Unit Operation I

Distillation

A feed stream made up of 40% mole benzene and 60% mole toluene is to be separated into benzene-rich and toluene-rich products using a distillation column. The column has 10 equilibrium stages including a partial condenser and a partial reboiler and is operated at 25 psia. The feed stream, with a flow rate of 100 moles/hr, is at its bubble point at 25 psia and is placed on the fourth stage from the top.

1- Determine the compositions of the two products and their flow rates at different reflux ratios of 0, 1, 10 and ∞.

2- Determine the condenser and reboiler temperatures at different reflux ratios.

Vapor-liquid equilibrium data for the benzene-toluene system are provided in the following table at 25 psia.

X (Benzene)	Y (Benzene)	T, F
0.00	0.00	267
0.1	0.19	259
0.2	0.35	252
0.3	0.49	245
0.4	0.60	239
0.5	0.70	233
0.6	0.77	227
0.7	0.84	222
0.8	0.90	218
0.9	0.95	213
1.00	1.00	209

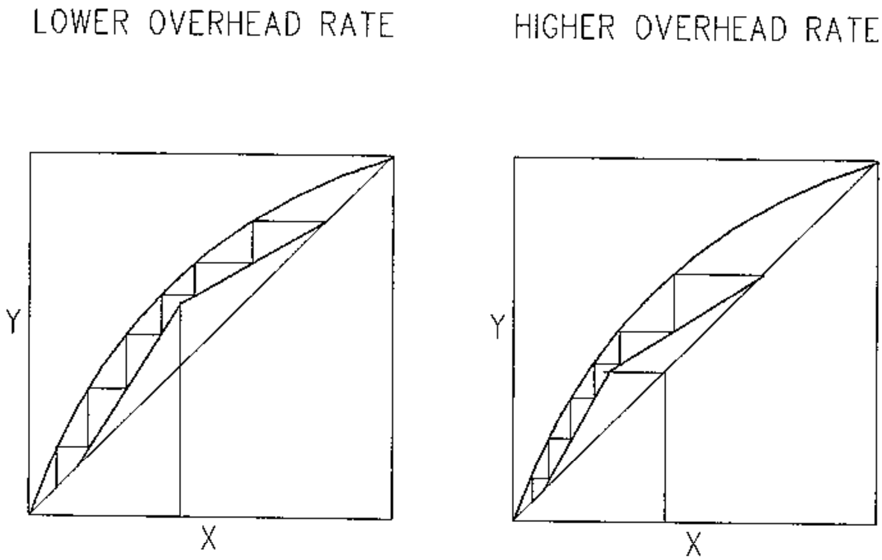

Figure 6-2. Effect of product rates on column performance.

and a partial reboiler and is operated at 25 psia. The feed stream, with a flow rate of 100 moles/hr, is at its bubble point at 25 psia and is placed on the fourth stage from the top. The problem is to determine the compositions of the two products at different reflux ratios.

Vapor-liquid equilibrium data for the benzene-toluene system are provided in Table 6-1 at 25 psia.

Solution. The McCabe-Thiele graphical method is applied using the Y-X diagram. The equilibrium curve is first plotted from the given data (Figure 6-3). A temperature coordinate is also included in the diagram (non-linear) to determine the condenser, reboiler, and tray temperatures.

The next step is to plot the q-line, which intersects the diagonal at the feed composition. The slope of the q-line is computed on the basis of the feed thermal conditions at the feed tray temperature, which is dependent on the product rates. It is assumed that the product rate (distillate or bottoms) is such that the feed is almost a saturated liquid at feed tray conditions so that the q-line is close to vertical.

The operating lines are drawn next. Assuming a reflux ratio R = 1, the slope of the rectifying section operating line is $L_r/V_r = 0.5$ (Equation 6-1). The rectifying section operating line is determined by trial and error by drawing lines with a slope of 0.5 between the q-line and the diagonal. The correct

Table 6-1
Vapor-liquid equilibrium data for the benzene-toluene binary at 25 psia

X (Benzene)	Y (Benzene)	T, F
0.00	0.00	267
0.10	0.19	259
0.20	0.35	252
0.30	0.49	245
0.40	0.60	239
0.50	0.70	233
0.60	0.77	227
0.70	0.84	222
0.80	0.90	218
0.90	0.95	213
1.00	1.00	209

line is that which results in four rectifying stages, which is the specified number of theoretical stages above the feed tray (Figure 6-3).

The stripping section operating line must pass through the intersection of the q-line with the rectifying section operating line. The slope of the former is varied until the number of stages in the stripping section is six.

The compositions of the products are read from the intersections of the operating lines with the diagonal. The results are tabulated in Table 6-2 for different reflux ratios. Also shown are the condenser and reboiler temperatures as read from Figure 6-3, and the product flow rates, calculated from a component material balance:

$$FX_F = DY_D + (F - D)X_B$$

The product rates at high and low reflux ratios are sensitive to the q-line slope, which varies slightly depending on feed tray conditions. As a result, certain variations in the product rates are observed.

