Kirk-Othmer Encyclopedia of Chemical Technology.

EVAPORATION

Evaporation by its broadest definition is the conversion of a liquid to a vapor and applies to such widely diverse equipment as boilers, cooling towers, dryers, and humidifiers, and losses from fields, storage tanks, and reservoirs. In the narrower chemical engineering sense, evaporation is the removal of volatile solvent from a solution or a relatively dilute slurry by vaporizing the solvent. In nearly all industrial applications the solvent is water, and in most cases the nonvolatile residue is the valuable constituent. Evaporation differs from distillation (qv) in that when the volatile stream consists of more than one component no attempt is made to separate these components. Thus production of distilled water from impure feedwater utilizes an evaporator rather than a distillation unit even though small capacity units are usually called stills. Although the product of an evaporator system may be a solid, the heat required for vaporization of the solvent must be transferred to a solution or a slurry of the solid in its saturated solution in order that the device be classified as an evaporator rather than a dryer (see also Dewatering; Drying). It is not unusual for an evaporator to be used to produce a solid as its only product. For instance, table salt is produced by feeding a saturated brine to an evaporator, precipitating the salt as water is removed. A side stream of salt crystals in brine is withdrawn to a filter or centrifuge where the salt is recovered in essentially dry form; the filtrate is returned to the evaporator as a supplementary feed. Thus the heat required for evaporation of the water is transferred to a slurry in the evaporator even though the only material leaving the system is a solid, except for the evaporated water; usually a small bleed of brine is necessary to purge from the system the impurities entering with the feed brine (see Chemicals from brine).

The highly varied purposes for which evaporators are used industrially include: (*1*) reducing the volume to economize on packaging, shipping, and storage costs, eg, of salt, sugar (qv), caustic soda (see Alkali and chlorine products), orange juice (see Fruit juices), and milk (see Milk and milk products); (*2*) obtaining a product in its most useful form, eg, salt from brine or sugar from cane juice; (*3*) eliminating minor impurities, eg, salt, sugar; (*4*) removing major contaminants from a product, eg, diaphragm cell caustic soda solutions contain more salt than caustic when produced but practically all the salt can be precipitated by concentrating to a 50% NaOH solution; (*5*) concentrating a process stream for recovery of resources, eg, pulp (qv) mill spent cooking liquor, if concentrated sufficiently in an evaporator, can be burned in a boiler to produce steam, yielding also an ash that can be used to reconstitute fresh cooking liquor; (*6*) concentrating wastes for easier disposal, such as nuclear reactor wastes (see Nuclear reactors), dyestuff plant effluents, and cooling tower blowdown streams; (*7*) transforming a waste into a valuable product, such as spent distillery slop after alcohol recovery, which can be concentrated to produce an animal feed (see Feeds and Feed additives); and (*8*) recovering distilled water (qv) from impure streams such as sea water and brackish waters.

Salt was produced in prehistoric times from seawater or saline waters by solar evaporation in ponds. This method is still in widespread use and probably accounts for more total evaporation than any other process. The first artificially heated evaporators date to Roman times, again for salt, in flat pans over wood fires. Originally the pans were of lead, later of wrought iron, and such pans heated by coal were still in use in England in the 1960s (primarily to produce a salt of low bulk density for which there was a substantial export market). Similar open pans, heated by steam coils immersed in the brine, are used for production of salt having special grain characteristics in the United States. Evaporators were introduced by the sugar industry: the first steam-heated evaporator about 1800; the first one using vacuum in 1812; the first multiple-effect type in 1843; and the first vapor-compression evaporator about 1880. In the 1990s, the majority of evaporators are steam heated and use multiple-effect or vapor compression as the means of reducing the energy required for evaporation.

1. Steam-Heated Evaporators

The three principal requirements of steam-heated evaporators are: (*1*) transfer to the liquid of large amounts of heat needed to vaporize the solvent, (*2*) efficient separation of the evolved vapor from the residual liquid, and (*3*) accomplishing these aims with the least expenditure of energy justifiable by the capital cost involved (see Energy management; Heat exchange technology). Most steam-heated evaporators use metal tubes as heat transfer surfaces, although some employ flat plates or, for special corrosion problems, impregnated carbon tubes. Final separation of the entrained liquid from evolved vapor may be obtained in external centrifugal or mesh-type separators but preliminary separation is generally required (see Separation, centrifugal). An evaporator is frequently also used as a crystallizer, and therefore its design may be influenced by the need to produce crystals of the desired size, shape, and purity without adversely affecting the vapor–liquid separation and heat transfer functions (see Crystallization). Many types of evaporators are available to perform these functions. The choice depends on the characteristics of the liquor being handled with regard to heat transfer properties and tendencies toward salting, scaling, fouling, foaming, and corrosion. The extent to which it is desired to conserve heat also influences the choice of evaporator type.

Evaporator may refer either to the type of construction utilized or to the entire assemblage of equipment in a single installation. Thus a single multiple-effect evaporator may contain a number of effects of either the same or different evaporator types. An effect is a section of the evaporator heated by steam at one pressure and releasing vapor (water) at a lower pressure to another section. The term steam generally indicates the heat supply, whereas vapor means the material evaporated. Thus vapor from one effect becomes steam at the next effect. The term prime steam identifies the steam supplied from an outside source to operate the evaporator (see also Steam). An effect may consist of several bodies, all operating at the same steam and vapor pressures. The purpose of more than one body in an effect may be to handle liquor at different concentrations, or the result of size limitations or of additions to increase the capacity of an existing evaporator.

1.1. Natural Circulation Evaporators

Natural circulation evaporators (Fig. 1) were the first developed commercially and still represent probably the largest number of units in operation. These evaporators utilize the density difference between the liquid and the generated vapor to circulate the liquid past the heating surface and thereby give good heat-transfer performance. The heat transfer tubes may be either vertical or horizontal, with the liquor either inside or outside the tubes. The horizontal tube type of Figure 1**a** has the heating steam inside the tubes that are immersed in the boiling liquid. This type was originally built with rectangular cast-iron bodies having a hemicylindrical top that required little floor space or headroom. The principal use is for making distilled water for boiler feed. These evaporators are incorporated in the power plant cycle, usually as single effects heated by turbine bleed steam and exhausting vapor to the feed heater circuit (see Power generation). They frequently operate under considerable pressure, and therefore employ horizontal cylindrical shells to better withstand the pressures and give a large liquid surface area for efficient disengagement. The type shown in Figure 1**b** was developed mainly for use in sugar mills, and was known as the standard evaporator; now it is known as the calandria or short-tube vertical (STV) evaporator. It employs fairly large (usually 0.05-m) diameter tubes only about 2 m long that are easily cleaned mechanically. Good heat transfer requires downtakes to permit recirculation through the tubes. The downtakes must have a flow area on the order of 60% or more of the flow

