ mole } (18) = \frac{17.811}{\text{total 18.293 kg/kmol}}$$

Mass frac E $= 0.48162/18.28 = 0.0263$

From Figure 2-4 $h_F (\text{satd liqd}) \approx 70 \text{kcal/kg}$

$$h_B (\text{satd liqd}) \approx 97$$

Then
$$Q_R = DH_{dist} + Bh_B - Fh_F - Q_c$$

$$Q_R = 1,480,426 + 171.9 \frac{kmol}{h} \left| \frac{18.29316 \text{ kg}}{kmol} \right| \frac{97 \text{ kcal}}{kg} - 300 \left| \frac{26.4 \text{ kg}}{kmol} \right| 70 \frac{kcal}{kg}$$

$$-(-2,400,517) = 1,480,426 + 305,525 - 554,408 - (-2,400,517) = 3,632,069 \text{ kcal/h}$$

3D9. *New Problem 3rd Edition.* B = $(x_D - z)/(x_D - x_B)$F = [(0.9999 - 0.76)/(0.9999 - 0.00002)](500) = 120

$$Q_R + \overline{L}h = \overline{V}H + Bh_B \text{ and } \overline{L} = \overline{V} + B$$

Assume $h = h_B$. $\quad Q_R = -(\overline{L} - B)h + \overline{V}h = \overline{V}(H - h) = \overline{V}\lambda$

$$\overline{V} = (\overline{V}/B)B = (1.5)(120) = 180 \text{ kmol/h}.$$

Bottoms is almost pure water. $\lambda_w = 9.72 \text{ kcal/mol} = 9720 \text{ kcal/kmol}$

$$Q_R = (180 \text{ kmol/h})(9720) = 1.750 \times 10^6 \text{ kcal/h}$$

3.D10. 2 atm × 101.3 kPa/atm = 202.6 kPa. Pentane Recovery: $0.995 \times Fz_P = Dx_D$

$$D = \frac{(0.995)(1000)(0.55)}{(0.9993)} = 547.6333 \text{ kmol/h}$$

$$B = 1000 - 547.6333 = 452.3667$$

Since $\quad Bx_B = (\text{Pentane Recovery Bot}) F z_p,$

$$x_B = \frac{(1 - .995)(1000)(0.55)}{452.3667} = 0.006079 \quad \text{mol frac pentane}$$

Distillate is essentially pure Pentane. Bottoms Pure in Hexane. From DePriester Chart

$$K_P = 1 @ p = 202.6 \text{ kPa when } T_{dist} = 59.5°C$$

$$K_{n-H} = 1 @ p = 202.6 \text{ kPa when } T_{bot} = 94°C$$

For Total Condenser, Eq. (3-14) $\quad Q_C = \left(1 + \frac{L_o}{D}\right) D (h_D - H_1)$

$$h_D (\text{pure pentane}) = C_{PLC5}(T_{dist} - T_{ref}) \text{ choose } T_{ref} = 25°C$$

$$h_D = 39.7 \frac{kcal}{kmol°C}(59.5 - 25) = 1369.65 \frac{kcal}{kmol}$$

$$H_1 = h_D + \lambda \text{ assuming } \lambda \text{ is independent of temperature}$$

$$H_1 = 1369.65 + 11369 \frac{Btu}{lbmol} \left[\frac{1}{0.454} \frac{lbmol}{kmol} \right] \left[\frac{0.252 \text{ kcal}}{Btu} \right] = 7680.196 \frac{kcal}{kmol}$$

Eq. (3-14) is $\quad Q_C = (1 + 2.8)(547.6333) \frac{kmol}{h}(-6310.5) = -13,132,288 \frac{kcal}{h}$

$$h_B (\text{pure hexane}) = C_{PLC6}(T_{bot} - T_{ref}) = 51.7 \frac{kcal}{kmol°C}(94 - 25) = 3567.3 \frac{kcal}{kmol}$$

