estimating the boiling temperature, the effect of temperature on the heat transfer characteristics of the type of unit involved must be taken into account. At low temperatures some evaporator types show a marked drop in the heat transfer coefficient which is often more than enough to offset any gain in available temperature difference. The temperature and cost of the cooling water fed to the condenser are also of importance in this respect.

Example 14.1

A single-effect evaporator is used to concentrate 7 kg/s of a solution from 10 to 50 per cent solids. Steam is available at 205 kN/m^2 and evaporation takes place at 13.5 kN/m^2. If the overall coefficient of heat transfer is 3 kW/m^2 deg K, estimate the heating surface required and the amount of steam used if the feed to the evaporator is at 294 K and the condensate leaves the heating space at 352.7 K. The specific heats of 10 and 50 per cent solutions are 3.76 and 3.14 kJ/kg deg K respectively.

Solution

Assuming that the steam is dry and saturated at 205 kN/m^2, then from the Steam Tables in the Appendix, the steam temperature = 394 K at which the total enthalpy = 2530 kJ/kg.

At 13.5 kN/m^2, water boils at 325 K and, in the absence of data on the boiling point elevation, this will be taken as the temperature of evaporation, assuming an aqueous solution. The total enthalpy of steam at 325 K is 2594 kJ/kg.

Thus the feed, containing 10 per cent solids, has to be heated from 294 to 325 K at which temperature the evaporation takes place.

$$\text{In the feed, mass of dry solids} = (7 \times 10)/100 = 0.7 \text{ kg/s}$$

and, for x kg/s of water in the product:

$$(0.7 \times 100)/(0.7 + x) = 50$$

from which: $x = 0.7$ kg/s

Thus: water to be evaporated $= (7.0 - 0.7) - 0.7 = 5.6$ kg/s

Summarising:

Stream	Solids (kg/s)	Liquid (kg/s)	Total (kg/s)
Feed	0.7	6.3	7.0
Product	0.7	0.7	1.4
Evaporation		5.6	5.6

Using a datum of 273 K:

Heat entering with the feed $= (7.0 \times 3.76)(294 - 273) = 552.7$ kW

Heat leaving with the product $= (1.4 \times 3.14)(325 - 273) = 228.6$ kW

Heat leaving with the evaporated water $= (5.6 \times 2594) = 14,526$ kW

Thus:

Heat transferred from the steam $= (14526 + 228.6) - 552.7 = 14,202$ kW

The enthalpy of the condensed steam leaving at 352.7 K = 4.18(352.7 − 273) = 333.2 kJ/kg

The heat transferred from 1 kg steam = (2530 − 333.2) = 2196.8 kJ/kg

and hence:

$$\text{Steam required} = (14,202/2196.8) = \underline{\underline{6.47 \text{ kg/s}}}$$

As the preheating of the solution and the sub-cooling of the condensate represent but a small proportion of the heat load, the temperature driving force may be taken as the difference between the temperatures of the condensing steam and the evaporating water, or:

$$\therefore \quad \Delta T = (394 - 325) = 69 \text{ deg K}$$

Thus:

$$\text{Heat transfer area, } A = Q/U\Delta T \qquad \text{(equation 14.1)}$$

$$= 14,202/(3 \times 69) = \underline{\underline{68.6 \text{ m}^2}}$$

14.4. MULTIPLE-EFFECT EVAPORATORS

The single effect evaporator uses rather more than 1 kg of steam to evaporate 1 kg of water. Three methods have been introduced which enable the performance to be improved, either by direct reduction in the steam consumption, or by improved energy efficiency of the whole unit. These are:

(a) Multiple effect operation
(b) Recompression of the vapour rising from the evaporator
(c) Evaporation at low temperatures using a heat pump cycle.

The first of these is considered in this section and (b) and (c) are considered in Section 14.5.

14.4.1. General principles

If an evaporator, fed with steam at 399 K with a total heat of 2714 kJ/kg, is evaporating water at 373 K, then each kilogram of water vapour produced will have a total heat content of 2675 kJ. If this heat is allowed to go to waste, by condensing it in a tubular condenser or by direct contact in a jet condenser for example, such a system makes very poor use of steam. The vapour produced is, however, suitable for passing to the calandria of a similar unit, provided the boiling temperature in the second unit is reduced so that an adequate temperature difference is maintained. This, as discussed in Section 14.2.4, can be effected by applying a vacuum to the second effect in order to reduce the boiling point of the liquor. This is the principle reached in the multiple effect systems which were introduced by Rillieux in about 1830.