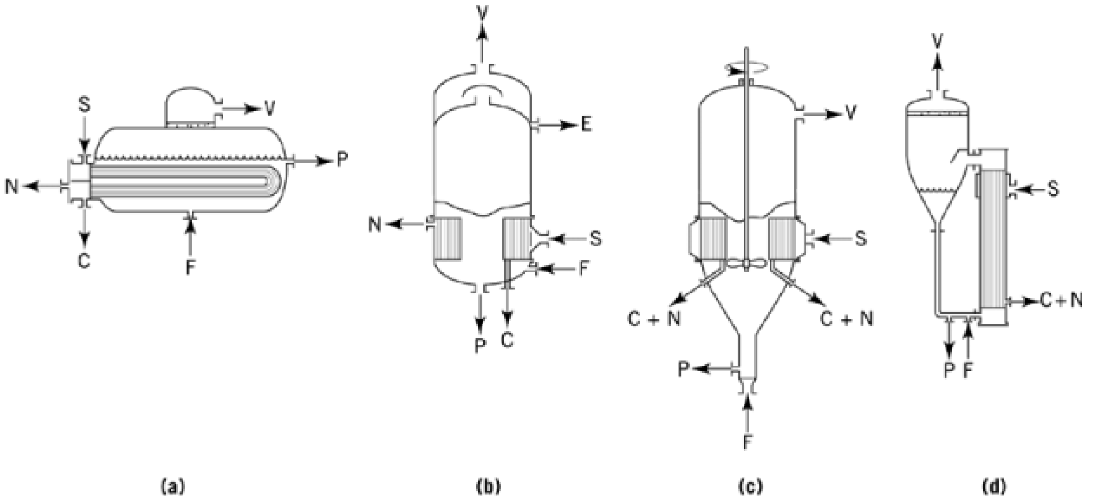

Fig. 1. Natural circulation evaporators where C=condensate, E=entrainment return, F=feed, N=noncondensibles′ vent, P=product or concentrate, S=steam, V=vapor, and ||| = knitmesh separator: (**a**) horizontal-tube, (**b**) short-tube vertical, (**c**) propeller calandria, and (**d**) long-tube recirculating.

area through the tubes themselves. The use of large-diameter short tubes and the need for a large downtake area result in a large body diameter relative to the amount of heating surface provided, usually larger than would be needed for vapor–liquid disengagement alone.

The natural circulation types of Figure 1**a** and 1**b** are not generally suited for handling feeds that deposit appreciable amounts of solids. The reason is that circulation is by boiling action alone and any interruption in boiling, or even a reduction in boiling rate, allows the solids to drop out of suspension, increasing the tendency for subsequent deposition to occur on the heating surface rather than forming new solids in suspension. However, by adding a propeller in the downtake, as in Figure 1**c**, the solids can be kept better in suspension. This type, called the propeller calandria, has been in use since the early 1900s for crystallizing table salt from brine. Although it might be thought of as another version of the forced circulation evaporator, its heat transfer performance is about the same as the STV type of Figure 1**b**, indicating that the propeller is not really contributing directly to heat-transfer performance but only keeps salts from forming on the tubes, which would then impede heat transfer.

The natural circulation type shown in Figure 1**d** is called the long-tube recirculation (LTR) or recirculating LTV evaporator. It employs longer tubes in an external heating element that is more easily accessible for cleaning. In this case, the vapor-head size is determined only by disengagement requirements and can be appreciably smaller than those shown in Figures 1**a–c**. Smaller vapor-head size has a resultant shorter holdup time, and the easier cleaning makes these evaporators well-suited for degradable products such as milk.

1.2. Forced Circulation Evaporators

The forced circulation evaporator, suitable for the largest variety of applications, is usually the most expensive type. It usually consists of a shell-and-tube heat exchanger, a vapor–liquid separator (variously called vapor head, vapor body, separator, flash chamber, or body), and a pump to circulate the liquor from the body through the heater and back to the body. The system is usually arranged so that there is no boiling in the heater. The heat input is therefore absorbed as sensible heat, and vapor liberation does not occur until the liquor enters the flash chamber. Absorption of the heat input as sensible heat results in a temperature rise that reduces the net temperature difference available for heat transfer. To keep this temperature rise to reasonable limits, usually on the order of 2–6 K, requires circulating large volumes of liquor relative to the amount evaporated, eg, ca 0.11 m^3 liquor per kilogram evaporated for dilute aqueous solutions at a 5 K rise. There is also an upper limit to temperature rise, usually on the order of 10 K, beyond which flashing at the entry to the flash chamber becomes so violent that large masses of liquor are ejected with the vapor. This makes entrainment separation more difficult and may impose structural shock loads on the separator. The head requirements of the circulating pump are generally quite low, consisting primarily of conventional friction and acceleration and deceleration losses at heater and body inlet and outlet, plus vortex losses in the body. The circulating pump is therefore usually of the propeller or mixed-flow type (see Pumps).

The vapor body of a forced circulation evaporator is sized primarily for vapor–liquid separation and is arranged so that as much of the liquid as possible entering from the heater "sees" the pressure existing in the vapor space. When that does not occur, some liquid is recycled to the pump without flashing fully to the equilibrium pressure, resulting in another loss in ΔT available for heat transfer, which is variously called the submergence, short-circuiting, nonequilibrium, or Δ' loss. This loss can be minimized by returning liquor above the liquid level in the body, which adds to pump head, or by introducing the liquor tangentially, which sets up secondary circulation patterns in the body, to bring more of the heated liquid to the surface. If the evaporator is used as a crystallizer, the sizing of the vapor body may also be influenced by crystallization requirements. These may dictate the liquor volume in the system, crystal surface area available for growth, temperature rise through the heater, and physical arrangement of the body. If used as a crystallizer, discontinuities should be avoided in the walls near the operating level or in the splash zone, such as peepholes, manholes, and body flanges, on which salts can deposit. Furthermore, body walls should be so smooth that the salt does not adhere, or else so rough that it stays in place until cleaning time. The intermediate situation is to be avoided because this results in salt coming off the walls in thicknesses on the order of 0.01–0.1 m which can be transported by the circulating pump and deposited over the inlet ends of the tubes in the heater.

The heating element of a forced circulation evaporator is usually of the conventional shell-and-tube type, most often single pass and vertical but frequently multiple pass and horizontal. The heater is usually located far enough below the liquor level in the body so that hydrostatic head prevents boiling in the tubes. In crystallizing service it is desirable, but not always possible, to locate the heater far enough below the liquor level so that boiling does not occur even in a tube which has had its inlet blocked and thus has liquor in temperature equilibrium with the heating medium. This avoids complete filling of the tube with cemented solids which are most difficult to remove. Tube size and length are chosen to give reasonable (1.5–3-m/s) tube velocities for the circulation rate available and the heating surface needed. In crystallizing service, small (less than 0.03-m) tube diameters are avoided to reduce risk of plugging, and the heaters are preferably vertical single-pass to afford more uniform distribution of flow to all tubes. Vortices in circulating lines and heater-inlet water boxes may result in such nonuniform velocities that there is little or no flow at all in some tubes and these quickly became plugged with solids.

