

If an operating line is added to the equilibrium curve in Figure 8.21b, a staircase construction of the type used in the McCabe-Thiele method of Chapter 7 can rapidly determine the number of equilibrium stages. However, unlike distillation, where the operating line is straight because of the assumption of constant molar overflow, the operating line for liquid-liquid extraction in a ternary system will always be curved except in the low-solute-concentration region. Fortunately, the curved operating line is quite readily drawn using the following technique of Varteressian and Fenske [30]. In Figure 8.19 for the equilateral-triangle diagram, or in Figure 8.24 for the right-triangle diagram, the intersections of the equilibrium curve with a line drawn through a difference (operating) point represent the compositions of the passing streams. Thus, for each such operating line on the triangular diagram, one point of the operating line for the y - x plot is determined. The operating lines passing through the difference point can be drawn at random; they need not coincide with passing streams of actual equilibrium-stage operating lines. Usually five or six such fictitious operating-line intersections, covering the expected range of compositions in the extraction cascade, are sufficient to establish the curved operating line in the y - x plot. For example, in Figure 8.21c, the arbitrary operating line that intersects the equilibrium curve at I and J in the right-triangle diagram becomes a point K on

the operating line of the y - x diagram. The y - x plot of Figure 8.25 for the A-C-S system includes an operating line established in this manner, based on the data of Figure 8.24, but with a solvent-to-feed ratio of 0.208, that is, $V_W = 100$, $L_{N+1} = 480$ (25% greater than the minimum ratio of 0.167). The stages are stepped off in the McCabe-Thiele manner starting from the feed end. The result is seen to be almost exactly three equilibrium stages.

Extract and Raffinate Reflux

The simple, single-section, countercurrent, equilibrium-stage extraction cascade shown in Figure 8.13 can be refluxed, as in Figure 8.26a, to resemble distillation. In Figure 8.26a, L is used for raffinate flows, V is used for extract flows, and stages are numbered from the solvent end of the process. Extract reflux, L_R , is provided by sending the extract, V_N , to a solvent-recovery step, which removes most of the solvent, to give a solute-rich solution, $L_R + D$, which is divided into extract reflux, L_R , which is returned to stage N , and solute product, D . At the other end of the cascade, a portion, B , of the raffinate, L_1 , is withdrawn in a stream divider and added as raffinate reflux, V_B , to fresh solvent, S . The remaining raffinate, B , is sent to a solvent-removal step (not shown) to produce a carrier-rich raffinate product. When using extract reflux,