For three evaporators arranged as shown in Figure 14.5, in which the temperatures and pressures are T_1, T_2, T_3, and P_1, P_2, P_3, respectively, in each unit, if the liquor has no

Thus 1 kg of steam fed to ① evaporates 1 kg of water in ①. Again the 1 kg of steam from ① evaporates about 1 kg of steam in ②. Thus, in a system of N effects, 1 kg of steam fed to the first effect will evaporate in all about N kg of liquid. This gives a simplified picture, as discussed later, although it does show that one of the great attractions of a multiple-effect system is that considerably more evaporation per kilogram of steam is obtained than in a single-effect unit. The economy of the system, measured by the kilograms of water vaporised per kilogram of steam condensed, increases with the number of effects.

The water evaporated in each effect is proportional to Q, since the latent heat is approximately constant. Thus the total capacity is:

$$\begin{aligned} Q &= Q_1 + Q_2 + Q_3 \\ &= U_1 A_1 \Delta T_1 + U_1 A_2 \Delta T_2 + U_3 A_3 \Delta T_3 \end{aligned} \tag{14.9}$$

If an average value of the coefficients U_{av} is taken, then:

$$Q = U_{av}(\Delta T_1 + \Delta T_2 + \Delta T_3)A \tag{14.10}$$

assuming the area of each effect is the same. A single-effect evaporator operating with a temperature difference $\Sigma\Delta T$, with this average coefficient U_{av}, would, however, have the same capacity $Q = U_{av} A \Sigma\Delta T$. Thus, it is seen that the capacity of a multiple-effect system is the same as that of a single effect, operating with the same total temperature difference and having an area A equal to that of one of the multiple-effect units. The value of the multiple-effect system is that better use is made of steam although, in order to achieve this, a much higher capital outlay is required for the increased number of units and accessories.

14.4.2. The calculation of multiple-effect systems

In the equations considered in Section 14.4.1, various simplifying assumptions have been made which are now considered further in the calculation of a multiple-effect system. In particular, the temperature distribution in such a system and the heat transfer area required in each effect are determined. The method illustrated in Example 14.2 is essentially based on that of HAUSBRAND[12].

Example 14.2A (Forward-feed)

4 kg/s (14.4 tonne/hour) of a liquor containing 10 per cent solids is fed at 294 K to the first effect of a triple-effect unit. Liquor with 50 per cent solids is to be withdrawn from the third effect, which is at a pressure of 13 kN/m² (~0.13 bar). The liquor may be assumed to have a specific heat of 4.18 kJ/kg K and to have no boiling point rise. Saturated dry steam at 205 kN/m² is fed to the heating element of the first effect, and the condensate is removed at the steam temperature in each effect as shown in Figure 14.5.

If the three units are to have equal areas, estimate the area, the temperature differences and the steam consumption. Heat transfer coefficients of 3.1, 2.0 and 1.1 kW/m² K for the first, second, and third effects respectively, may be assumed.

Solution 1

A precise theoretical solution is neither necessary nor possible, since during the operation of the evaporator, variations of the liquor levels, for example, will alter the heat transfer coefficients and hence the temperature distribution. It is necessary to assume values of heat transfer coefficients, although, as noted previously, these will only be approximate and will be based on practical experience with similar liquors in similar types of evaporators.

Temperature of dry saturated steam at 205 kN/m^2 = 394 K.

At a pressure of 13 kN/m^2 (0.13 bar), the boiling point of water is 325 K, so that the total temperature difference $\Sigma\Delta T = (394 - 325) = 69$ deg K.

First Approximation.

Assuming that: $$U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3 \qquad \text{(equation 14.8)}$$

then substituting the values of U_1, U_2 and U_3 and $\Sigma\Delta T = 69$ deg K gives:

$$\Delta T_1 = 13 \text{ deg K}, \quad \Delta T_2 = 20 \text{ deg K}, \quad \Delta T_3 = 36 \text{ deg K}$$

Since the feed is cold, it will be necessary to have a greater value of ΔT_1 than given by this analysis. It will be assumed that $\Delta T_1 = 18$ deg K, $\Delta T_2 = 17$ deg K, $\Delta T_3 = 34$ deg K.

