DISTILLATION

11.4 DISTILLATION WITH REFLUX AND McCABE–THIELE METHOD

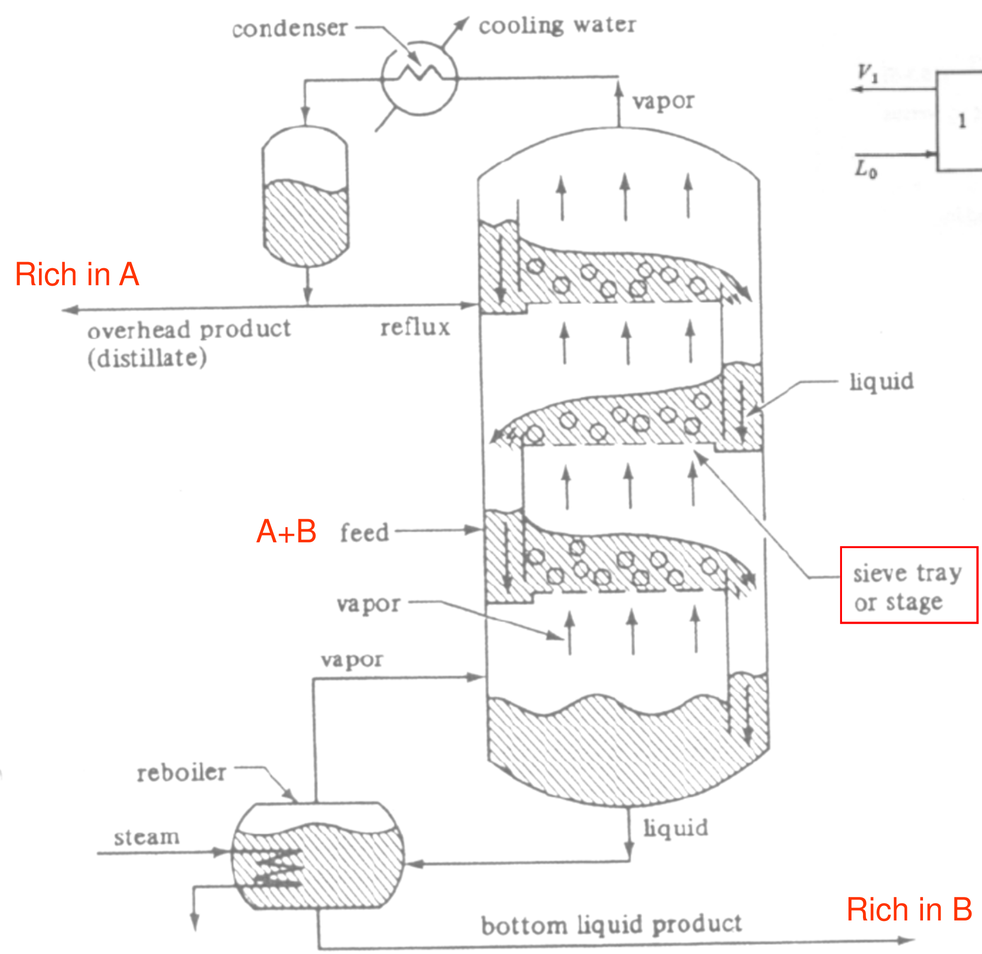


FIGURE 11.4-1. *Process flow of a fractionating tower containing sieve trays.*

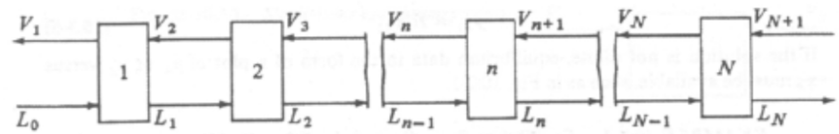


FIGURE 10.3-2. *Countercurrent multiple-stage process.*

Concentration of A (component with lower boiling point) increases as the vapor goes up in the vapor phase, decreased in the liquid phase

11.4B McCabe–Thiele Method of Calculation for Number of Theoretical Stages

A total material balance gives

$$V_{n+1} + L_{n-1} = V_n + L_n$$

A component balance on A gives

$$V_{n+1}y_{n+1} + L_{n-1}x_{n-1} = V_n y_n + L_n x_n$$

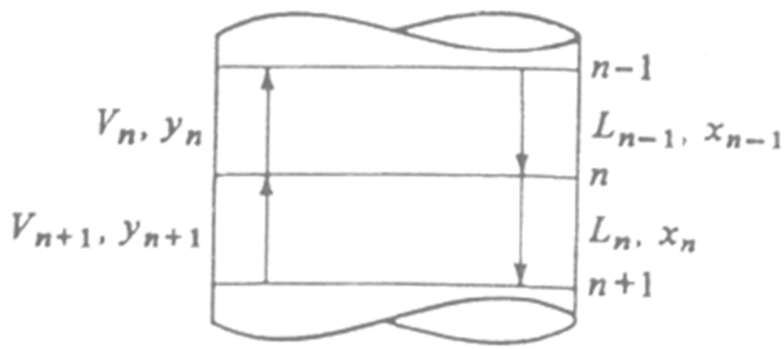


FIGURE 11.4-2. *Vapor and liquid flows entering and leaving a tray.*

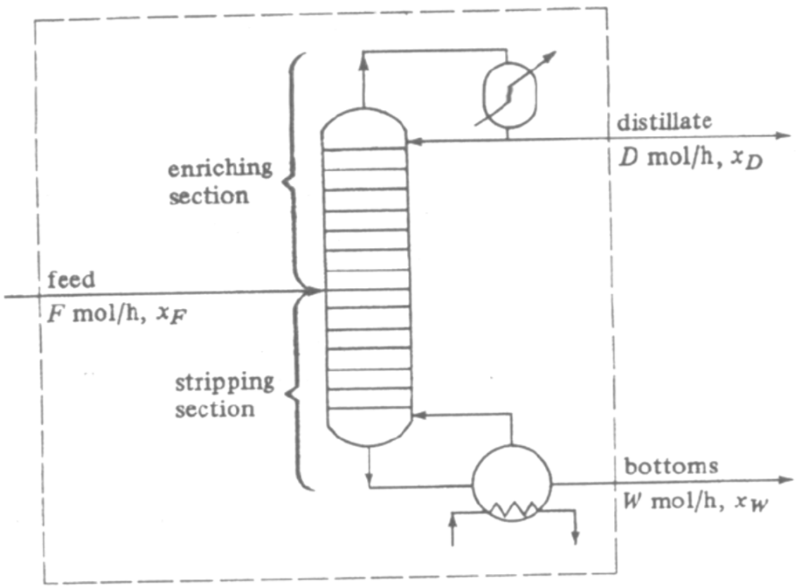


FIGURE 11.4-3. *Distillation column showing material-balance sections for McCabe–Thiele method.*

