The intersection of the operating lines

It is seen from the example shown in Figure 11.15 in which the feed enters as liquid at its boiling point that the two operating lines intersect at a point having an X-coordinate of x_f. The locus of the point of intersection of the operating lines is of considerable importance since, as will be seen, it is dependent on the temperature and physical condition of the feed.

If the two operating lines intersect at a point with coordinates (x_q, y_q), then from equations 11.35 and 11.37:

$$V_n y_q = L_n x_q + D x_d \tag{11.40}$$

and:

$$V_m y_q = L_m x_q - W x_w \tag{11.41}$$

or:

$$y_q(V_m - V_n) = (L_m - L_n)x_q - (D x_d + W x_w) \tag{11.42}$$

A material balance over the feed plate gives:

$$F + L_n + V_m = L_m + V_n$$

or:

$$V_m - V_n = L_m - L_n - F \tag{11.43}$$

To obtain a relation between L_n and L_m, it is necessary to make an enthalpy balance over the feed plate, and to consider what happens when the feed enters the column. If the feed is all in the form of liquid at its boiling point, the reflux L_m overflowing to the plate below will be $L_n + F$. If however the feed is a liquid at a temperature T_f, that is less than the boiling point, some vapour rising from the plate below will condense to provide sufficient heat to bring the feed liquor to the boiling point.

If H_f is the enthalpy per mole of feed, and H_{fs} is the enthalpy of one mole of feed at its boiling point, then the heat to be supplied to bring feed to the boiling point is $F(H_{fs} - H_f)$, and the number of moles of vapour to be condensed to provide this heat is $F(H_{fs} - H_f)/\lambda$, where λ is the molar latent heat of the vapour.

The reflux liquor is then:

$$\begin{aligned} L_m &= L_n + F + \frac{F(H_{fs} - H_f)}{\lambda} \\ &= L_n + F\left(\frac{\lambda + H_{fs} - H_f}{\lambda}\right) \\ &= L_n + qF \end{aligned} \tag{11.44}$$

where:

$$q = \frac{\text{heat to vaporise 1 mole of feed}}{\text{molar latent heat of the feed}}$$

Thus, from equation 11.43:

$$V_m - V_n = qF - F \tag{11.45}$$

A material balance of the more volatile component over the whole column gives:

$$F x_f = D x_d + W x_w$$

Thus, from equation 11.42:

$$F(q-1)y_q = qFx_q - Fx_f$$

or:

$$y_q = \left(\frac{q}{q-1}\right)x_q - \left(\frac{x_f}{q-1}\right) \tag{11.46}$$

This equation is commonly known as the equation of the q-line. If $x_q = x_f$, then $y_q = x_f$. Thus, the point of intersection of the two operating lines lies on the straight line of slope $q/(q-1)$ passing through the point (x_f, x_f). When $y_q = 0$, $x_q = x_f/q$. The line may thus be drawn through two easily determined points. From the definition of q, it follows that the slope of the q-line is governed by the nature of the feed as follows.

(a) Cold feed as liquor	$q > 1$	q line /
(b) Feed at boiling point	$q = 1$	q line |
(c) Feed partly vapour	$0 < q < 1$	q line \
(d) Feed saturated vapour	$q = 0$	q line —
(e) Feed superheated vapour	$q < 0$	q line /

These various conditions are indicated in Figure 11.16.

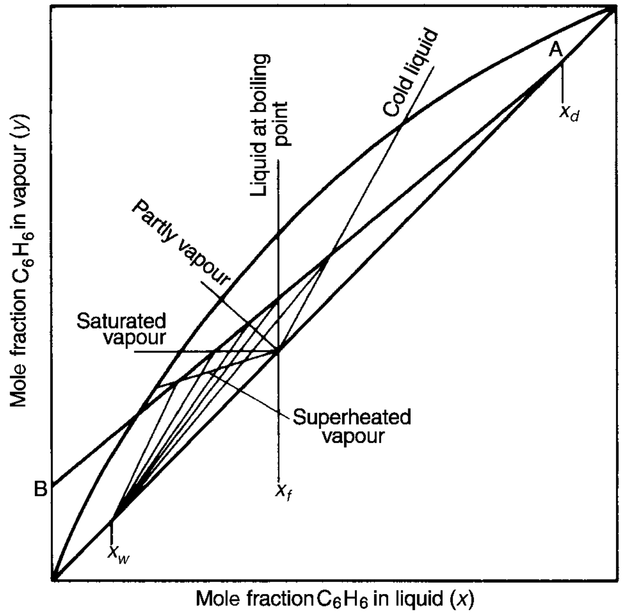

Figure 11.16. Effect of the condition of the feed on the intersection of the operating lines for a fixed reflux ratio

Altering the slope of the q-line will alter the liquid concentration at which the two operating lines cut each other for a given reflux ratio. This will mean a slight alteration in the number of plates required for the given separation. Whilst the change in the number of plates is usually rather small, if the feed is cold, there will be an increase in reflux flow below the feed plate, and hence an increased heat consumption from the boiler per mole of distillate.

11.4.3. The importance of the reflux ratio

Influence on the number of plates required

The ratio L_n/D, that is the ratio of the top overflow to the quantity of product, is denoted by R, and this enables the equation of the operating line to be expressed in another way, which is often more convenient. Thus, introducing R in equation 11.35 gives:

$$y_n = \left(\frac{L_n}{L_n + D}\right) x_{n+1} + \left(\frac{D}{L_n + D}\right) x_d \tag{11.47}$$

$$= \left(\frac{R}{R+1}\right) x_{n+1} + \left(\frac{x_d}{R+1}\right) \tag{11.48}$$

Any change in the reflux ratio R will therefore modify the slope of the operating line and, as may be seen from Figure 11.15, this will alter the number of plates required for a given separation. If R is known, the top line is most easily drawn by joining point A (x_d, x_d) to B $(0, x_d/(R+1))$ as shown in Figure 11.17. This method avoids the calculation of the actual flow rates L_n and V_n, when the number of plates only is to be estimated.

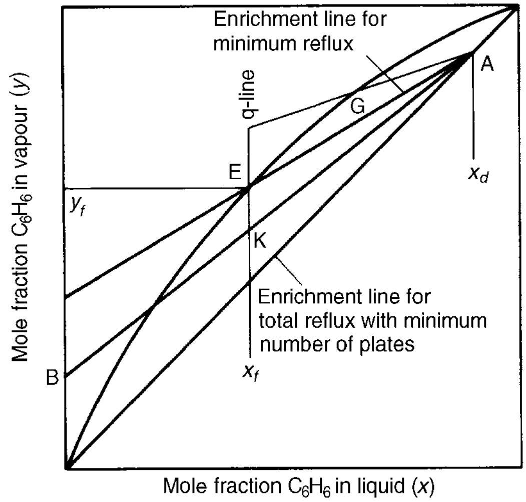

Figure 11.17. Influence of reflux ratio on the number of plates required for a given separation

If no product is withdrawn from the still, that is $D = 0$, then the column is said to operate under conditions of total reflux and, as seen from equation 11.47, the top operating line has its maximum slope of unity, and coincides with the line $x = y$. If the reflux ratio is reduced, the slope of the operating line is reduced and more stages are required to pass