If the latent heats are given by λ_0, λ_1, λ_2 and λ_3, then from the Steam Tables in the Appendix:

For steam to 1:	$T_0 = 394$ K and $\lambda_0 = 2200$ kJ/kg
For steam to 2:	$T_1 = 376$ K and $\lambda_1 = 2249$ kJ/kg
For steam to 3:	$T_2 = 359$ K and $\lambda_2 = 2293$ kJ/kg
	$T_3 = 325$ K and $\lambda_3 = 2377$ kJ/kg

Assuming that the condensate leaves at the steam temperature, then heat balances across each effect may be made as follows:

Effect 1:

$$D_0\lambda_0 = G_F C_p(T_1 - T_f) + D_1\lambda_1, \text{ or } 2200\ D_0 = 4 \times 4.18(376 - 294) + 2249\ D_1$$

Effect 2:

$$D_1\lambda_1 + (G_F - D_1)C_p(T_1 - T_2) = D_2\lambda_2, \text{ or } 2249\ D_1 + (4 - D_1)4.18(376 - 359) = 2293\ D_2$$

Effect 3:

$$D_2\lambda_2 + (G_F - D_1 - D_2)C_p(T_2 - T_3) = D_3\lambda_3,$$

$$\text{or } 2293\ D_2 + (4 - D_1 - D_2)4.18(359 - 325) = 2377\ D_3$$

where G_F is the mass flowrate of liquor fed to the system, and C_p is the specific heat capacity of the liquid, which is assumed to be constant.

A material balance over the evaporator is:

	Solids (kg/s)	Liquor (kg/s)	Total (kg/s)
Feed	0.4	3.6	4.0
Product	0.4	0.4	0.8
Evaporation		3.2	3.2

Making use of the previous equations and the fact that $(D_1 + D_2 + D_3) = 3.2$ kg/s, the evaporation in each unit is, $D_1 \approx 0.991$, $D_2 \approx 1.065$, $D_3 \approx 1.144$, $D_0 \approx 1.635$ kg/s. The area of the surface of each calandria necessary to transmit the necessary heat under the given temperature difference may then be obtained as:

$$A_1 = \frac{D_0\lambda_0}{U_1\Delta T_1} = \frac{(1.635 \times 2200)}{(3.1 \times 18)} = 64.5\ \text{m}^2$$

$$A_2 = \frac{D_1\lambda_1}{U_2\Delta T_2} = \frac{(0.991 \times 2249)}{(2.0 \times 17)} = 65.6\ \text{m}^2$$

$$A_3 = \frac{D_2\lambda_2}{U_3\Delta T_3} = \frac{(1.085 \times 2293)}{(1.1 \times 34)} = 65.3\ \text{m}^2$$

These three calculated areas are approximately equal, so that the temperature differences assumed may be taken as nearly correct. In practice, ΔT_1 would have to be a little larger since A_1 is the smallest area. It may be noted that, on the basis of these calculations, the economy is given by $e = (3.2/1.635) = \underline{\underline{2.0}}$. Thus, a triple effect unit working under these conditions gives a reduction in steam utilisation compared with a single effect, though not as large an economy as might be expected.

A simplified method of solving problems of multiple effect evaporation, suggested by STORROW[13], is particularly useful for systems with a large number of effects because it obviates the necessity for solving many simultaneous equations. Essentially the method depends on obtaining only an approximate value for those heat quantities which are a small proportion of the whole. Example 14.2A is now solved by this method.

Solution 2

From Figure 14.5 it may be seen that for a feed G_F to the first effect, vapour D_1 and liquor $(G_F - D_1)$ are fed forward to the second effect. In the first effect, steam is condensed partly in order to raise the feed to its boiling point and partly to effect evaporation. In the second effect, further vapour is produced mainly as a result of condensation of the vapour from the first effect and to a smaller extent by flash vaporisation of the concentrated liquor which is fed forward. As the amount of vapour produced by the latter means is generally only comparatively small, this may be estimated only approximately. Similarly, the vapour produced by flash evaporation in the third effect will be a small proportion of the total and only an approximate evaluation is required.