Feed is a liquid at 65°C

$$h_F = [C_{PC5}z_{C5} + C_{PC6}z_{C6}](T_F - T_{ref})$$

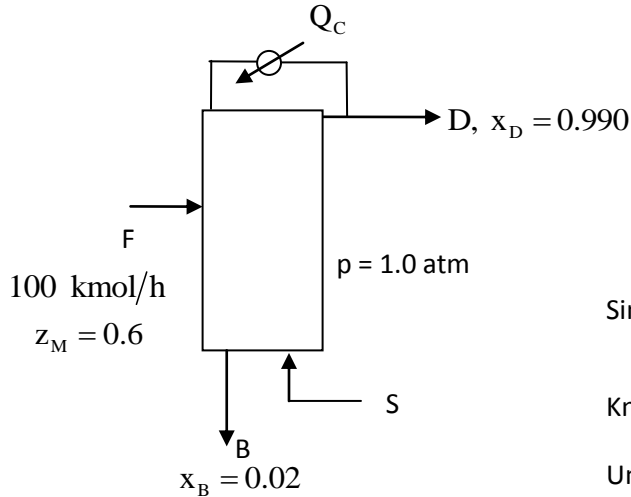$$h_F = [39.7(0.55) + 51.7(0.45)](65.25) = 1804 \text{kcal} / \text{kmol}$$

$$Q_R = Dh_D + Bh_B - Fh_F - Q_C$$
$$Q_R = (547.6333)(1369.65) + (452.3667)(3567.3) - (1000)(1804) - (-13,132,288)$$
$$Q_R = 13,692,081 \text{ kcal/h.}$$

Note that $|Q_C|$ and Q_R are relatively close.

3.E1. *Was 3.D8 in 2nd Edition.*

M.B.   F + S = D + B

$$Fz_M + Sy_{S,M} = Dx_D + Bx_B$$

Since steam is pure, $y_{S,M} = 0$

Know F, z_M, x_D, x_B

Unknowns S, D, B,   Need E.B.

$$Fh_F + Q_C + SH_S = Dh_D + Bh_B$$

Pick as basis liquid at 0°C, $h_W = 0$ & $h_M = 0$ (essentially steam table choice)
Assume ideal mixtures.

$$h_F = C_{P_{avg}} (T_P - T_{ref}) \text{ where } C_{P_{avg}} = 0.4 \, \bar{C}_{P_{W,L}} + 0.6 \, \bar{C}_{P_{M,L}}$$

Felder & Rouseau p. 637 $\bar{C}_{PW} = 0.0754$ kJ/mol

$$C_{PM} = 0.07586 + 16.83 \times 10^{-5} T \text{ kJ/mol}$$

$$\bar{C}_{PM} = C_{PM}(T_{avg}) = C_{PM}((0+40)/2) = C_{PM}(20°C)$$

$$\bar{C}_{PM} = 0.07586 + 16.83 \times 10^{-5}(20) = 0.079226$$

$$C_{P_{avg}} = 0.4(0.0754) + 0.6(0.079226) = 0.077696$$

$$h_F = 0.077696(40 - 0) = 3.1078 \text{ kJ/mol feed} = 3107.8 \text{ kJ/kmol}$$

Can also use steam table for water

$$H_S \text{ is sat'd vapor steam 1 atm,} \quad H_S = 2676.0 \frac{\text{kJ}}{\text{kg}} \frac{18.0 \text{ kg}}{\text{kmol}}$$

Steam Table F&R, p. 645 $H_S = 48,168$ kJ/kmol

h_D is sat'd liquid at $x_D = 0.99$. From Table 2-7, T = 64.6°C

$$h_D = C_{P_{avg}}(64.6 - 0) \text{ where } C_{P_{avg}} = 0.01 \, \bar{C}_{PW} + 0.99 \, \bar{C}_{PM}$$

$$\bar{C}_{PM} = C_{PM}(T_{avg}) = C_{PM}(32.3°C) = 0.07586 + 16.83 \times 10^{-5}(32.3) = 0.081296$$