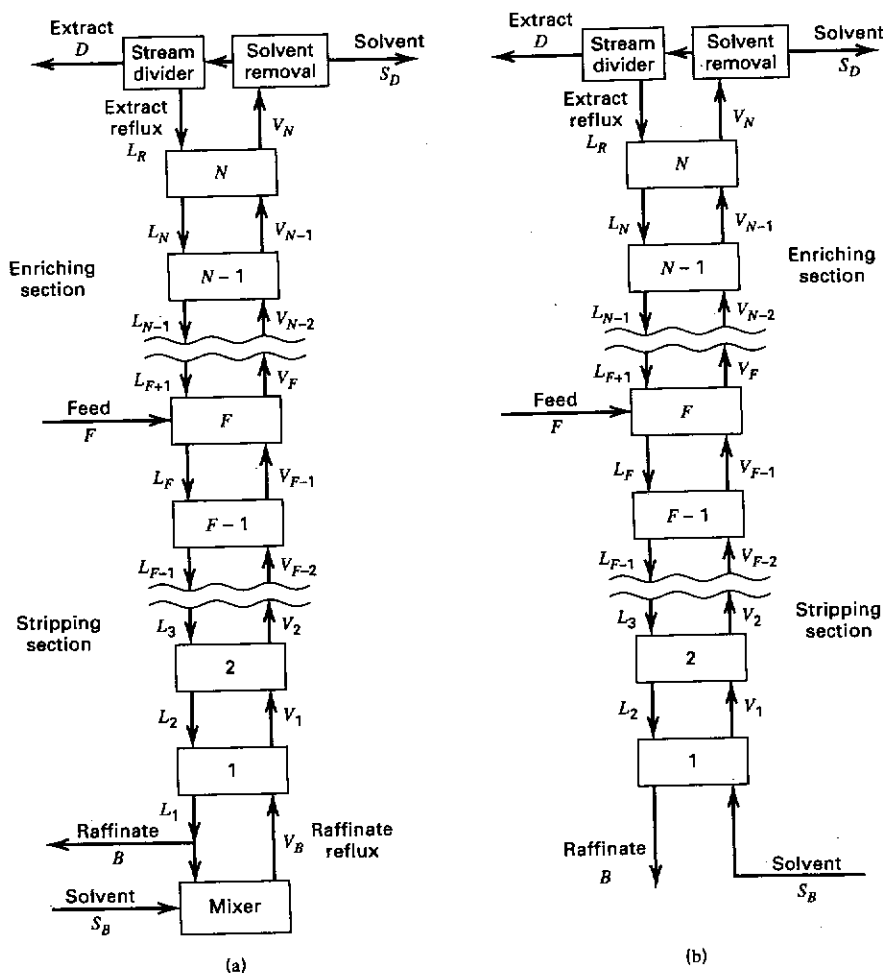


Figure 8.26 Liquid-liquid extraction with reflux: (a) with extract and raffinate reflux; (b) with extract reflux only.

Table 8.5 Analogy between Distillation and Extraction

Distillation	Extraction
Addition of heat	Addition of solvent
Reboiler	Solvent mixer
Removal of heat	Removal of solvent
Condenser	Solvent separator
Vapor at the boiling point	Solvent-rich solution saturated with solvent
Superheated vapor	Solvent-rich solution containing more solvent than that required to saturate it
Liquid below the boiling point	Solvent-lean solution, containing less solvent than that required to saturate it
Liquid at the boiling point	Solvent-lean solution saturated with solvent
Mixture of liquid and vapor	Two-phase liquid mixture
Relative volatility	Relative selectivity
Change of pressure	Change of temperature
D = distillate	D = extract product (solute on a solvent-free basis)
B = bottoms	B = raffinate (solvent-free basis)
L = saturated liquid	L = saturated raffinate (solvent-free)
V = saturated vapor	V = saturated extract (solvent-free)
A = more volatile component	A = solute to be recovered
C = less volatile component	C = carrier from which A is extracted
F = feed	F = feed
x = mole fraction A in liquid	X = mole or weight ratio of A (solvent-free), $A/(A + C)$
y = mole fraction A in vapor	$Y = S/(A + C)$

minimum- and total-reflux conditions, corresponding to infinite and minimum number of stages, bracket the optimal extract reflux ratio. Raffinate reflux is not processed through the solvent-removal unit because fresh solvent is added at this end of the cascade. It is necessary, however, to remove solvent from extract reflux at the enriching end of the cascade.

The analogy between a two-section liquid-liquid extractor with feed entering a middle stage, and distillation, is considered in some detail by Randall and Longtin [32]. Different aspects of the analogy are listed in Table 8.5. The most important analogy is that the solvent (a mass-separating agent) in extraction serves the same purpose as heat (an energy-separating agent) in distillation.

The use of raffinate reflux has been judged to be of little, if any, benefit by Skelland [31], who shows that the amount of raffinate reflux does not affect the number of stages required. Accordingly, we will consider a two-section, countercurrent cascade that includes only extract reflux, as shown in Figure 8.26b.

Analysis of a refluxed extractor, such as that of Figure 8.26b, involves relatively straightforward extensions of the procedures already developed. As will be shown, however, results for a type I system depend critically on the feed composition and the nature of the equilibrium-phase diagram, and it is very difficult to draw any general conclusions with respect to the effect (or even feasibility) of reflux.

For the two-section cascade with extract reflux shown in Figure 8.26b, a degrees-of-freedom analysis can be performed as described in Chapter 5. The result, using as elements

two countercurrent cascades, a feed stage, a splitter, and a divider, is $N_D = 2N + 3C + 13$. All but four of the specifications will usually be

Variable Specification	Number of Variables
Pressure at each stage	N
Temperature for each stage	N
Feed-stream flow rate, composition, temperature, and pressure	$C + 2$
Solvent composition, temperature, and pressure	$C + 1$
Split of each component in the splitter (solvent removal step)	C
Temperature and pressure of the two streams leaving the splitter	4
Pressure and temperature of the divider	2
	$2N + 3C + 9$

The four additional specifications can be taken from one of the following sets:

Set 1	Set 2	Set 3
Solvent rate	Reflux ratio	Solvent rate
Solute concentration in extract (solvent free)	Solute concentration in extract (solvent-free)	Reflux ratio
Solute concentration in raffinate (solvent-free)	Solute concentration in raffinate (solvent-free)	Number of stages
Optimal feed-stage location	Optimal feed-stage location	Feed-stage location