Vapour production by flash vaporisation — approximate evaluation

If the heat transferred in each effect is the same, then:

$$U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3 \qquad \text{(equation 14.8)}$$

or:

$$3.1\Delta T_1 = 2.0\Delta T_2 = 1.1\Delta T_3$$

Steam temperature = 394 K. Temperature in condenser = 325 K.

Thus:

$$\Sigma\Delta T = (394 - 325) = 69 \text{ deg K}$$

Solving:

$$\Delta T_1 = 13 \text{ deg K} \quad \Delta T_2 = 20 \text{ deg K} \quad \Delta T_3 = 36 \text{ deg K}$$

These values of ΔT will be valid provided the feed is approximately at its boiling point.

Weighting the temperature differences to allow for the fact that the feed enters at ambient temperature gives:

$$\Delta T_1 = 18 \text{ deg K} \quad \Delta T_2 = 18 \text{ deg K} \quad \Delta T_3 = 33 \text{ deg K}$$

and the temperatures in each effect are:

$$T_1 = 376 \text{ K} \quad T_2 = 358 \text{ K} \quad \text{and} \quad T_3 = 325 \text{ K}$$

The total evaporation ($D_1 + D_2 + D_3$) is obtained from a material balance:

	Solids (kg/s)	Liquor (kg/s)	Total (kg/s)
Feed	0.4	3.6	4.0
Product	0.4	0.4	0.8
Evaporation		3.2	3.2

Assuming, as an approximation, equal evaporation in each effect, or $D_1 = D_2 = D_3 = 1.07$ kg/s, then the latent heat of flash vaporisation in the second effect is given by:

$$4.18(4.0 - 1.07)(376 - 358) = 220.5 \text{ kW}$$

and latent heat of flash vaporisation in the third effect is:

$$4.18(4.0 - 2 \times 1.07)(358 - 325) = 256.6 \text{ kW}$$

Final calculation of temperature differences

Subsequent calculations are considerably simplified if it is assumed that the latent heat of vaporisation is the same at all temperatures in the multiple-effect system, since under these conditions the condensation of 1 kg of steam gives rise to the formation of 1 kg of vapour.

Thus: At 394 K, the latent heat = 2200 kJ/kg

At 325 K, the latent heat = 2377 kJ/kg

Mean value, $\lambda = 2289$ kJ/kg

The amounts of heat transferred in each effect (Q_1, Q_2, Q_3) and in the condenser (Q_c) are related by:

$$Q_1 - G_F C_p(T_1 - T_f) = Q_2 = (Q_3 - 220.5) = (Q_c - 220.5 - 256.6)$$

or: $$Q_1 - 4.0 \times 4.18(394 - \Delta T_1 - 294) = Q_2 = (Q_3 - 220.5) = (Q_c - 477.1) \text{ kW}$$

$$\text{Total evaporation} = (Q_2 + Q_3 + Q_c)/2289 = 3.2 \text{ kg/s}$$

Thus: $$Q_2 + (Q_2 + 220.5) + (Q_2 + 477.1) = 7325 \text{ kW}$$

or: $$Q_2 = 2209 \text{ kW}$$

$$Q_3 = 2430 \text{ kW}$$

and:
$$Q_1 = 2209 + 4.0 \times 4.18(394 - \Delta T_1 - 294)$$
$$= (3881 - 16.72\Delta T_1)\ \text{kW}$$

Applying the heat transfer equations, then:

$$3881 - 16.72\Delta T_1 = 3.1A\Delta T_1, \quad \text{or} \quad A\Delta T_1 = (1252 - 5.4\Delta T_1)\ \text{m}^2\text{K}$$
$$2209 = 2.0A\Delta T_2, \quad \text{or} \quad A\Delta T_2 = 1105\ \text{m}^2\text{K}$$
$$2430 = 1.1A\Delta T_3, \quad \text{or} \quad A\Delta T_3 = 2209\ \text{m}^2\text{K}$$

Further:
$$\Delta T_1 + \Delta T_2 + \Delta T_3 = 69\ \text{deg K}$$

Values of ΔT_1, ΔT_2, ΔT_3 are now chosen by trial and error to give equal values of A in each effect, as follows:

ΔT_1 (deg K)	A_1 (m^2)	ΔT_2 (deg K)	A_2 (m^2)	ΔT_3 (deg K)	A_3 (m^2)
18	64.2	18	61.4	33	66.9
19	60.5	17	65.0	33	66.9
18	64.2	17.5	63.1	33.5	65.9
18	64.2	17	65.0	34	64.9