Several configurations of forced circulation evaporators are shown in Figure 2. The most common arrangement is shown in Figure 2**a** having an external vertical single-pass heater and a tangential inlet to the body. Figure 2**b** shows the Oslo type of crystallizing evaporator in which the crystals are retained in a fluidized bed below the flash chamber. Because it is not always necessary to avoid boiling in the heating element, the element can project into the vapor head, as shown in Figure 2**c**. Auxiliaries shown in Figure 2 are not exclusive to each type of unit. Entrainment separators shown are top- and bottom-outlet centrifugal type and knit-mesh, respectively. The evaporator in Figure 2**a** includes a swirl breaker over the circulating pump inlet to reduce vortex losses in the vapor head and an elutriation leg to size, wash, and cool a crystallized product with part or all of the feed. In all cases, the steam inlet and vent outlet on the heat exchanger are placed so as to provide a positive flow path over the heating surface between the two. Forced circulation evaporators can be built for high single-unit capacities, having bodies as large as 15 m in diameter. The circulating pump is usually the limiting factor and it is not unusual to provide a single large body with as many as four or five separate heaters

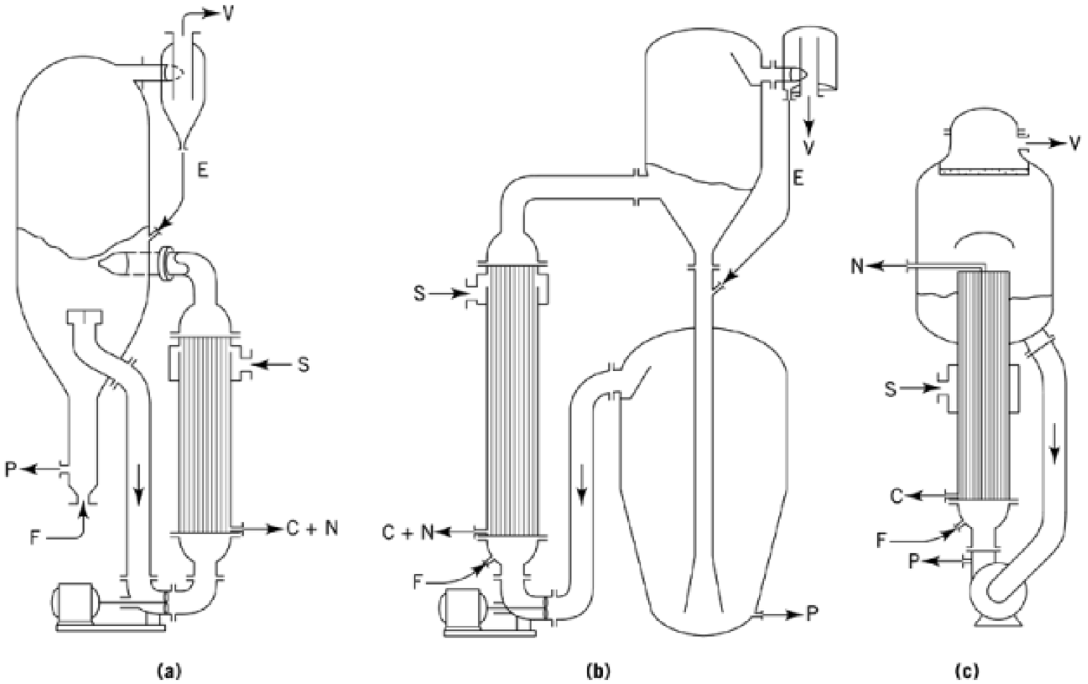

Fig. 2. Forced circulation evaporators: (**a**) submerged-tube, shown as circulating magma crystallizer; (**b**) submerged-tube, shown as suspension type crystallizer; and (**c**) boiling type. Terms are defined in Figure 1.

and circulating systems. For extreme fouling or salting conditions, the individual heaters can be arranged to be valved from the evaporator and cleaned without interrupting system operation.

1.3. Film-Type Evaporators

Film-type evaporators are illustrated in Figure 3. Figure 3**a** shows the rising film or long-tube vertical (LTV) evaporator most widely used in the United States. It consists of a vertical shell-and-tube heat exchanger surmounted by a vapor–liquid separator. Another version uses an offset vapor head similar to Figure 1**d**. Tubes are generally 0.05 m or less in diameter and 6–10 m long, which permits packing a large amount of heating surface into a single shippable tube bundle (on the order of 3000 m^2). Because of the simplicity of construction, costs per heating surface area are the lowest of any type, and heat-transfer performance is good under most operating conditions. Liquor flow through the LTV is generally once-through, distinguishing the LTV from the LTR of Figure 1**d**. However, if feed and discharge liquor properties differ widely, the evaporator may have partitions in the upper vapor head and lower inlet water box so that the effluent from one section can be returned to the inlet of another section of the total number of tubes in the bundle, and only the last group of tubes must handle liquor at the finished density. The LTV-type evaporator cannot handle crystallizing solutions but is excellent for foaming solutions because the deflector above the tube bundle acts as a foam breaker. Its widest use is for kraft-mill black liquor, which has foaming, fouling, and scaling tendencies and becomes quite viscous as it approaches discharge concentration (see Pulp).

The LTV is classified as a film-type evaporator because boiling takes place within the tubes and the vapor–liquid mixture is usually in the annular or film-flow regime for much of the tube length. High vapor velocities are generated and the interfacial shear also causes the liquid to move at high velocity, yielding good

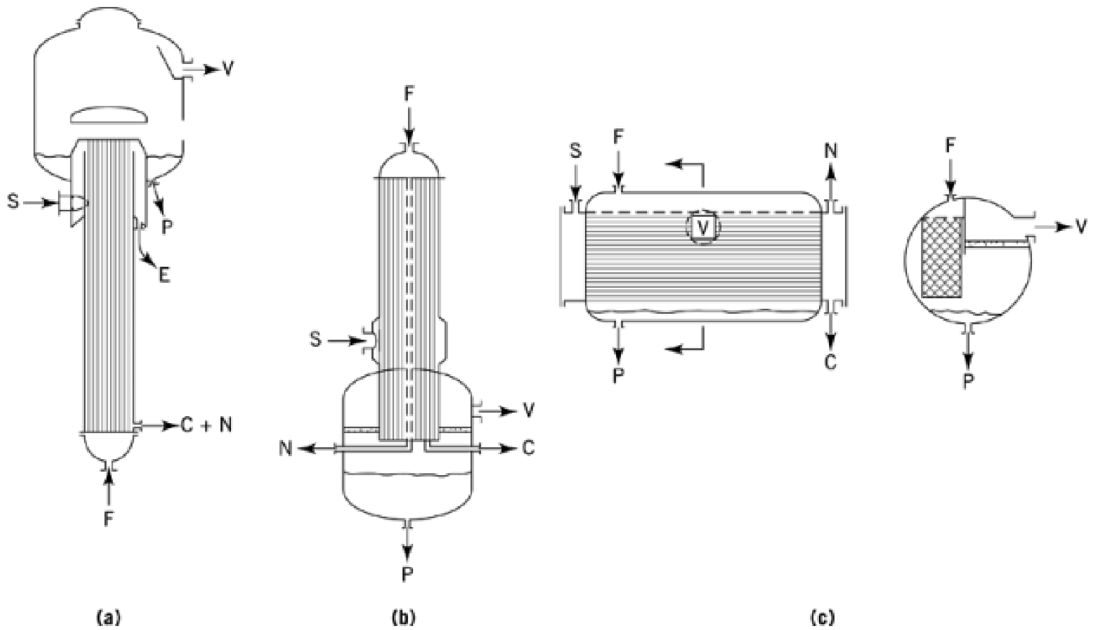

Fig. 3. Film-type evaporators: (**a**) long-tube vertical, (**b**) falling film, and (**c**) horizontal tube. Terms are defined in Figure 1. ⊠ represents end view of (**a**).

heat-transfer coefficients. However, frictional pressure drop, acceleration head developed as the vapor is generated, and hydrostatic head of the vapor–liquid mixture all cause the pressure and hence boiling temperature to be higher within the tube than at the tube exit, the temperature and pressure increasing with distance down from the outlet. Thus even if the feed is at its boiling point at the pressure in the vapor head, there is a section in the lower part of the tubes where the liquid cannot boil and is traveling at low velocity, and thus has poor heat-transfer characteristics. Proper selection of tube dimensions helps to minimize the adverse effects of reduced available ΔT and poor heat transfer in the non-boiling zone, as does the use of preheaters on the feed. These preheaters may be either external or incorporated as a part of the main tube bundle. Because LTV performance depends on the vapor–liquid velocities developed in the boiling zone, it follows that heat-transfer coefficients are a function of the load or of the overall ΔT. Coefficients are low at low temperature differences and low temperatures. This type of evaporator sometimes suffers from instability problems when operated under part-load conditions.