A+B

Enriching section: rich in A
Stripping section: lean in A

An overall material balance around the entire column in Fig. 11.4-3 states that the entering feed of F mol/h must equal the distillate D in mol/h plus the bottoms W in mol/h.

$$F = D + W \tag{11.4-3}$$

A total material balance on component A gives

$$Fx_F = Dx_D + Wx_W \tag{11.4-4}$$

Enriching section

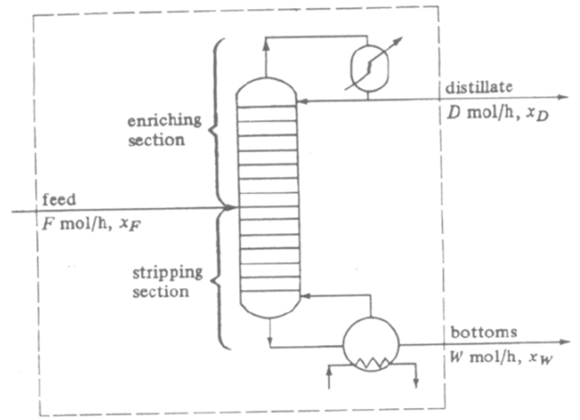
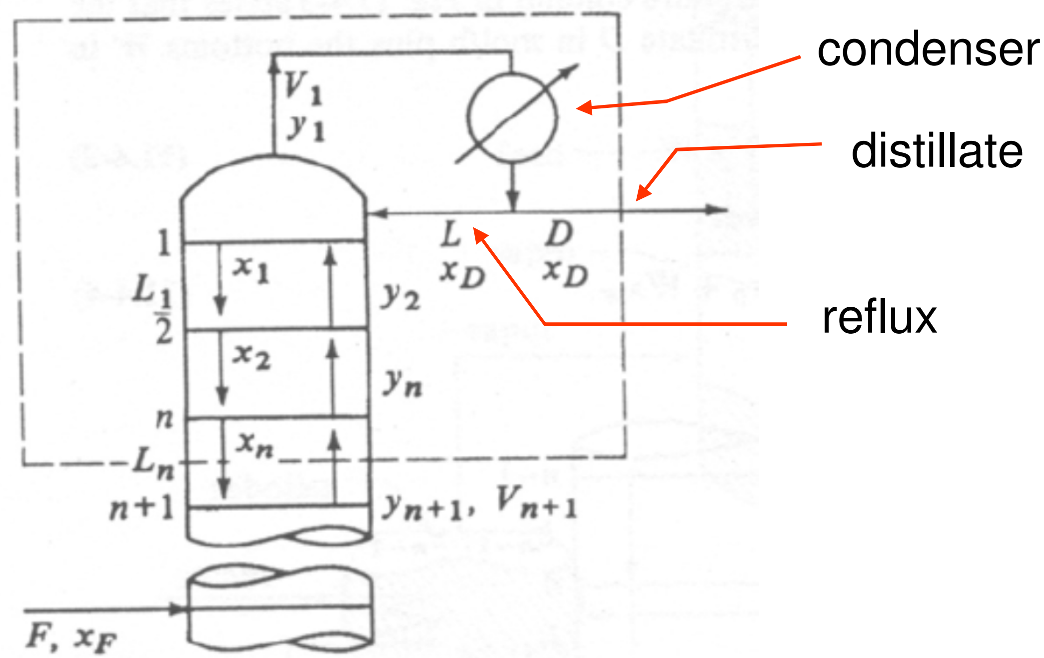


FIGURE 11.4-3. *Distillation column showing material-balance sections for McCabe–Thiele method.*



(a)

FIGURE 11.4-4.

In Fig. 11.4-4a the distillation tower section above the feed, the enriching section, is shown schematically. The vapor from the top tray having a composition y_1 passes to the condenser, where it is condensed so that the resulting liquid is at the boiling point. The reflux stream L mol/h and distillate D mol/h have the same composition, so $y_1 = x_D$. Since equimolal overflow is assumed, $L_1 = L_2 = L_n$ and $V_1 = V_2 = V_n = V_{n+1}$.

Making a total material balance over the dashed-line section in Fig. 11.4-4a,

$$V_{n+1} = L_n + D \tag{11.4-5}$$

Making a balance on component A,

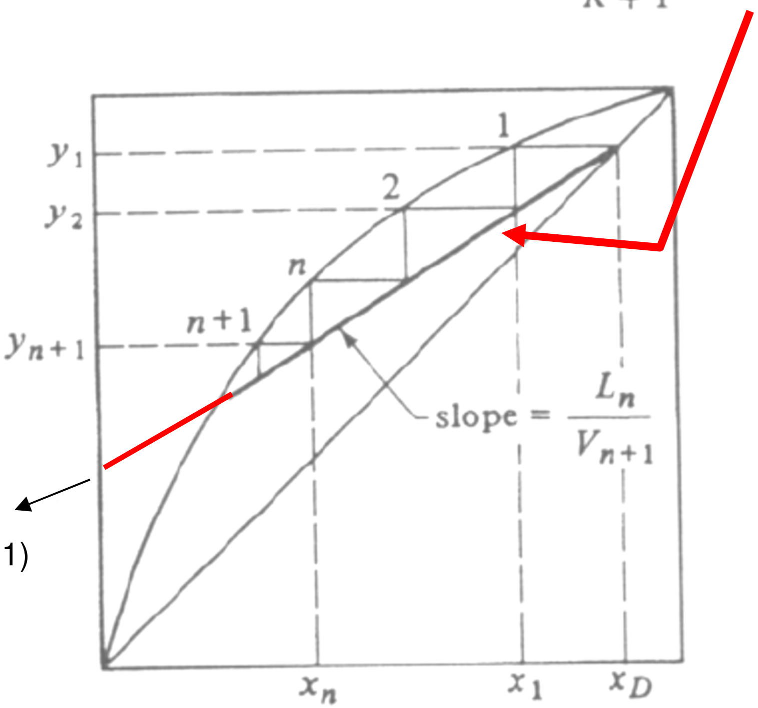
$$V_{n+1} y_{n+1} = L_n x_n + D x_D \qquad (11.4\text{-}6)$$