The areas, as calculated in the last line, are approximately equal, so that the assumed temperature differences are acceptable and:

$$\text{Steam consumption} = (Q_1/2289) = (3580/2289) = 1.56\ \text{kg/s}$$
$$\text{Economy} = (3.2/1.56) \approx \underline{\underline{2.0}}\ \text{kg/kg}$$

The calculation of areas in multiple-effect systems is relatively straightforward for one or two configurations, although it becomes tedious in the extreme where a wide range of operating conditions is to be investigated. Fortunately the calculations involved lend themselves admirably to processing by computer, and in this respect reference should be made to work such as that by STEWART and BEVERIDGE[14].

14.4.3. Comparison of forward and backward feeds

In the unit considered in Example 14.2A, the weak liquor is fed to effect ① and flows on to ② and then to ③. The steam is also fed to ①, and the process is known as forward-feed since the feed is to the same unit as the steam and travels down the unit in the same direction as the steam or vapour. It is possible, however, to introduce the weak liquor to effect ③ and cause it to travel from ③ to ② to ①, whilst the steam and vapour still travel in the direction of ① to ② to ③. This system, shown in Figure 14.6, is known as backward-feed. A further arrangement for the feed is known as parallel-feed, which is shown in Figure 14.7. In this case, the liquor is fed to each of the three effects in parallel although the steam is fed only to the first effect. This arrangement is commonly used in the concentration of salt solutions, where the deposition of crystals makes it difficult to use

As has just been shown, q_1 and q_2 are nearly equal, and therefore

$$A_1 U_1 \,\Delta T_1 = A_2 U_2 \,\Delta T_2 \tag{16.11}$$

This same reasoning may be extended to show that, roughly,

$$A_1 U_1 \,\Delta T_1 = A_2 U_2 \,\Delta T_2 = A_3 U_3 \,\Delta T_3 \tag{16.12}$$

It should be understood that Eqs. (16.11) and (16.12) are only approximate equations that must be corrected by the addition of terms which are, however, relatively small compared to the quantities involved in the expressions above.

In ordinary practice the heating areas in all the effects of a multiple-effect evaporator are equal. This is to obtain economy of construction. Therefore, from Eq. (16.12) it follows that since $q_1 = q_2 = q_3 = q$,

$$U_1 \,\Delta T_1 = U_2 \,\Delta T_2 = U_3 \,\Delta T_3 = \frac{q}{A} \tag{16.13}$$

From this it follows that the temperature drops in a multiple-effect evaporator are approximately inversely proportional to the heat-transfer coefficients.

EXAMPLE 16.2. A triple-effect evaporator is concentrating a liquid that has no appreciable elevation in boiling point. The temperature of the steam to the first effect is 108°C, and the boiling point of the solution in the last effect is 52°C. The overall heat-transfer coefficients, in $W/m^2 \cdot °C$, are 2,500 in the first effect, 2,000 in the second effect, and 1,500 in the third effect. (At the solution becomes more concentrated, the viscosity increases and the overall coefficient is reduced.) At what temperatures will the liquid boil in the first and second effects?

Solution. The total temperature drop is 108 − 52 = 56°C. As shown by Eq. (16.13), the temperature drops in the several effects will be approximately inversely proportional to the coefficients. Thus, for example,

$$\Delta T_1 = \frac{\dfrac{1}{2{,}500}}{\dfrac{1}{2{,}500} + \dfrac{1}{2{,}000} + \dfrac{1}{1{,}500}} 56 = 14.3°C$$

In the same manner $\Delta T_2 = 17.9°C$ and $\Delta T_3 = 23.8°C$. Consequently the boiling point in the first effect will be 108 − 14.3 = 93.7°C, and that in the second effect, 75.8°C.

Methods of feeding

The usual method of feeding a multiple-effect evaporator is to pump the thin liquid into the first effect and send it in turn through the other effects, as shown in Fig. 16.8*a*. This is called *forward feed*. The concentration of the liquid increases from the first effect to the last. This pattern of liquid flow is the simplest. It requires a pump for feeding dilute solution to the first effect, since this effect is often at about atmospheric pressure, and a pump to remove thick liquor from the last effect. The transfer from effect to effect, however, can be done without pumps, since the flow is in the direction of decreasing pressure, and control valves in the transfer line are all that is required.