The falling-film evaporator shown in Figure 3**b** is an inverted version of the LTV that greatly reduces the adverse effects of pressure drop on available ΔT exhibited by the rising-film LTV. The hydrostatic head loss is eliminated, acceleration losses are lower because the liquid film is not accelerated substantially by the vapor flow, and the frictional pressure drop is generally only a little more than that of vapor flowing alone in a dry tube. In addition, heat-transfer performance is practically the same regardless of whether or not the film is boiling. This eliminates a poorly performing nonboiling zone at the inlet end of the tubes, even when the feed enters far below its boiling point. Uniform feed distribution to all tubes is usually the principal difficulty. Methods to overcome this include individual distributors in each tube, a full cone spray nozzle in the upper water box, a perforated plate above the top tube sheet with holes allowing feed to impinge on the tube sheet web between tubes, or, for high flow rates, no distribution devices at all. Feed rates are generally on the order of 1.5–8 $\mathrm{m^3/(h{\cdot}m)}$ of wetted tube perimeter. Because these are usually higher than the net feed rate, some recirculation is required. Thus the falling-film evaporator also belongs to the forced circulation class. As with the LTV, the inlet water box and the vapor head may be partitioned, permitting evaporation of the feed in stages; only the last stage has to operate at final density. This is advantageous when viscosity or boiling point increases rapidly as discharge concentration is approached but requires separate pumps for each stage.

The principal advantages of the falling-film evaporator are good heat-transfer performance, even at low temperature and low temperature differences, low initial cost, and excellent vapor–liquid separation characteristics. Principal applications have been for citrus juices, where performance at low temperature and low holdup is important, and applications requiring operation at low temperature differences, such as vapor compression or multiple-effect evaporators needing a large number of effects to be economical, eg, for producing fresh water from saline waters. The falling-film evaporator is normally not suitable for the usual crystallizing operations but has been very effective in scaling environments, scaling being avoided by maintaining a suspension of the scaling ingredient in the circulating liquid (1).

A special heating surface developed for this type of evaporator is the doubly fluted tube (2), which gives two to three times the heat-transfer coefficient of a smooth wall tube. On the steam side, the condensing coefficient is enhanced by the presence of longitudinal grooves. Surface tension forces draw the condensate into the grooves, leaving the area between the grooves bare so that they give coefficients comparable to those achieved with dropwise condensation. Heat-transfer coefficients on the boiling liquor side are also markedly higher than they are on smooth tubes. The principal application for these tubes is for production of distilled water from seawater (see Water).

A combination of rising-film–falling-film evaporator utilizes a two-pass vertical heating element situated above the vapor head. The first pass, fed at the bottom, operates as a rising film and the vapor–liquid mixture then goes through the second pass as a falling film. This type evaporator usually operates with recirculation, but the amount of recirculation is less than in a normal forced circulation or falling-film evaporator. It was developed primarily for handling high viscosity fluids and for applications requiring low residence times.

Another version of the film evaporator is that in which liquid is showered over the outside of substantially horizontal tubes as shown in Figure 3**c**. This was originally called the Lillie evaporator and is now termed the horizontal-tube or spray-film evaporator. It has essentially the same advantageous heat-transfer characteristics as the falling-film type of Figure 3**b** and in addition requires much less headroom. Its main disadvantages are poorer vapor–liquid separation and greater difficulty of cleaning fouled tubes. Uniform liquor distribution at the top of the tube bundle is usually accomplished by perforated troughs or spray nozzles. Uniform distribution may not prevail further down in the bundle as vapor release from the side or ends of the bundle tends to drive liquid with it instead of the liquid falling vertically from one tube row to the next. In the original Lillie and in some modern versions, the tubes are rolled into a tube sheet at only one end and are sloped uphill so that condensate can drain countercurrent to the steam. The other end is then fitted with a perforated plug to act as a vent. Other versions employ tube sheets at both ends and frequently have several steam side passes, with a smaller number of tubes in each succeeding pass, to provide a tapered flow path from steam inlet to vent outlet.

The wiped-film or agitated-film evaporator, shown in Figure 4, uses mechanical energy to promote heat transfer. It employs a single large-diameter straight or tapered tube as the heating surface, in which a set of blades is rotated. The axis of rotation is frequently vertical. The blades maintain either a fixed close clearance from the wall or actually ride on the film of liquid and help to carry the liquid as a film around and along the length of the heating surface. The cost of these evaporators per unit of heating surface is very high and the capacity is relatively low, because a maximum of only about 40 m^2 of surface can be provided in a single tube. Thus, these evaporators are used primarily only for materials that cannot be handled in other evaporators, such as highly viscous liquids or liquids requiring very low residence times in contact with the heating surface. Because of the high capital cost and limited heating surface, these units are usually operated as a single effect at high ΔTs. This and structural considerations require that the large diameter tubes be of fairly heavy wall construction. Such evaporators exhibit poor heat-transfer performance on low viscosity fluids because of the added resistance of the metal wall.

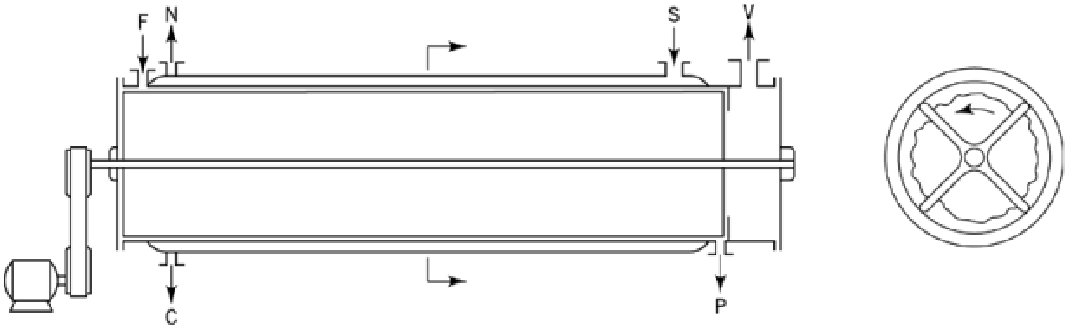

Fig. 4. Wiped-film evaporator. Terms are defined in Figure 1.