$$C_{P_{avg}} = 0.01(0.0754) + 0.99(0.081296) = 0.08124$$

66

$$H_D = 0.08124(64.6) = 5.2479 \text{ kJ/mol} = 5247.9 \text{ kJ/kmol}$$

h_B : Since leaving an equilibrium stage, sat'd liqd. 2% MeOH

Table 2-7, T = 96.4°C

$$h_B = C_{P_{avg}}(96.4-0) \text{ where } C_{P_{avg}} = 0.98\, \bar{C}_{PW} + 0.02\, \bar{C}_{PM}$$

$$\bar{C}_{PM} = C_{PM}((96.4+0)/2) = C_{PM}(48.2°C)$$

$$\bar{C}_{PM} = 0.07586 + 16.83\times10^{-5}(48.2) = 0.08397$$

$$\bar{C}_{P_{avg}} = 0.98(0.0754) + 0.02(0.08397) = 0.07557 \text{ kJ/mol}$$

$$h_B = 0.07557(96.4) = 7.28509 \text{ kJ/mol} = 7285.09 \text{ kJ/mol}$$

Q_C = do EB around condenser

$$Q_C = -\lambda_{dist}V_1 = -\lambda_{dist}(L_o + D) = -\lambda_{dist}\left(\frac{L_o}{D}+1\right)D$$

$$\lambda_{dist} \approx 0.99\lambda_{MeOH} + 0.01\lambda_W$$

Felder & Rousseau: $\lambda_M = 35.27 \text{ kJ/mol} \,\& \, \lambda_W = 40.656 \text{ kJ/mol}$

$$\lambda_{dist} = (0.99)(35.27) + (0.01)(40.656) = 35.324 \frac{\text{kJ}}{\text{mol}} = 35,323,86 \text{ kJ/kmol}$$

$$Q_C = -(35,323.86)(2.3+1)D = -116,568.7D \text{ kJ/h}$$

Plug Q_C & numbers into E.B.

$$100(3107.8) - 116,568.7D + 48,168S = 5247.9D + 7285.09B$$

or $310,780 + 48,168S = 121,816.6D + 7285.09B$

Solve simultaneously with 2 MB. $100 + S = D + B$

$60 + 0 = 0.99D + 0.02B$

One can use algebra or various computer packages.

Obtain: D = 56.33 kmol/h, B = 211.71 kmol/h

S = 168.04 kmol/h, $Q_C = -6,566,000$ kJ/h.

E2. *Was 3.D9 in 2nd Edition.* $F = 500\dfrac{\text{kmol}}{\text{h}} = 500,000\dfrac{\text{mol}}{\text{h}}$

$F + S = D + B$

$Fz + S\cancel{y_S} = Dx_D + Bx_B$

2 eq. 3 unknowns

Condenser: $Q_C = (1 + L_0/D)D(h_o - H_1)$

Note Eq (3-14) not valid.

For enthalpy pick reference pure liquid water 0°C and pure liquid methanol 0°C. Felder & Rouseau: $C_{P_{MeOH}} = 75.86 + 0.01683T$ at $T_{avg} = \dfrac{64.5+0}{2} = 3225$, $C_{P_{MeOH}} = 76.4 \text{ J/mol}°\text{C}$.

Assuming distillate pure methanol, boils at 64.5°C

$$h_D = C_{P_{Meoh,liq}}(T - T_{ref}) = (76.4 \text{ J/mol})(64.5 - 0) = 4928.0 \text{ J/mol}$$

$$H_1 = h_D + \lambda_1 (\text{at } 64.5°F) = 4928 + 35270 \text{ J/mol} = 40,198 \text{ J/mol}$$

$$Q_C = (4)(4928 - 40198)D = -141,080D \text{ J/h} \text{ where D is mol/h}$$

Overall Energy balance: $F h_F + SH_S + Q_C = Dh_D + Bh_B$

Bottoms is essentially pure H_2O at 100°C

$$h_B = C_{P_{W,liq}}(T - T_{ref}) = \left(75.4 \ \frac{J}{mol°C}\right)(100 - 0) = 7540 \ \frac{J}{mol}$$

$$H_S = h_B + \lambda_W (\text{at } 100°C) = 7540 + 40656 \text{ J/mol} = 48196$$

For feed. 60 mole % Methanol boils at 71.2°C (Table 2-7).