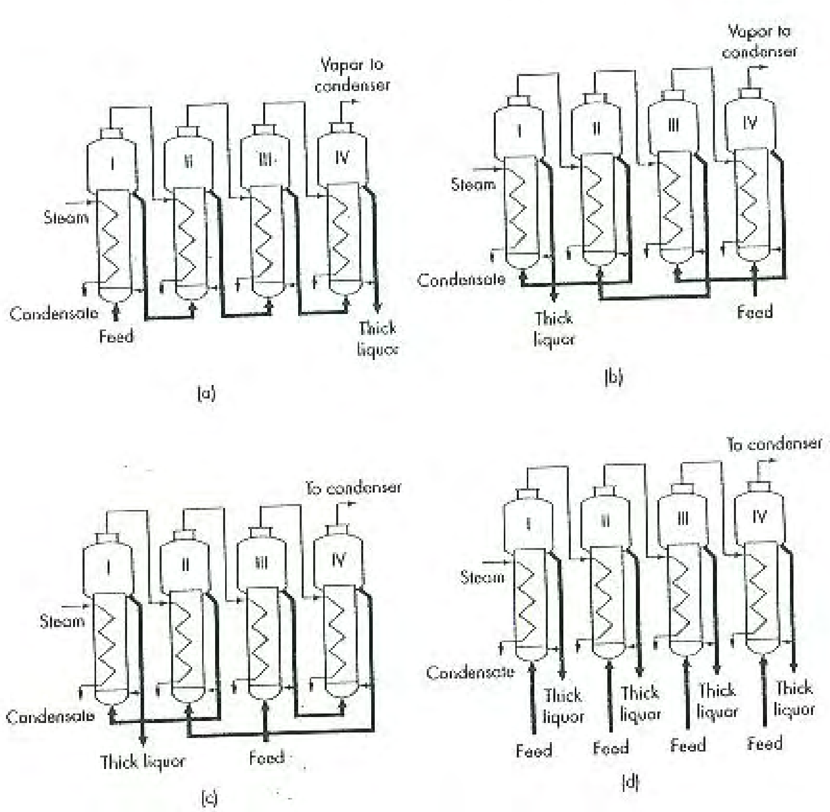

FIGURE 16.8
Patterns of liquor flow in multiple-effect evaporators: (*a*) forward feed; (*b*) backward feed; (*c*) mixed feed; (*d*) parallel feed. (———) Liquor streams. (———) Steam and vapor condensate streams.

Another common method is *backward feed*, in which dilute liquid is fed to the last effect and then pumped through the successive effects to the first, as shown in Fig. 16.8*b*. This method requires a pump between each pair of effects in addition to the thick-liquor pump, since the flow is from low pressure to high pressure. Backward feed often gives a higher capacity than forward feed when the thick liquor is viscous, but it may give a lower economy than forward feed when the feed liquor is cold.

Other patterns of feed are sometimes used. In *mixed feed* the dilute liquid enters an intermediate effect, flows in forward feed to the end of the series, and is then pumped back to the first effects for final concentration, as shown in Fig. 16.8*c*. This eliminates some of the pumps needed in backward feed and yet permits the final first effect and the saturation temperature of the vapor evolved from the last effect are identical in all three evaporators. Each effect contains a liquid with a boiling-point elevation. The total height of each column represents the total temperature spread from the steam temperature to the saturation temperature of the vapor from the last effect.

Consider the single-effect evaporator. Of the total temperature drop of 181°, the shaded part represents the loss in temperature drop due to boiling-point elevation. The remaining temperature drop, 105°, the actual driving force for heat transfer, is represented by the unshaded part. The diagram for the double-effect evaporator shows two shaded portions because there is a boiling-point elevation in each of the two effects, and the residual unshaded part, totaling 85°, is smaller than in the diagram for the single effect. In the triple-effect evaporator there are three shaded portions since there is a loss of temperature drop in each of three effects, and the total net available temperature drop, 79°, is correspondingly smaller.

In extreme cases of a large number of effects or very high boiling-point elevations, the sum of the boiling-point elevations in a proposed evaporator could be greater than the total temperature drop available. Operation under such conditions is impossible. The design or the operating conditions of the evaporator would have to be revised to reduce the number of effects or increase the total temperature drop.