2. Energy Conservation

Most of the complexity and cost of an evaporator installation is a result of attempts to reduce energy consumption, which is usually by far the most important element of operating cost. Evaporators are not normally rated directly in efficiency of energy usage because the separation of solvent from the solution requires very little theoretical energy in an ideal system. Thus, for separating water from a salt solution having a boiling point rise of 5 K at its atmospheric boiling point, the minimum theoretical work energy requirement is only 30.1 kJ/kg (13.0 Btu/lb) of water removed, whereas it takes 2250 kJ/kg (970 Btu/lb) of heat to vaporize the water. Heat and work energy are not directly interchangeable in utility or in cost. Thus steam-heated evaporators are generally rated in terms of steam economy, ie, weight of water evaporated per weight of steam used, also called gained output ratio or performance ratio, and frequently standardized at pounds of water evaporated per 1000 Btu extracted from the steam (kg evaporated per 2324 kJ). Even evaporators that do use work energy (electrical or mechanical) for operation are not usually rated in terms of efficiency but instead in such terms as J/m^3 ($= 1.05 \times 10^{-6}$ kWh/1000 gal) evaporated.

The single-effect evaporator is the simplest arrangement. It uses steam from an outside source and exhausts its vapor to the atmosphere or to an air- or water-cooled condenser. Such an evaporator requires about a 1-to-1 ratio of steam to water evaporated, but somewhat more if the feed is colder than the product and heat cannot be recovered by preheating the feed with concentrate and condensate. The high steam consumption limits the use of single effects to small capacities and to materials requiring an expensive type of evaporator, such as the wiped-film type, or having a very high boiling point, or to cases where the vapor is contaminated by materials that would cause excessive fouling or corrosion of heating surfaces when condensed, eg, rayon spin-bath liquor. Such evaporators may be operated on a continuous, batch, or semibatch basis with very little difference in heat requirements. In both batch and semibatch operation, final concentration is not reached until the end of the cycle, and these methods are therefore used primarily when the heat-transfer properties become markedly poorer as final concentration is approached. Semibatch operation is the more common. Feed is added continuously during most of the cycle in order to maintain a liquid inventory large enough to permit the evaporator to operate properly.

The single-effect evaporator produces almost as much vapor as the amount of steam used, the only difference being that the vapor is at a lower temperature and hence lower pressure. Compressing the vapor for reuse as the heat source was put into operation in the nineteenth century. This thermocompression or vapor recompression operation can be accomplished by either mechanical or steam-jet compressors. Mechanical compressors are by far the more efficient and may be driven by electric motors, gas or diesel engines, or steam or gas turbines. Because of the high specific volume of water vapor, positive displacement compressors are suitable for only the smallest capacities. Centrifugal compressors are most frequently used, whereas axial-flow multistage compressors are needed for the highest capacities, ca 50–500 m^3/s (10^5–10^6 ft^3/min). Compressor efficiencies are usually in the range of 70–75% for single-stage centrifugal machines (for compression ratios to about 1.75) and 80–85% for axial-flow machines (for compression) ratios of about 1.15 per stage). Steam-jet compressors, on the other hand, are only about 25–30% efficient. Therefore, if high pressure steam is available and capacity requirements are appreciable, a mechanical compressor driven by a steam turbine is preferred to a steam jet.

The ideal mechanical power requirement of a thermocompression evaporator is given by the Carnot equation:

$$W = Q\,\Delta T/T$$

where W is the work done, Q is the heat received at absolute suction temperature T, and ΔT is the difference in saturation temperature at compressor discharge and suction pressures. To minimize the work required ΔT is kept low so that the evaporator must have a large heating surface area. The optimum balance between power consumption and evaporator cost is usually at net a ΔT in the range of 3–10 K. The need to operate at low net ΔT is a disadvantage of some types of evaporator, such as natural circulation and LTV units, where coefficients fall off at low ΔT; and the submerged, forced circulation types, which lose ΔT as a result of temperature rise in the heating element and short-circuiting in the vapor head. The most advantageous evaporator type for vapor compression operation, when suitable for the liquor handled, is the falling film, which has very little ΔT loss (3). Because the ΔT across which the compressor must work also includes the boiling point rise (BPR) and any losses owing to pressure drop in vapor circuits, special care is exercised to minimize these. If the BPR of the product is high, multiple stages on the liquor side are advantageous so that only the last portion of the evaporation occurs at final product concentration. Vapor-side ΔT losses are minimized primarily by adequate duct sizing and the use of an entrainment separator having a low pressure drop, such as knit mesh. Entrainment separation is particularly critical because the vapor becomes superheated on passing through the compressor and any liquid carried with it evaporates, depositing its contained solids on the blades. Entrainment should preferably be held to 5 ppm total solids or less to minimize compressor problems.

A thermocompression evaporator is like a flywheel because the compressor keeps a large amount of heat content circulating. However, heat input must balance heat output in order that the total energy content or temperature of the system remain constant. The work input of the compressor ultimately appears as a heat input to the system, and ideally this should balance the heat losses from the system so that no supplementary source of heat is needed, except at startup. The heat input from the compressor is generally quite small; thus it is necessary to preheat the feed very close to the evaporator temperature by heat exchange with condensate and concentrate. The approach temperature differences required in these feed heaters, in order to achieve a balanced system, decrease with decreasing evaporator ΔT and input power. Making a thermocompression evaporator more efficient requires increases in both evaporator and preheater heating surface area. Where possible, supplementary sources of makeup heat are utilized, such as waste-heat boilers on gas turbine drives or diesel engines. If steam-turbine driven or steam-jet compressors are used, a surplus of heat is usually available and it is necessary to bleed vapor at the compressor suction to maintain the evaporator at constant temperature.

The largest number of vapor-compression evaporators have been built for producing potable water from seawater or brackish water. These are usually relatively small capacity units for military use, offshore drill rigs, marine vessels, and the like, and use engine-driven compressors and short-tube vertical evaporators. Makeup heat is obtained from engine exhaust and engine cooling water. The principal advantage is the ability to build a complete, compact, highly efficient, easily transportable unit that needs only connection to fuel supply and a feedwater source for its operation. Another use has been for citrus juice concentration, which must be done at low temperatures to avoid degradation (see Fruit juices). The need for low temperatures prevents use of multiple-effect evaporators for heat economy but also causes problems for vapor-compression operation because of the very high specific volume of steam under these conditions. A refrigerant, such as ammonia or Freon, can be employed as a secondary working fluid. The evaporator is then heated by the compressed refrigerant and the evaporator vapor is condensed in the refrigerant reboiler (see Refrigeration and refrigerants). Thus this system has the disadvantage that the heat must be passed through two heating surfaces instead of one. Since the 1973 energy crisis, and as a result of higher efficiency, thermocompression evaporators are used in fields where they were not previously considered, such as for paper-mill waste cooking liquors (4) and for disposal of cooling-tower blowdown wastes. In the latter application, the cooling-tower water is usually nearly saturated with calcium sulfate, $CaSO_4$, and thus the evaporator must handle a severely scaling liquor. The falling-film evaporator has been used successfully in this case; seeding with $CaSO_4$ solids can prevent scale formation completely (1). Other uses include applications where lack of need for a heat sink is important and as a preconcentrator to increase the capacity and efficiency of existing multiple-effect installations. Diaphragm-cell caustic soda, for instance, is normally concentrated in forced circulation evaporators because of the large amounts of salt precipitated. However, an appreciable amount of water can be removed from the cell liquor before saturation is first reached with salt and the BPR is still relatively low; therefore, a falling-film thermocompression preconcentrator is advantageous.

