Solution

The number of plates at total reflux is given by:

$$n + 1 = \frac{\log\left[\left(\frac{0.9}{0.1}\right)\left(\frac{0.9}{0.1}\right)\right]}{\log 2.4} = 5.0 \qquad \text{(equation 11.58)}$$

Thus the number of theoretical plates in the column is $\underline{\underline{4}}$, a value which is independent of the feed composition.

If the feed is liquid at its boiling point, then the minimum reflux ratio R_m is given by:

$$R_m = \frac{1}{\alpha - 1}\left[\frac{x_d}{x_f} - \alpha\frac{(1 - x_d)}{(1 - x_f)}\right] \qquad \text{(equation 11.56)}$$

$$= \frac{1}{2.4 - 1}\left[\frac{0.9}{0.4} - \frac{(2.4 \times 0.1)}{0.6}\right]$$

$$= \underline{\underline{1.32}}$$

Using the graphical construction shown in Figure 11.18, with $y_f = 0.61$, the value of R_m is:

$$R_m = \frac{x_d - y_f}{y_f - x_f} = \frac{(0.9 - 0.61)}{(0.61 - 0.4)} = \underline{\underline{1.38}}$$

Selection of economic reflux ratio

The cost of a distillation unit includes the capital cost of the column, determined largely by the number and diameter of the plates, and the operating costs, determined by the steam and cooling water requirements. The depreciation charges may be taken as a percentage of the capital cost, and the two together taken as the overall charges. The steam required will be proportional to V_m, which may be taken as V_n where the feed is liquid at its boiling point. From a material balance over the top portion of the column, $V_n = D(R + 1)$, and hence the steam required per mole of product is proportional to $(R + 1)$. This will be a minimum when R equals R_m, and will steadily rise as R is increased. The relationship between the number of plates n and the reflux ratio R, as derived by GILLILAND[30], is discussed in Section 11.7.7.

The reduction in the required number of plates as R is increased beyond R_m will tend to reduce the cost of the column. For a column separating a benzene–toluene mixture, for example, where $x_f = 0.79$, $x_d = 0.99$ and $x_w = 0.01$, the numbers of theoretical plates as given by the McCabe–Thiele method for various values of R are given as follows. The minimum reflux ratio for this case is 0.81.

Reflux ratio R	0.81	0.9	1.0	1.1	1.2
Number of plates	∞	25	22	19	18

Thus, an increase in R, at values near R_m, gives a marked reduction in the number of plates, although at higher values of R, further increases have little effect on the number of plates. Increasing the reflux ratio from R_m therefore affects the capital and operating costs of a column as follows:

(a) The operating costs rise and are approximately proportional to $(R + 1)$.
(b) The capital cost initially falls since the number of plates falls off rapidly at this stage.
(c) The capital cost rises at high values of R, since there is then only a very small reduction in the number of plates, although the diameter, and hence the area, continually increases because the vapour load becomes greater. The associated condenser and reboiler will also be larger and hence more expensive.

The total charges may be obtained by adding the fixed and operating charges as shown in Figure 11.19, where curve A shows the steam costs and B the fixed costs. The final total is shown by curve C which has a minimum value corresponding to the economic reflux ratio. There is no simple relation between R_m and the optimum value, although practical values are generally 1.1–1.5 times the minimum, with much higher values being employed, particularly in the case of vacuum distillation. It may be noted that, for a fixed degree of enrichment from the feed to the top product, the number of trays required increases rapidly as the difficulty of separation increases, that is as the relative volatility approaches unity. A demand for a higher purity of product necessitates a very considerable increase in the number of trays, particularly when α is near unity. In these circumstances only a limited improvement in product purity may be obtained by increasing the reflux ratio. The designer must be careful to consider the increase in cost of plant resulting from specification of a higher degree of purity of production and at the same time assess the highest degree of purity that may be obtained with the proposed plant.

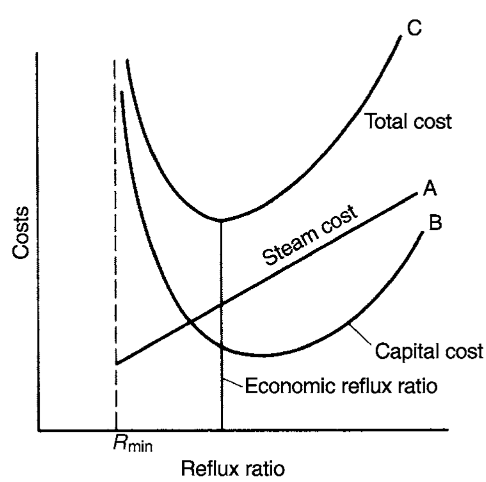

Figure 11.19. Influence of reflux ratio on capital and operating costs of a still

In general, the greater the reflux ratio, the lower is the number of plates or transfer units required although the requirements of steam in the reboiler and cooling water in the condenser are both increased and a column of larger diameter is required in order to achieve acceptable vapour velocities. An optimum value of the reflux ratio may be obtained by using the following argument which is based on the work of COLBURN[31].