The economy of a multiple-effect evaporator is not influenced by boiling-point elevations if minor factors, such as the temperature of the feed and changes in the heats of vaporization, are neglected. A kilogram of steam condensing in the first effect generates about a kilogram of vapor, which condenses in the second effect, generating another kilogram there, and so on. The *economy* of a multiple-effect, evaporator depends on heat-balance considerations and not on the rate of heat transfer. The *capacity*, on the other hand, is reduced by the boiling-point elevation. The capacity of a double-effect evaporator concentrating a solution with a boiling-point elevation is generally less than one-half the capacity of two single effects, each operating with the same overall temperature drop. The capacity of a triple effect is generally less than one-third that of three single effects with the same terminal temperatures.

Optimum number of effects. The cost of each effect of an evaporator per square meter or square foot of surface is a function of its total area and decreases with area, approaching an asymptote for very large installations. Thus the investment required for an *N*-effect evaporator is about *N* times that for a single-effect evaporator of the same capacity. The optimum number of effects must be found from an economic balance between the savings in steam obtained by multiple-effect operation and the added investment required.

Multiple-effect calculations

In designing a multiple-effect evaporator the results usually desired are the amount of steam consumed, the area of the heating surface required, the approximate temperatures in the various effects, and the amount of vapor leaving the last effect. As in a single-effect evaporator, these quantities are found from material balances, enthalpy balances, and the capacity equation (16.1). In a multiple-effect evaporator, however, a trial-and-error method is used in place of a direct algebraic solution.

Consider, for example, a triple-effect evaporator. There are seven equations which may be written: an enthalpy balance for each effect, a capacity equation for each effect, and the known total evaporation, or the difference between the thin- and thick-liquor rates. If the amount of heating surface in each effect is assumed to be the same, there are seven unknowns in these equations: (1) the rate of steam flow to the first effect, (2) to (4) the rate of flow from each effect, (5) the boiling temperature in the first effect, (6) the boiling temperature in the second effect, and (7) the heating surface per effect. It is possible to solve these equations for the seven unknowns, but the method is tedious and involved. Another method of calculation is as follows:

1. Assume values for the boiling temperatures in the first and second effects.
2. From enthalpy balances find the rates of steam flow and of liquor from effect to effect.
3. Calculate the heating surface needed in each effect from the capacity equations.
4. If the heating areas so found are not nearly equal, estimate new values for the boiling temperatures and repeat items 2 and 3 until the heating surfaces are equal.

In practice these calculations are done by computer. Results of a typical calculation are shown in the following example.

EXAMPLE 16.3. A triple-effect forced-circulation evaporator is to be fed with 60,000 lb/h (27,215 kg/h) of 10% caustic soda solution at a temperature 180°F (82.2°C). The concentrated liquor is to be 50% NaOH. Saturated steam at 50 $\mathrm{lb}_f/\mathrm{in.}^2$ (3.43 atm) abs is to be used, and the condensing temperature of vapor from the third effect is to be 100°F (37.8°C). The feed order is II, III, I. Radiation and undercooling of condensate may be neglected. Estimated overall coefficients corrected for boiling-point elevation are given in Table 16.2. Calculate (*a*) the heating surface required in each effect, assuming equal surfaces in each, (*b*) the steam consumption, and (*c*) the steam economy.

Solution. The total rate of evaporation is calculated from an overall material balance, assuming that the solids go through the evaporator without loss (Table 16.3).

Repeated calculations lead to the temperatures, enthalpies, and flow rates shown in Table 16.4. Note that the steam fed to I becomes the condensate from I, the vapor from I becomes the condensate from II, and the vapor from II becomes the condensate from III. From these results the answers to the problems are found to be

(*a*) Area per effect: 719 ft^2 (66.8 m^2)
(*b*) Steam consumption: 19,370 lb/h (8,786 kg/h)
(*c*) Economy: 48,000/19,370 = 2.48

TABLE 16.2

Effect	Overall coefficient	
	$\mathrm{Btu/ft^2 \cdot h \cdot {}^\circ F}$	$\mathrm{W/m^2 \cdot {}^\circ C}$
I	700	3,970
II	1,000	5,680
III	800	4,540