Solving for y_{n+1}, the enriching-section operating line is

$$y_{n+1} = \frac{L_n}{V_{n+1}} x_n + \frac{D x_D}{V_{n+1}} \qquad (11.4\text{-}7)$$

Since $V_{n+1} = L_n + D$, $L_n/V_{n+1} = R/(R+1)$ and Eq. (11.4-7) becomes

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1} \qquad (11.4\text{-}8)$$

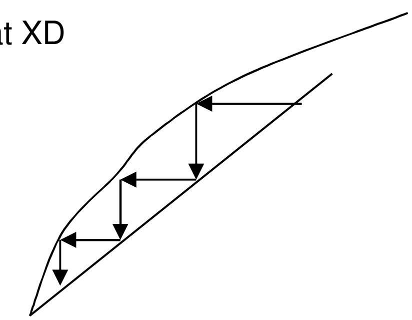


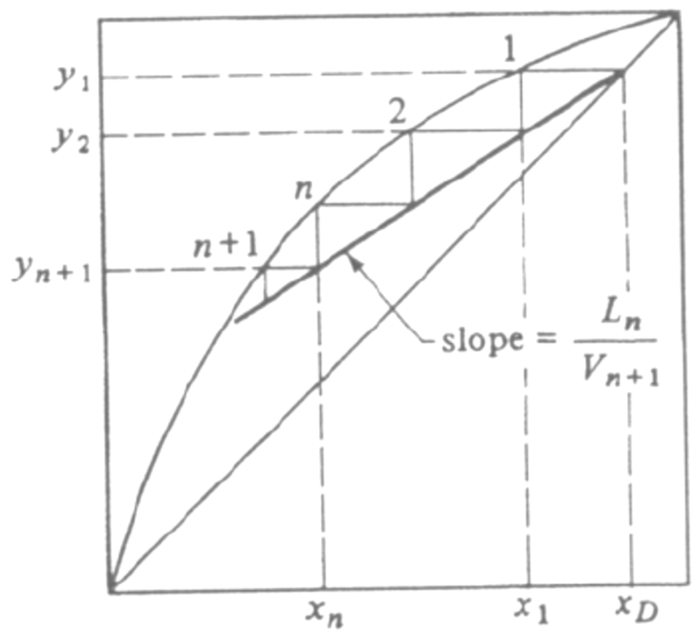
(b)

y=xD/(R+1)

No of stages

Start at XD





(b)

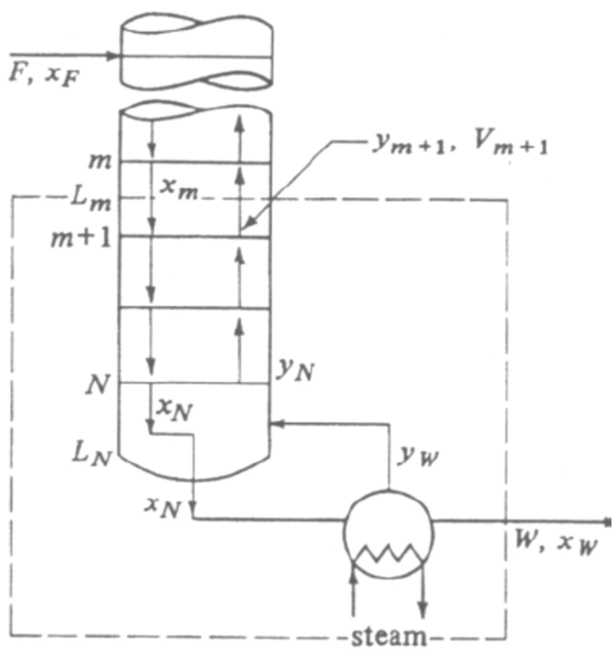
The theoretical stages are determined by starting at x_D and stepping off the first plate to x_1. Then y_2 is the composition of the vapor passing the liquid x_1. In a similar manner, the other theoretical trays are stepped off down the tower in the enriching section to the feed tray.

3. Equations for stripping section. Making a total material balance over the dashed-line section in Fig. 11.4-5a for the stripping section of the tower below the feed entrance,

$$V_{m+1} = L_m - W \tag{11.4-9}$$

Making a balance on component A,

$$V_{m+1} y_{m+1} = L_m x_m - W x_W \tag{11.4-10}$$

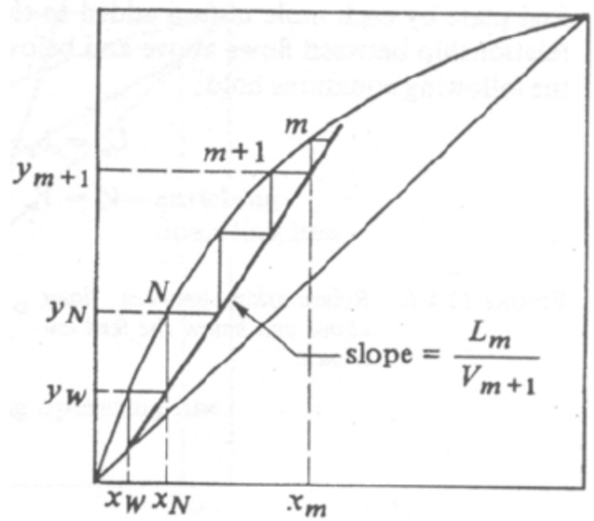


(a)