If steam instead of power is the source of energy, multiple-effect evaporation is the principal means of energy conservation. In this operation, the vapor from one effect is used to heat another effect boiling at a lower temperature and the vapor from this effect is used to heat yet another effect boiling at still lower temperature. In such evaporators it is desirable to use an initial steam temperature as high as possible in the first effect and a heat sink temperature as low as possible to condense the vapor from the last effect, in order to develop the highest practical total temperature difference for heat transfer. The upper temperature limit is usually set by available steam pressure or scaling, fouling, product degradation, or corrosion characteristics of the liquor. The lower temperature limit is determined either by temperature and availability of cooling water or the need for low temperature steam for some other use. Other factors that may affect the lower temperature limit, which usually corresponds to a high vacuum, are poor heat transfer for most evaporator types at low temperature, high liquor viscosity, the very high vapor volumes from which liquor must be separated, and the cost of removing noncondensibles from the system.

Because each effect of an evaporator produces almost as much vapor as the amount it condenses, the total evaporation accomplished per unit of prime steam, or steam economy, increases in almost direct proportion to the number of effects used. The total heat load is also split up between the effects so that each effect has a much lower heat duty than a single effect for the same total evaporation load. However, the total available ΔT is also split up similarly so that each effect of a multiple effect requires about as much heating surface as a single effect operating over the same total temperature difference. Thus in selecting the number of effects to use in any installation, steam cost savings and capital cost of effects have to be balanced. Even before the energy crisis of the 1970s, evaporators having six or seven effects were common in the pulp and paper (qv) industry. As many as 17 effects had been used in large seawater evaporators.

The relationships between number of effects, steam economy, and heating surface needs are not exact and can only be determined for a particular project by detailed heat and material balances, as well as consideration of the effects of temperature level and temperature difference on heat-transfer performance. The steam economy is generally not equal to the number of effects, primarily because of the influence of sensible heating loads. It frequently can be improved by alterations in feed sequence or installation of intereffect heat exchangers. The steam economy is usually close to a fixed fraction of the number of effects. The fraction may be over 1.0 when the feed is hot and may be as high as 0.9 even when the feed is cold, provided efficient means are included for preheating feed and for recovering waste heat at the least practical temperature differences. The most common method of heat recovery is by flashing the condensate produced in each effect to each of the lower temperature effects in turn so that the flash vapor is added to evaporator vapor to accomplish more useful evaporation. Prime steam condensate is usually not flashed because the flash vapor would be working at lower steam economy (over fewer effects) than the prime steam, and the condensate would then have to be reheated in the boiler circuit at the same efficiency as generating latent heat in the prime steam.

Similarly, heating surface area needs are not directly proportional to the number of effects used. For some types of evaporator, heat-transfer coefficients decline with temperature difference; as effects are added the surface needed in each effect increases. On the other hand, heat-transfer coefficients increase with temperature level. In a single effect, all evaporation takes place at a temperature near that of the heat sink, whereas in a double effect half the evaporation takes place at this temperature and the other half at a higher temperature, thereby improving the mean evaporating temperature. Other factors to be considered are the BPR, which is additive in a multiple-effect evaporator and therefore reduces the net ΔT available for heat transfer as the number of effects is increased, and the reduced demand for steam and cooling water and hence the capital costs of these auxiliaries as the number of effects is increased.

In a multiple-effect evaporator, the effects are numbered in the direction of steam flow, the first effect being the one heated by prime steam. Liquor feed sequence through the evaporator may be forward, backward, parallel, or mixed. Backward feed (to the coolest effect first and then successively through the higher temperature effects) is generally used when the feed is cold, because only a small volume has to be heated to the highest temperature, thereby reducing sensible heating losses and improving steam economy. Forward feed is generally used when feed is hot and when the concentrated product is not too viscous at the last effect temperature. Where necessary, forward feed can be used on a cold feed and can give almost the same steam economy as backward feed if the feed is preheated in stages by vapor extracted from each higher temperature effect of the evaporator in turn. Such an arrangement is used for seawater, which can be concentrated only in small amounts at high temperature without scaling but about threefold at the lowest effect temperature. These preheaters add to the complexity of the evaporator but not necessarily to total heating surface needs because they reduce the heat loads in the effects themselves. Parallel feed is frequently used in crystallizing operations and involves feeding to and withdrawing product from each effect. Mixed feed operation is common if feed is at some temperature intermediate between first and last effect, the finished product is too viscous to handle at low temperature, or liquor at an intermediate concentration and temperature is desired for further processing. All such conditions prevail in a kraft-mill liquor evaporator (see Pulp). The evaporators are usually of the LTV type and the feed heaters are an integral part of the evaporator tube bundles. The highest temperature effect is frequently subdivided so that only a part of the tubes must work on liquor of the highest concentration and viscosity. Other flow-sheet variations include evaporators with several bodies in parallel on steam and vapor but in series on feed. Thus the kraft-mill evaporator might be an eight-body seven effect with two bodies in parallel in the last effect position in order to better handle the very large vapor volumes generated at the lowest temperature. Variations may also involve the steam path; eg, a combination double-triple effect, which may have one effect on prime steam with the evolved vapor being split, one part to a single effect and the other to a double effect. This variant is used when the liquor has a high BPR as it approaches final concentration, so high that not all evaporation can be accomplished, in this example, in a triple effect. Other flow sheets have been developed for specific types of evaporator, such as parallel split feed, which is used for desalination evaporators arranged in vertical stacks. In this case, about half the feed goes to the odd-numbered effects in one stack and the other half to the even-numbered effects in a second stack next to the first, with vapor connections crossing from one stack to the other.

Another means of gaining multiple-effect steam economy is by multistage flash operation, developed originally as the Alberger salt process. In this process, cool liquor is preheated in stages by vapor condensing at successively higher temperatures in a recovery section and finally by prime steam in a brine heater. The heated liquor is then flashed down in stages to generate the vapor used for preheating. The condensate from this vapor is also flashed down in the same manner so that the total flow being flashed is the same as the flow being heated. As a result, the temperature rise and flashing range in all heaters and flashers is about the same. Flashing through a 75 K range evaporates only about 12% of the feed; thus it is necessary to recirculate the liquor through the heaters and flashers when an appreciable degree of concentration is required. This then requires a rejection section in the flash train, containing one or more stages in which liquor is flashed to reject heat to cooling water before being recirculated to the recovery section. Even when recovering fresh water from seawater, recirculation is usually employed to reduce the amount of fresh feed that must be treated for scale prevention and deaerated before introduction into the evaporator. The characteristics of a flash evaporator are entirely different from those of a multiple-effect evaporator. Many more stages than effects are needed to achieve the same steam economy. Whereas in a multiple-effect evaporator the amount of heating surface provided is the most important determinant of capacity, and only the number of effects has a strong influence on steam economy, in a multistage flash evaporator the production rate is proportional only to the product of liquor circulation rate and total flash range. The steam economy is affected by both the number of stages and the amount of heating surface provided. The principal advantages of the multistage flash evaporator are that only one circulating pump is needed and that a number of stages, comprising both flash space and heating elements, can be combined in one vessel. The evaporator is in essence a number of forced circulation evaporator heating elements connected in series on one circulating pump, plus a number of forced circulation flash chambers connected in series. Because all heat is absorbed as sensible heat, the multistage flash evaporator suffers from the same loss in ΔT as the forced circulation evaporator, and also has short-circuiting losses of the same magnitude. The disadvantages of the multistage flash evaporator are therefore primarily this loss in net ΔT available for heat transfer, plus the fact that all liquor in the system is close to discharge concentration.