$$h_F = \sum C_{P_i} z_i (T - T_{ref}) = (0.6)(76.459)(71.2) + (0.4)(75.4)(71.2) = 5413.7 \text{ J/mol}$$

Now, Eqs are

(1) $F + S = D + B$ or $500,000 + S = D + B$

(2) $Fz = Dx_D + Bx_B$ or $(500,000)(.6) = 0.998D + 0.0013B$

(3) $Q_C = \left(1 + \dfrac{L_o}{D}\right)D(h_D - H_1)$ or $Q_C = 141,080D$

(4) $Fh_F + Sh_S + Q_C = Dh_D + Bh_B$ or (500,000) (54137) + S (48196)

$$+ Q_C = D(4928) + B (7540)$$

Solve simultaneously: D = 298.98, B = 1245.5, S = 1044.2 kmol/h

$$Q_C = -4.218 \times 10^{+7} \text{ kJ/h}$$

3.F1.   An enthalpy composition diagram is available on p. 272 of Perry's Chemical Engineer's Handbook, 3rd ed., 1950.

Eq. (3-3) $D = \left(\dfrac{z - x_B}{x_D - x_B}\right)F = \dfrac{0.79 - 0.004}{0.997 - 0.004}(25,000) = 19,788.5 \text{ kmol/h}$

Note that N_2 mole fractions were used since N_2 is more volatile. B = F − D = 5211.5

From enthalpy comp. diag. $h_D = 0$, $H_1 = 1350 \text{ kcal/kmol}$, $h_B = 160$, $h_F = 1575$.   Then,

$$Q_C = (1 + L_o/D)D(h_D - H_1) = (5)(19788.5)(0 - 1350) = -133,572,000 \text{ kcal/h}$$

$$Q_R = Dh_D + Bh_B - Fh_F - Q_C$$

$$Q_R = 0 + (5211.5)(160) - (25,000)(1575) - Q_C = 95,030,000 \text{ kcal/h}$$

3.F2.   We will use the enthalpy composition diagram on p. 3-171 of Perry's 6th edition or p. 3-158 of Perry's 5th ed. Do for 1 kmol of feed:

Conversion of feed from kg to moles.   Basis 100 kg

30 kg NH_3 = 1.765 kmol

70 kg H_2O = 3.888

Total 5.653 kmol

Thus 1 kmol is 100/5.653 = 17.69 kg

Will work problem in weight fractions since data is presented that way.

95% recovery: $(0.95) Fz = Dx_D$ or, $D = (.95) Fz / x_D = (.95) (17.69) (.3)/(.98) = 5.15$ kg.

$B = F - D = 12.54$ kg

$x_B = (Fz - Dx_D)/B = [(17.69)(.3) - (5.15)(98)]/(12.54) = 0.021$

From diagram: $h_D = 55$, $H_1 = 415$, $h_B = 150$, $h_F = -5$ kcal/kg

Eq. (3-14), $Q_C = (1 + L_o/D)D(h_D - H_1) = (3)(5.15)(55 - 415) = -5562$ kcal/kmol feed

and $Q_R = Dh_D + Bh_B - Fh_F - Q_C$

$Q_R = (5.15)(55) + (12.54)(150) - (17.69)(-5) - Q_C = 7815$ kcal/kmol of feed

G1. a.) Using NRTL. $Q_C = -778,863$ kcal/h, $Q_R = 709,520$ kcal/h

b.) $Q_C = -1,064,820$ kcal/h, $Q_R = 995,478$ kcal/h

G2. *New Problem in 3ʳᵈ Edition.*

ASPENPlus. $D = 988$, $L/D = 3$, Peng Robinson, $N = 40$, $N_F = 20$ (arbitrary values in Radfrac)

$$x_D = 1.000 \qquad x_{DC6} = 1.211 \times 10^{-7}$$

$$x_B = 0.0013316$$

$$\boxed{\begin{array}{l} Q_C = -4.4426 \times 10^7 \text{ Btu/h,} \\ Q_R = 4.9852 \times 10^7 \text{ Btu/h} \end{array}}$$