Solving for y_{m+1}, the stripping-section operating line is

$$y_{m+1} = \frac{L_m}{V_{m+1}} x_m - \frac{W x_W}{V_{m+1}}$$

Equimolal flow
$L_m = L_N$ = constant
$V_{m+1} = V_N$ = constant



(b)

Solving for y_{m+1}, the stripping-section operating line is

$$y_{m+1} = \frac{L_m}{V_{m+1}} x_m - \frac{W x_W}{V_{m+1}} \tag{11.4-11}$$

Again, since equimolal flow is assumed, $L_m = L_N =$ constant and $V_{m+1} = V_N =$ constant. Equation (11.4-11) is a straight line when plotted as y versus x in Fig. 11.4-5b, with a slope of L_m/V_{m+1}. It intersects the $y = x$ line at $x = x_W$. The intercept at $x = 0$ is $y = -Wx_W/V_{m+1}$.

Again the theoretical stages for the stripping section are determined by starting at x_W, going up to y_W, and then across to the operating line, etc.

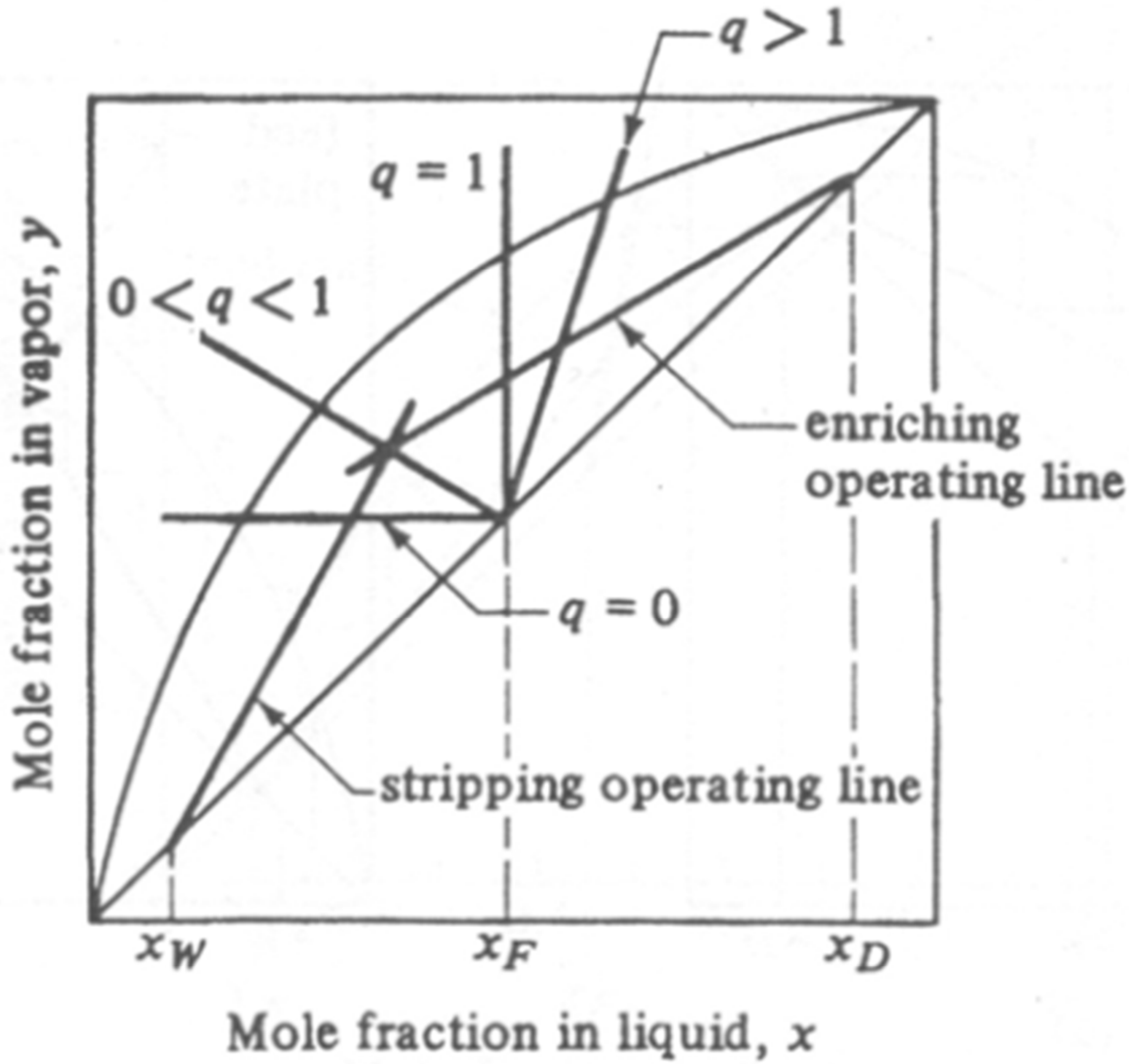
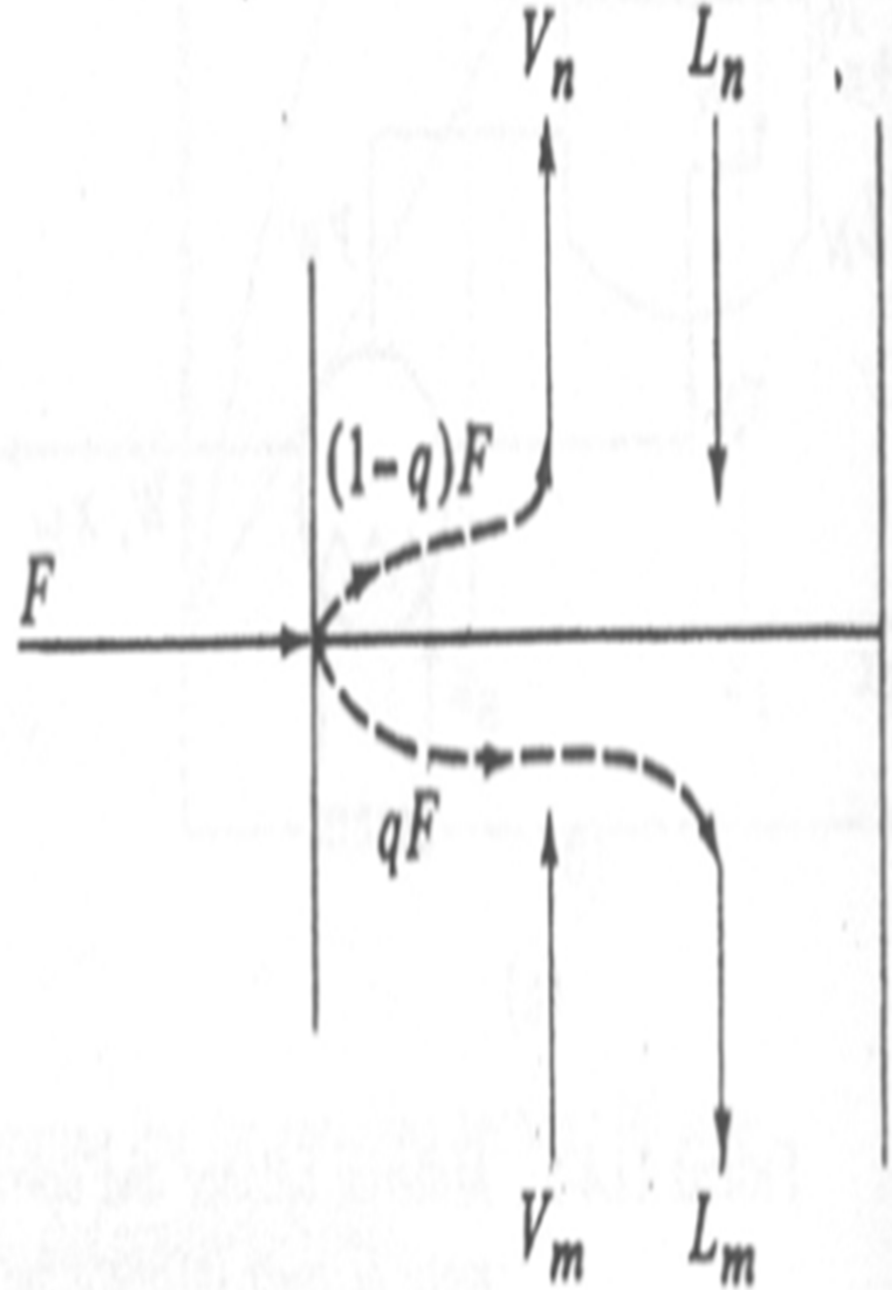