TABLE 16.3

Material	Flow rate, lb/h Total	Solid	Water
Feed solution	60,000	6,000	54,000
Thick liquor	12,000	6,000	6,000
Water evaporated	48,000		48,000

TABLE 16.4
Temperatures, enthalpies, and flow rates for Example 16.3

Stream	Temperature °F	Saturation temperature, °F	Concentration, weight fraction	Enthalpy, Btu/lb	Flow rate, lb/h
Steam	281	281		1,174	19,370
Feed to I	113		0.228	68	26,300
Vapor from I	245	170		1,170	14,300
Condensate from I	281			249	19,370
Thick liquor from I	246		0.50	249	12,000
Raw feed to II	180		0.10	135	60,000
Vapor from II	149	142		1,126	16,340
Liquid from II	149		0.137	101	43,660
Condensate from II	170			138	14,300
Vapor from III	114	100		1,111	17,360
Condensate from III	142			110	16,340

VAPOR RECOMPRESSION

The energy in the vapor evolved from a boiling solution can be used to vaporize more water, provided there is a temperature drop for heat transfer in the desired direction. In a multiple-effect evaporator this temperature drop is created by progressively lowering the boiling point of the solution in a series of evaporators through the use of lower absolute pressures. The desired driving force can also be obtained by increasing the pressure (and, therefore, the condensing temperature) of the evolved vapor by mechanical or thermal recompression.[1] The compressed vapor is then condensed in the steam chest of the evaporator from which it came.

Mechanical recompression

The principle of mechanical vapor recompression is illustrated in Fig. 16.10. Cold feed is preheated almost to its boiling point by exchange with hot liquor and is pumped through a heater as in a conventional forced-circulation evaporator. The vapor evolved, however, is not condensed; instead it is compressed to a somewhat higher pressure by a positive-displacement or centrifugal compressor and becomes the "steam" which is fed to the heater. Since the saturation temperature of the compressed vapor is higher than the boiling point of the feed, heat flows from the vapor to the solution, generating more vapor. A small amount of makeup steam may be necessary. The optimum temperature drop for a typical system is about 5°C. The energy utilization of such a system is very good: Based on the steam equivalent of the

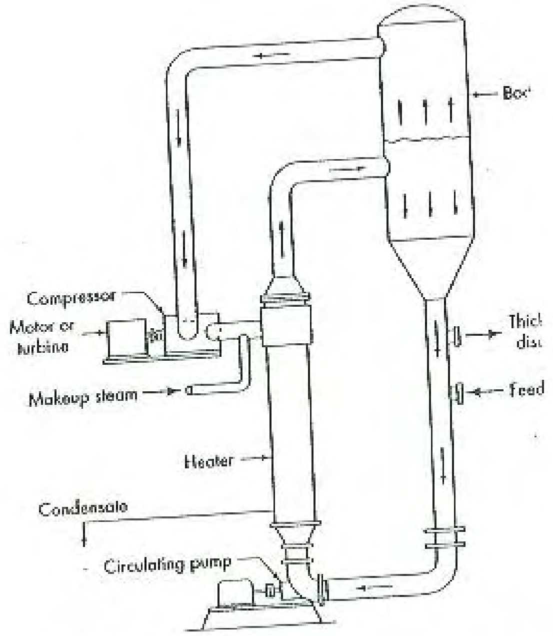

FIGURE 16.10
Mechanical recompression applied to forced-circulation evaporat

power required to drive the compressor, the economy corresponds to
orator containing 10 to 15 effects. Important applications of mechanic
evaporation include production of distilled water from seawater, evap
liquor in the paper industry,[6] evaporation of heat-sensitive materia
juices, and crystallization of salts having inverted solubility curves[4]
Falling-film evaporators are especially well suited for operat
recompression systems.[13]

Thermal recompression

In a thermal recompression system the vapor is compressed by a
high-pressure steam in a jet ejector. This results in more steam tha
boiling the solution, so that excess steam must be vented or condens
motive steam to the vapor from the solution depends on the evapo
for many low-temperature operations, with steam at 8 to 10 atm pr
of steam required to the mass of water evaporated is about 0.5.

Since steam jets can handle large volumes of low-density
recompression is better suited than mechanical recompression to va
tion. Jets are cheaper and easier to maintain than blowers and co
chief disadvantages of thermal recompression are the low efficiency
lack of flexibility in the system toward changed operating condition