The annual capital cost of a distillation column, c_c per mole of distillate, including depreciation, interest and overheads, may be written as:

$$c_c = c_a An/(Et_a D) \tag{11.59}$$

where c_a is the annual cost of the column per unit area of plate, A is the cross-sectional area of the column, n is the number of theoretical plates, E is the plate efficiency, t_a is the annual period of operation and D is the molar flowrate of distillate. The cross-sectional area of the column is given by:

$$A = V/u' \tag{11.60}$$

where V is the molar flow of vapour and u' is the allowable molar vapour velocity per unit area. Since $V = D(R + 1)$, where R is the reflux ratio, then the cost of the column is:

$$c_c = c_a n(R + 1)/(Et_a u') \tag{11.61}$$

The annual cost of the reboiler and the condenser, c_h per mole of distillate may be written as:

$$c_h = c_b A_h/(t_a D) \tag{11.62}$$

where c_b is the annual cost of the heat exchange equipment per unit area including depreciation and interest and A_h is the area for heat transfer. $A_h = V/N''$ where N'' is the vapour handling capacity of the boiler and condenser in terms of molar flow per unit area. Thus $A_h = D(R + 1)/N''$ and the cost of the reboiler and the condenser is:

$$c_h = c_b(R + 1)/(t_a N'') \tag{11.63}$$

As far as operating costs are concerned, the important annual variable costs are that of the steam in the reboiler and that of the cooling water in the condenser. These may be written as:

$$c_w = c_d V/D = c_3(R + 1) \tag{11.64}$$

where c_d is the annual cost of the steam and the cooling water. The total annual cost, c per mole of distillate, is the cost of the steam and the cooling water plus the costs of the column, reboiler and condenser, or:

$$c = (R + 1)[(c_a n/Et_a u') + (c_b/t_a N'') + c_d] \tag{11.65}$$

As the number of plates, n, is a function of R, equation 11.65 may be differentiated with respect to R to give:

$$\mathrm{d}c/\mathrm{d}R = c_a n/(Et_a V') + [(c_a/(Et_a u'))(R + 1)\,\mathrm{d}n/\mathrm{d}R] + c_b/(t_a N'') + c_d \tag{11.66}$$

Equating to zero for minimum cost, the optimum value of the reflux ratio is:

$$R_{\text{opt}} + 1 = (n_{\text{opt}} + F)/(-\mathrm{d}n/\mathrm{d}R) \tag{11.67}$$

where n_{opt} is the optimum number of theoretical plates corresponding to R_{opt} and the cost factor, F, is:

$$F = [c_d + c_b/(t_a N'')][(Et_a u')/c_a] \tag{11.68}$$

Because there is no simple equation relating n and dn/dR, it is not possible to obtain an expression for R_{opt} although a method of solution is given in the Example 11.18 which is based on the work of HARKER[32].

In practice, values of 110–150 per cent of the minimum reflux ratio are used although higher values are sometimes employed particularly in vacuum distillation. Where a high purity product is required, only limited improvements can be obtained by increasing the reflux ratio and since there is a very large increase in the number of trays required, an arrangement by which the minimum acceptable purity is achieved in the product is usually adopted.

11.4.4. Location of feed point in a continuous still

From Figure 11.20 it may be seen that, when stepping off plates down the top operating line AB, the bottom operating line CE cannot be used until the value of x_n on any plate is less than x_e. Again it is essential to pass to the lower line CE by the time $x_n = x_b$. The best conditions are those where the minimum number of plates is used. From the geometry of the figure, the largest steps in the enriching section occur down to the point of intersection of the operating lines at $x = x_q$. Below this value of x, the steps are larger on the lower operating line. Thus, although the column will operate for a feed composition between x_e and x_b, the minimum number of plates will be required if $x_f = x_q$. For a binary mixture at its boiling point, this is equivalent to making x_f equal to the composition of the liquid on the feed plate.

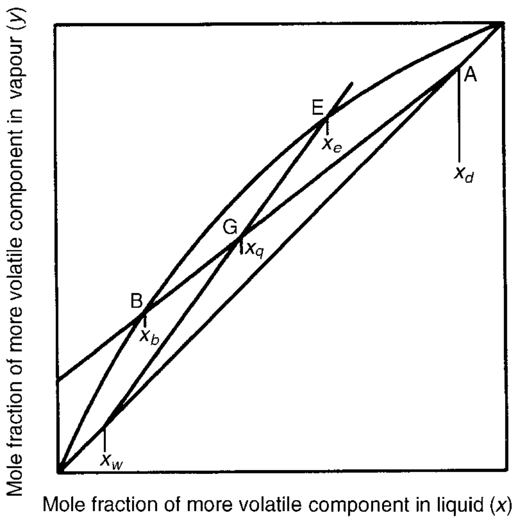

Figure 11.20. Location of feed point

11.4.5. Multiple feeds and sidestreams

In general, a sidestream is defined as any product stream other than the overhead product and the residue such as the streams S′, S″, and S‴ in Figure 11.21. In a similar way,