FIGURE 11.4-7. *Location of the q line for various feed conditions : liquid below boiling point ($q > 1$), liquid at boiling point ($q = 1$), liquid + vapor ($0 < q < 1$), saturated vapor ($q = 0$).*

FIGURE 11.4-6. *Relationship between flows above and below the feed entrance.*



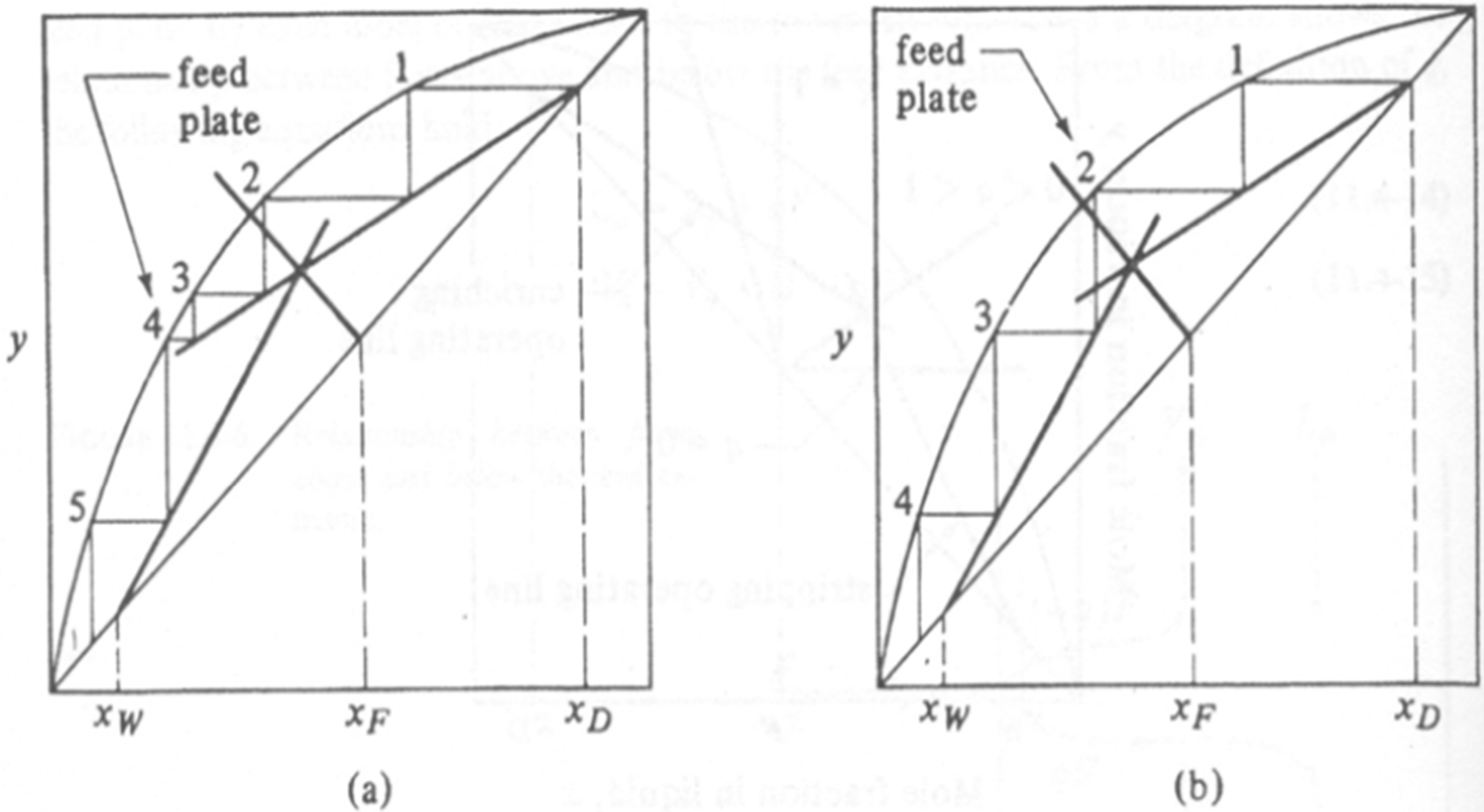


FIGURE 11.4-8. *Method of stepping off number of theoretical trays and location of feed plate : (a) improper location of feed on tray 4, (b) proper location of feed on tray 2 to give minimum number of steps.*

EXAMPLE 11.4-1. ***Rectification of a Benzene–Toluene Mixture***
A liquid mixture of benzene–toluene is to be distilled in a fractionating tower at 101.3 kPa pressure. The feed of 100 kg mol/h is liquid and it contains 45 mol % benzene and 55 mol % toluene and enters at 327.6 K (130°F). A distillate containing 95 mol % benzene and 5 mol % toluene and a bottoms containing 10 mol % benzene and 90 mol % toluene are to be obtained. The reflux ratio is 4: 1. The average heat capacity of the feed is 159 kJ/kg mol · K (38 btu/lb mol · °F) and the average latent heat 32 099 kJ/kg mol (13 800 btu/lb mol). Equilibrium data for this system are given in Table 11.1-1 and in Fig. 11.1-1. Calculate the kg moles per hour distillate, kg moles per hour bottoms, and the number of theoretical trays needed.

TABLE 11.1-1. *Vapor-Pressure and Equilibrium-Mole-Fraction Data for Benzene–Toluene System*

		Vapor Pressure					
Temperature		*Benzene*		*Toluene*		*Mole Fraction Benzene at 101.325 kPa*	
K	°*C*	*kPa*	*mm Hg*	*kPa*	*mm Hg*	x_A	y_A
353.3	80.1	101.32	760			1.000	1.000
358.2	85	116.9	877	46.0	345	0.780	0.900
363.2	90	135.5	1016	54.0	405	0.581	0.777
368.2	95	155.7	1168	63.3	475	0.411	0.632
373.2	100	179.2	1344	74.3	557	0.258	0.456
378.2	105	204.2	1532	86.0	645	0.130	0.261
383.8	110.6	240.0	1800	101.32	760	0	0