Although the interrelationships of the variables in a multistage flash evaporator is complex, the sizing of the heating surfaces is relatively simple, using the following factors (5): (*1*) heat-transfer coefficients from conventional correlations for condensing vapor and for liquid heating in tubes; (*2*) heat load, excluding brine heater: $Q = D\Delta H/(1 - \Delta t/1250)$, (*3*) weight of brine circulated: $W = Q/C_p\Delta t$; and (*4*) net ΔT for heat transfer $= \Delta t/N \ln{(1 - \Delta t/1250 - R{\cdot}P/\Delta t)/(1 - \Delta t/1250 - R{\cdot}P/\Delta t - P/N)}$, where Q = amount of heat transferred through heating surfaces; D = distillate production rate; ΔH = average latent heat of evaporation; Δt = total flashing range, K; C_p = specific heat of circulating brine; N = number of flash stages; R = average sum of BPR and short-circuiting losses; and P = steam economy desired based on 2324 kJ/kg (1000 Btu/lb) latent heat. From these, it is observed that heating surface can be traded against number of flash stages but that the number of stages should be on the order of three times the steam economy in order not to seriously decrease the net Δt available for heat transfer. Furthermore, the ratio of heating surface needed to the amount of brine circulated is usually so high that the recirculating liquid must be pumped through long lengths of small-diameter tubing in order to achieve reasonable tube velocities and hence reasonable heat-transfer coefficients. This need for small-diameter tubing and very long flow lengths, which necessitates a number of intermediate water boxes, makes the multistage flash evaporator generally unsuitable for crystallizing service.

It is possible, of course, to combine the different types of evaporator as well as the various methods of energy conservation into a single system. Thus if a crystallizing solution is being handled but saturation is not reached until after an appreciable amount of solvent has been evaporated, the preliminary concentration can be done in several effects of the natural circulation or film type, followed by forced circulation effects for the crystallizing duty. In a thermocompression evaporator of the steam-jet type, one with a steam-turbine-driven mechanical compressor, or one driven by a gas turbine to which a waste-heat boiler can be added, more low pressure steam can be generated than can be used effectively in the thermocompression section. Vapor can, therefore, be bled at the compressor suction and used to operate a multiple-effect or multistage flash-evaporator section. The latter usually can also serve as a preheater for the feed to the thermocompression section. Such evaporators are most useful when the evaporation requirements are the sole or principal reason for installing the facilities for steam or power production. Because it costs only little more to generate steam at a far higher pressure than can be possibly used directly in the evaporator, the addition of a steam-jet or steam-turbine compressor accomplishes additional evaporation at very little additional operating cost. Similarly, a gas turbine may be relatively inefficient when generating only power but if also used to generate low pressure steam in a waste heat boiler, it becomes as efficient as a more expensive high pressure boiler and steam turbine system.

3. Temperature Difference and Heat Transfer

The capacity of a steam-heated evaporator is governed by the amount of heat it can transfer, which is determined in turn by the amount of heating surface area and temperature difference available, and the heat-transfer coefficients achieved (see Heat exchange technology, heat transfer). There are common conventions in the industry for these terms but they are not universally used; therefore, care must be exercised in interpreting and applying available data. Heating surface area is almost always taken as the total tubing area on the side in contact with the liquor being evaporated, which is different from normal heat exchanger practice, where it is always the outside area of the tubes. The definition of temperature difference is open to the widest interpretation and is the most frequent cause of misapplication of data. Considering only one effect of an evaporator, it is the difference between saturated steam temperature on one side of the heating surface and the liquor temperature on the other side that is effective for heat transfer. However, for the effect as a whole, with its associated liquor circuits, vapor piping, and entrainment separators, it is the difference between saturated steam temperature at the inlet to the heating element and the condensing temperature of the evolved vapor at the exit of the vapor discharge piping that determines how the evaporator effect reacts with its surroundings. Certain losses in temperature difference are inherent, including boiling point rise, vapor circuit losses (those from friction and acceleration and deceleration heads of steam and vapor flowing into and through the heating element, entrainment separator, and vapor piping) and liquor circuit losses (the difference between the temperature at which heat is absorbed at the heating surface and the temperature at which it is released in the vapor head). Boiling point rise, or boiling point elevation (BPE), is usually the most important of these losses and is the difference between the boiling point of the solution in the evaporator and the boiling point of pure solvent at the same pressure. Because the vapor cannot condense and give up the bulk of its heat content until it has cooled to the boiling point of the pure solvent, BPR represents a loss of available ΔT and is deducted from the overall ΔT before computing heat-transfer coefficients. It is usually estimated from known properties of the solution at the discharge concentration of each effect or each body, but care must be exercised here also, because it is sometimes obtained from direct measurements of vapor temperature made at a point where the vapor may still be somewhat superheated. Furthermore, in the falling-film-type evaporator, eg, the discharge is frequently taken from the circulating pump that feeds the heating surface, with the result that the discharge from the heating surface is at a higher concentration than the discharge from the effect.

Any pressure drop losses of steam in the heater or of vapor in the entrainment separator and vapor piping also reduce condensing temperatures, and therefore represent a loss in ΔT available for heat transfer. These losses become more serious at the lower temperatures, because of the increasing difficulty of handling lower density vapor and the decreasing slope of the vapor pressure curve. In many cases, these vapor circuit losses are tabulated separately and deducted from the overall ΔT before computing heat-transfer coefficients. However, at times these losses are ignored or combined with the BPR loss or the heat-transfer ΔT, which must be borne in mind when interpreting heat-transfer data. Incorporating these losses in the BPR term is especially dangerous because actual chemical BPR changes very little with evaporator load whereas the net ΔT across the heating surface increases in almost direct proportion to load, and vapor circuit losses increase as almost the square of the load.

Losses of ΔT in the liquor circuit may also be substantial but are not always taken into consideration. Only in the forced circulation evaporator are at least part of these losses usually calculated. Because heat is absorbed as sensible heat, a temperature rise results that can be either measured or calculated from known heat input and known circulation rate. If this is done, coefficients are reported on the basis of log mean temperature difference. The submergence or short-circuiting losses are frequently included in the coefficient, eg, when the heater inlet temperature is not measured directly but instead is calculated from saturation temperature at the measured vapor head pressure, plus BPR. In natural circulation evaporators the boiling point at the heating surface is higher than that in the vapor space because of the hydrostatic head of liquid above the heating

Table 1. Temperature Distribution, °C

Effect	I	II	III	IV	Condenser
steam temperature[a]	125.7	112.7	94.2	72.8	47.0
net ΔT	9.6	13.4	11.9	12.9	3.0[b]
liquor temperature	116.1	99.3	82.3	59.9	
BPR[c]	3.2	4.3	6.9	8.6	
vapor temperature[a]	112.9	95.0	75.4	51.3	
vapor-circuit loss	0.2	0.8	2.6	4.3	
heater inlet			83.1	61.6	30
outlet			86.1	64.5	44
net $\Delta T_{\text{logmean}}$			9.5	9.7	8.1[d]
submergence loss			0.8	1.7	

[a] Calculated from measured steam chest and vapor-head pressures.
[b] Effective ΔT if a direct contact condenser.
[c] From known properties of solution, at measured or calculated concentration.
[d] Effective ΔT if a surface condenser.

surface. This loss was frequently allowed for in early data presentations. For LTR or LTV evaporators the course of the liquor temperature as it passes the heating surface cannot readily be measured or calculated and coefficients are based on steam and vapor head temperatures. In general, it is practical to consider these losses only when heat-transfer coefficients can be calculated from theory, as in forced circulation and falling-film evaporators. For the latter, the loss caused by friction and acceleration of vapor generated in the tubes must be considered when calculating coefficients from theory, but may or may not have been included in the coefficients reported in the literature.