6.1.2 Effect of Number of Stages and Feed Location

The effect of the number of stages on separation may be readily inspected using the binary Y-X diagram. Other parameters, namely the reflux ratio and the product rates, are assumed constant. The condition of constant product rate is implied by fixing the q-line slope.

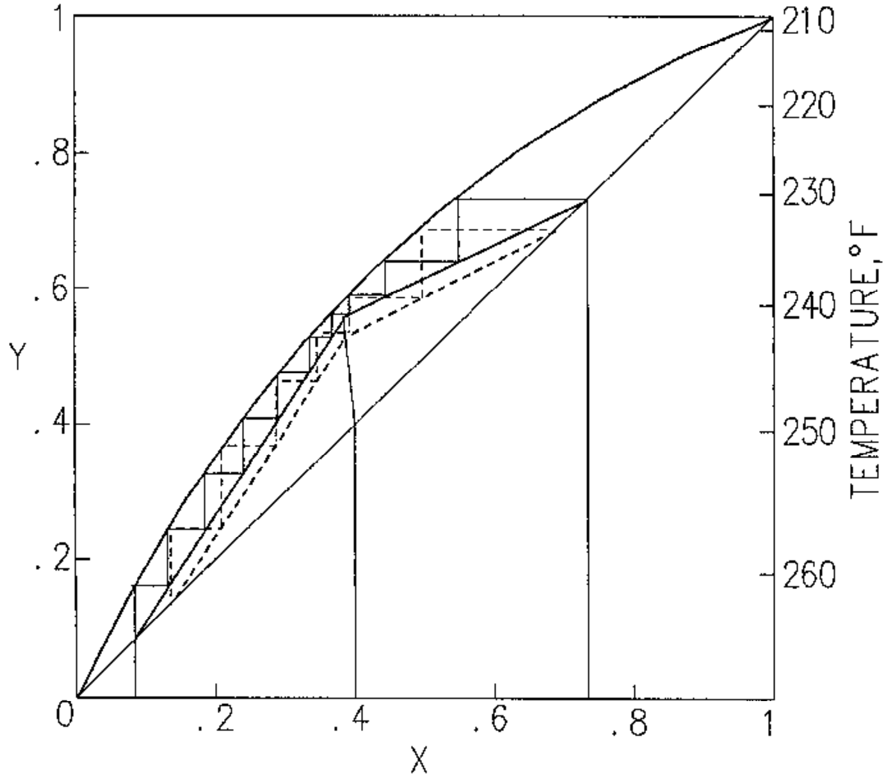

Figure 6-3. *Y-X* diagram for benzene-toluene.

The equilibrium curve and q-line are first drawn as usual on a Y-X diagram. The slope of the rectifying section operating line is known from the specified reflux ratio. For a given number of stages in the rectifying section, the correct operating line is found by trial and error aimed at matching the given number of stages while maintaining a constant slope. As the operating line gets closer to the equilibrium line, it intersects the diagonal at a higher concentration of the light component and the number of rectifying stages increases.

The stripping section operating line is drawn by joining the q-line intersection with the rectifying operating line to the diagonal. Again, the correct stripping operating line is one that matches the number of stripping stages. Stripping section operating lines closer to the equilibrium curve imply more stripping stages and lower concentrations of the light component in the bottoms.

In conclusion, with other parameters held constant, more stages in a given section result in higher purity of the corresponding product, and vice versa.

Table 6-2
Results of Example 6-1

Reflux Ratio	0	1	10	Infinity
Distillate Composition Y (Benzene)	0.540	0.735	0.796	0.950
Bottoms Composition X (Benzene)	0.340	0.070	0.004	0.002
Distillate Rate, Mole/Hr	30	50	50	40
Condenser Temperature, °F	242	230	226	213
Reboiler Temperature, °F	242	261	266	267

Consequently, if the total number of stages is held constant, but the feed location is raised, higher purity bottoms and lower purity distillate products are expected. The reverse is true if the feed location is lowered.

Using the H-X diagram, if the feed tray is not fixed, its optimum location can be determined as discussed in Section 5.3.3.

Example 6.2 Benzene-Toluene Column: Number of Stages and Feed Location Specified

The benzene-toluene mixture of Example 6-1 is to be separated into approximately 50 moles/hr distillate and 50 moles/hr bottoms products. The column is to be operated at a reflux ratio of 1. Determine the effect of the number of stages and feed location on the purity of the products.

Solution. Based on the results of Example 6-1, a distillate rate of about 50 moles/hr corresponds to a near vertical q-line, i.e., a bubble point feed. The equilibrium curve is drawn from data given in Table 6-1.

The operating lines are drawn as described above. Figure 6-3 illustrates the effect of varying the number of stages in each section and Table 6-3 summarizes the results. The first two points in the table represent columns with the same number of stripping stages (four) but with different numbers of rectifying stages (three and four). The results show that the bottoms