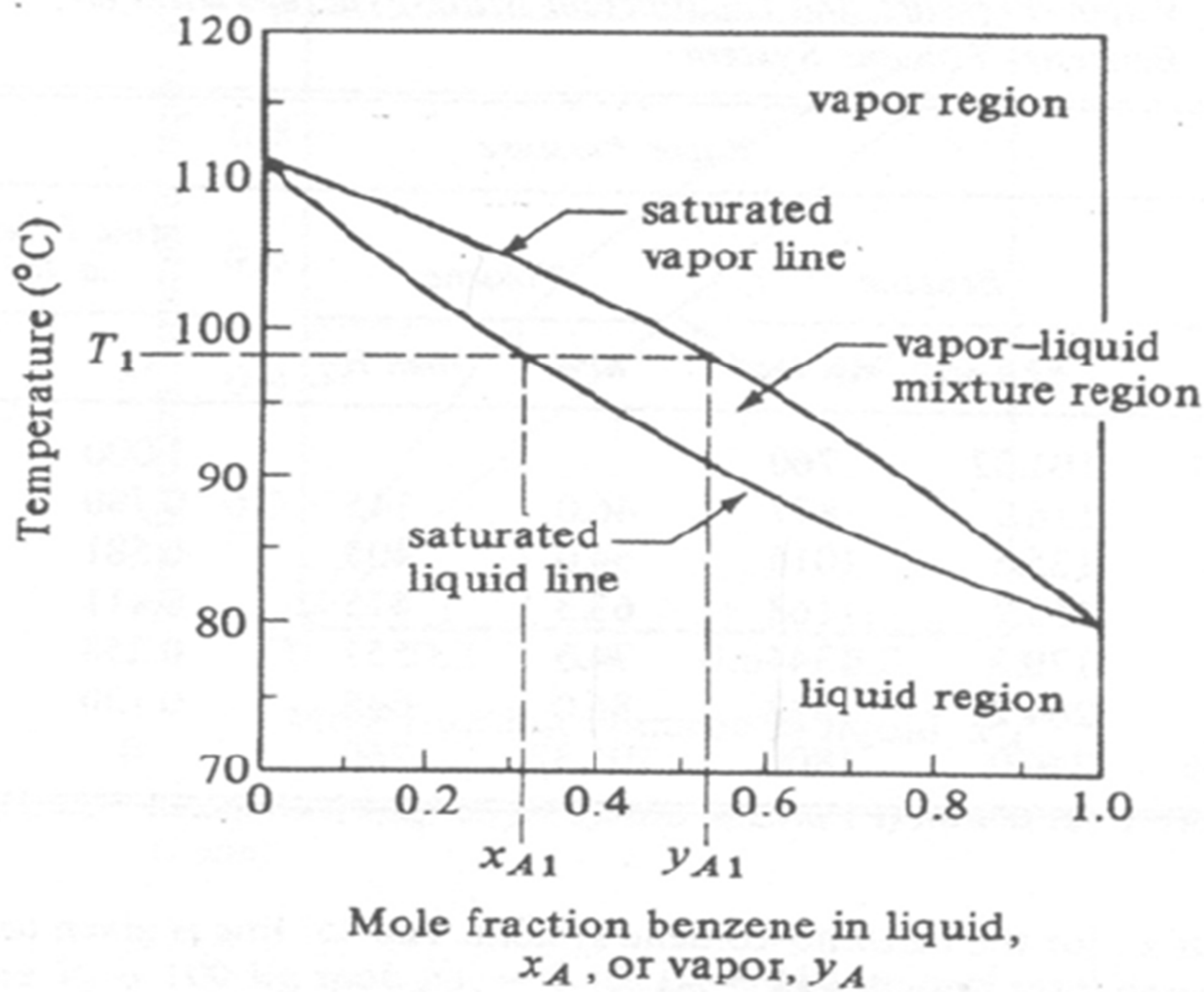


FIGURE 11.1-1. *Boiling point diagram for benzene (A)–toluene (B) at 101.325 kPa (1 atm) total pressure.*

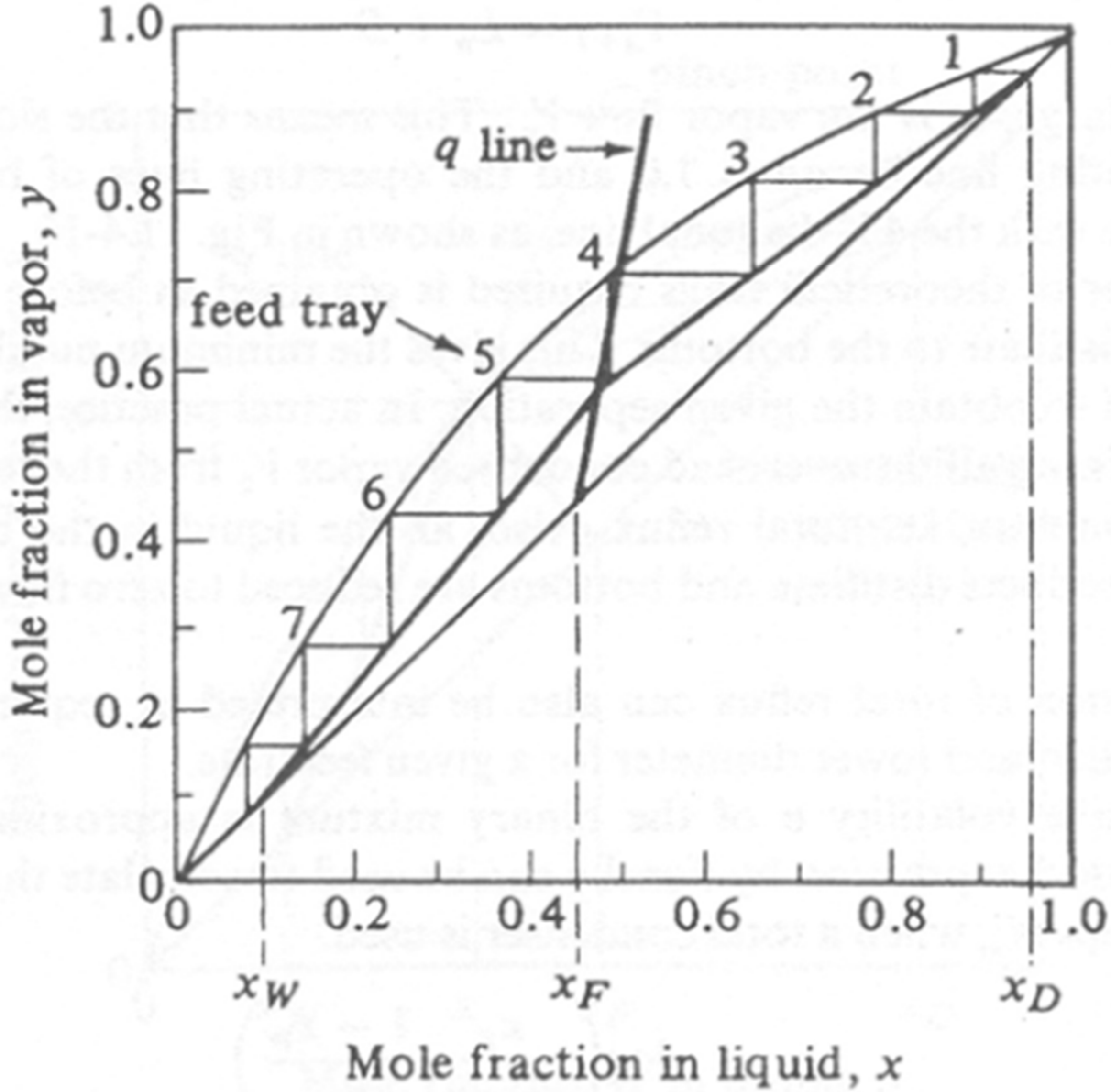
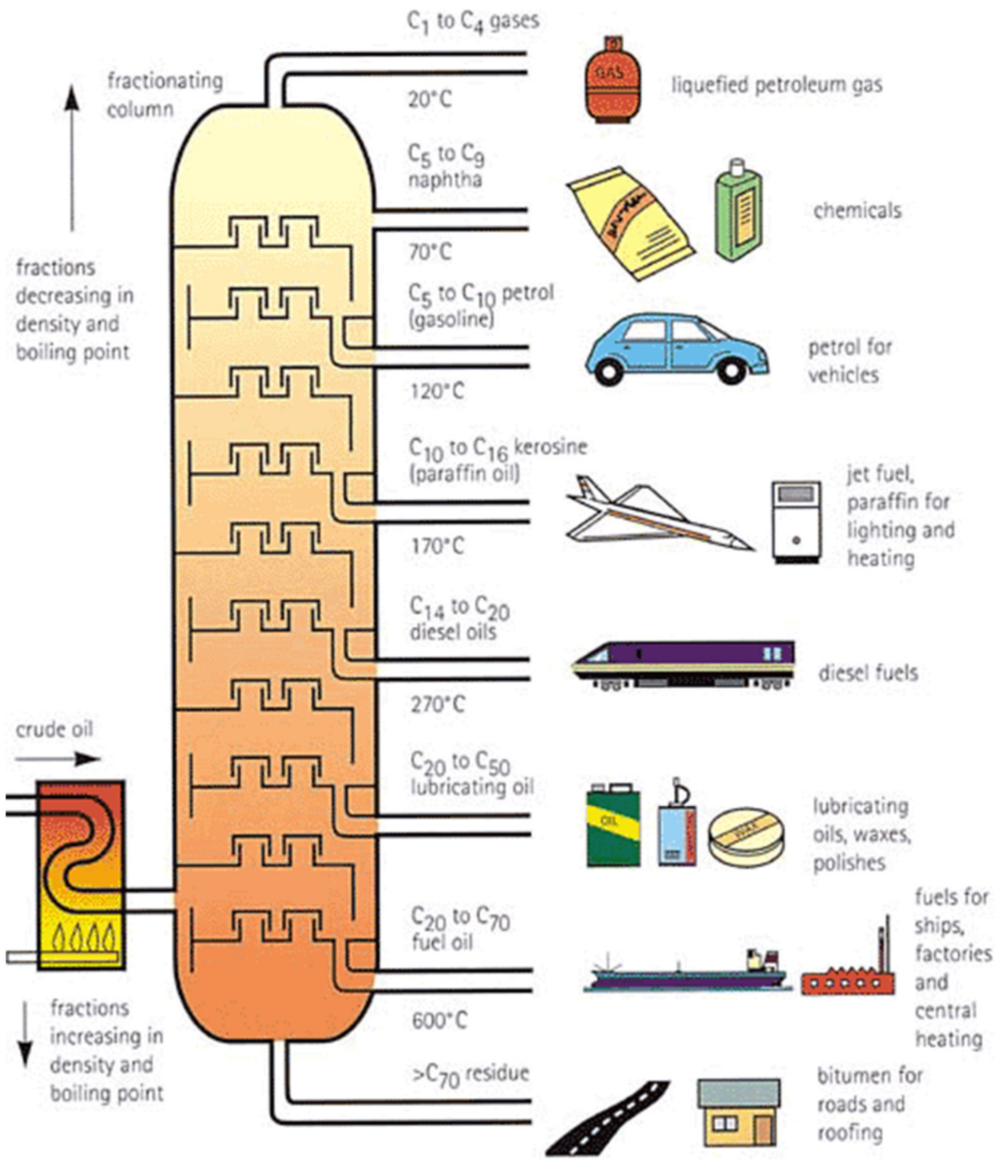
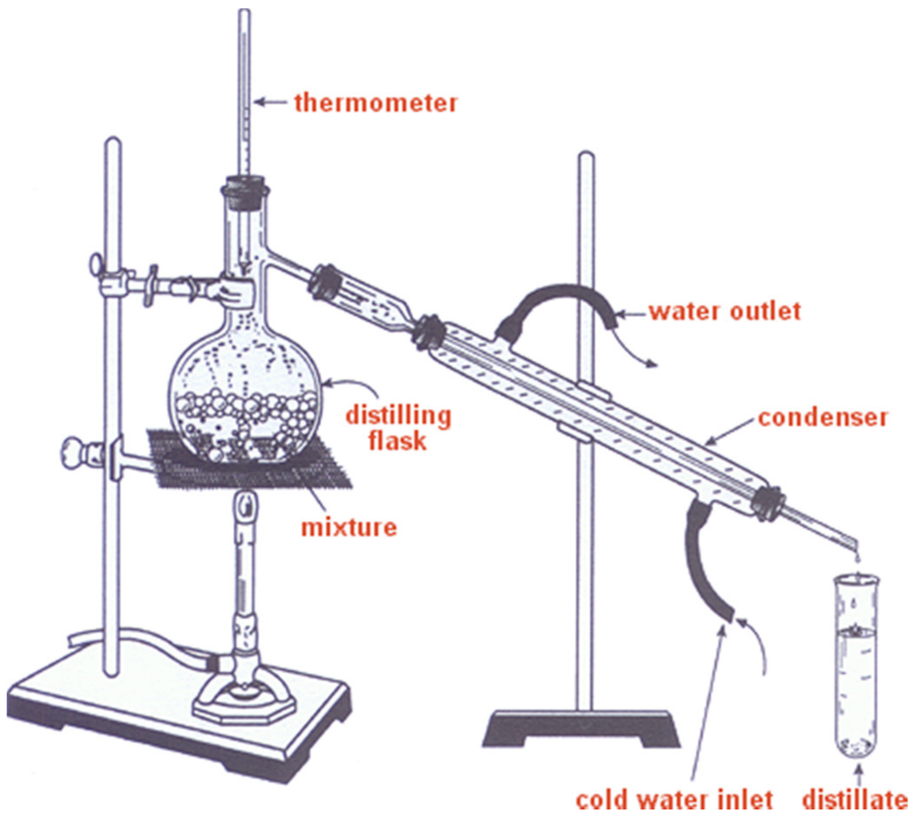


FIGURE 11.4-9. *McCabe-Thiele diagram for distillation of benzene–toluene for Example 11.4-1.*



C_1 to C_4 gases
fractionating column
20°C
liquefied petroleum gas
GAS
C_5 to C_9 naphtha
chemicals
70°C
fractions decreasing in density and boiling point
C_5 to C_{10} petrol (gasoline)
petrol for vehicles
120°C
C_{10} to C_{16} kerosine (paraffin oil)
jet fuel, paraffin for lighting and heating
170°C
C_{14} to C_{20} diesel oils
diesel fuels
270°C
crude oil
C_{20} to C_{50} lubricating oil
OIL
WAX
lubricating oils, waxes, polishes
C_{20} to C_{70} fuel oil
fuels for ships, factories and central heating
600°C
fractions increasing in density and boiling point
$>C_{70}$ residue
bitumen for roads and roofing


thermometer
water outlet
distilling
flask
condenser
mixture
cold water inlet
distillate