When designing a new evaporator or analyzing the operation of an existing evaporator, a temperature distribution table first should be prepared. Table 1 gives the data on a quadruple-effect evaporator containing two natural circulation effects followed by two forced circulation effects. Such a table compares the magnitude of the various losses in ΔT and hence indicates the principal obstructions to capacity. Thus if one of the effect's net ΔTs were substantially higher than the others, improvements in performance of that effect would give the greatest gain in capacity. If these data were taken when the evaporator was operating considerably below design capacity, the last effect vapor-circuit loss would be of special concern. It would increase approximately with the square of capacity and soon would become a much more important obstruction as conditions elsewhere were improved.

When used in design, a temperature distribution table serves as the basis for calculating a heat and material balance around the evaporator to determine heat loads in the individual effects, vapor flows, and liquor concentrations, from which vapor-circuit losses or line sizes and BPR estimates can be reconfirmed. The designer does not simply take the net ΔTs from such a table and the calculated or estimated heat-transfer coefficients to arrive at the heating surface needed in each effect. The designer also uses it for optimizing. For instance, the temperature distribution may be altered so that the heating surface areas and heating element designs are identical in two or more effects. In the example of Table 1 the ΔTs might be reduced in the first two effects which are of the natural circulation type and cheaper per unit of heating surface, in order to give greater ΔTs and hence lower surface requirements in the more expensive last two forced circulation effects. The added cost of reducing vapor-circuit losses through use of larger lines and entrainment separators can be compared with the savings resulting therefrom in increased net ΔTs across the heating surfaces.

Actual heat-transfer coefficients encountered in evaporators cover a wide range, depending on the physical properties of the solution, its fouling characteristics, the type of evaporator employed, the boiling temperature, and the temperature difference. Only in the submerged-tube forced circulation and the falling-film evaporator can heat-transfer coefficients easily be calculated from theory (2). For other types, performance estimates are usually based on earlier experience with the same or a similar liquor. In general, coefficients range from a low of about 175 J/(m^2·s·K) (100 Btu/(h·ft^2·°F)) to a high of about 3500 (2000). The lowest coefficients are encountered at low temperatures and low ΔTs in film-type or natural circulation evaporators, or at very high viscosities. The highest coefficients are encountered when employing doubly fluted tubes. These high coefficients are possible only when fouling resistances are very low, eg, when handling seawater that has been properly treated for scale prevention and deaerated.

4. Vapor–Liquid Separation

The heating surface usually determines the evaporator cost and the vapor head the space requirements. The vapor–liquid separator must have enough horizontal plan area to allow the bulk of the initial entrainment to settle back against the rising flow of vapor and enough height to smooth out variations in vapor velocity and to prevent splashing directly into the vapor outlet. Separators are usually sized on the basis of the Souders-Brown expression:

$$U = K\left(\left(\rho_l - \rho_g\right)/\rho_g\right)^{1/2}$$

where U = vapor velocity, ρ_l = density of liquid, ρ_g = density of gas. For most types of evaporator, the decontamination factor DF (DF = kg of vapor per kg of entrained liquid) decreases as K increases, approximately as follows (5):

	K	
DF	m/s	ft/s
100	0.051	0.167
200	0.033	0.108
500	0.020	0.067
1000	0.015	0.049
2000	0.011	0.036

In general, it is not economically attractive to provide the full degree of entrainment separation desired in the vapor head alone. Instead, the vapor head is sized for a decontamination factor on the order of 200 and reliance is placed on supplementary separators such as shown in Figures 1, 2, 3 for removal of residual entrainment. Somewhat lower separator velocities are frequently used in crystallizing evaporators to help reduce the buildup of salts on the walls of the vessel above the liquor level. In the falling-film evaporator, most of the entrainment separation occurs within the tubes and higher velocities are permissible in the vapor head and through the curtain of liquor falling from the ends of the tubes. Here, decontamination factors of 1000 or more can be achieved at K values of 0.15 m/s under favorable conditions, primarily avoidance of long fall distances from tube ends to the liquid pool below the tubes, which generates finer, more easily entrainable droplets.

5. Heat Removal and Noncondensible Gases

A single- or multiple-effect evaporator does not consume heat; it merely degrades the heat input and means must be provided for removing the waste heat. Heat is usually rejected to a river, wells, or a cooling tower. The most common means of heat rejection is by a barometric condenser in which the vapor from the last effect is condensed by direct, countercurrent contact with water cascading over weirs or trays. The condenser is elevated far enough above grade so that water can drain away to a hot well barometrically against the vacuum in the system. Noncondensible gases in the vapor accumulate at the top of the condenser and are cooled close to the temperature of the incoming water, thereby reducing the amount of water vapor associated with the gases. These gases are removed by either a steam-jet ejector (usually of several stages) or a mechanical vacuum pump. Steam-jet ejectors are the most common but are relatively inefficient. Mechanical vacuum pumps have substantially lower operating costs. Another type of direct contact condenser is the cocurrent or jet condenser, in which the water is delivered through nozzles at a velocity high enough to carry the noncondensible gases out the tailpipe. Although this eliminates the need for a separate vacuum pump, the water flow and pressure requirements are sufficiently higher than those of a countercurrent condenser that overall energy consumption is increased. A surface condenser is much more expensive than a direct-contact condenser and is used only when contaminants in the vapor, eg, SO_2, would pollute the condenser water or when the pure condensate has a substantial value. Surface condensers are designed by conventional shell-and-tube methods. Particular care must be taken to minimize shell-side pressure drop, since even a small pressure drop at the high vacuum usually employed represents a substantial loss in available ΔT. Furthermore, in general, more noncondensible gases are present than in the usual steam-heated exchanger and special precautions must be taken to properly channel the vapor flow past the surface between steam inlet and vent outlet, and to allow for the effects of noncondensible gases on heat-transfer performance.

Noncondensible gases are more prevalent in an evaporator system than in most other steam-heated equipment and must be properly handled to avoid serious impairment of heat transfer or reduction in steam economy (6). These may be present as gases dissolved in the feed or liberated by decomposition reactions in the liquor, eg, by bicarbonate breakdown, air in-leakage, and air dissolved in the condenser water. Although venting in practice is almost always empirical and done in excess, the optimum vent rate usually corresponds to a noncondensible gas content of 5–10 vol % in the vents. Vents from heating elements operating under pressure may be released to the atmosphere, whereas vents from vacuum effects are passed through the condenser to remove as much of the associated water vapor as possible ahead of the vacuum pump. Vents are frequently cascaded from one effect to the next on their way to the condenser. Such cascading results in increased concentrations of noncondensible gases in the later effects, and its only potential benefits are the recovery of heat from an upstream vent that has accidentally been opened too wide or to provide sufficient velocity to sweep noncondensibles to the vent. In general, noncondensible gases have little effect on heat-transfer performance provided that they are properly channeled through the evaporator heating elements. This requires a positive vapor flow path from steam inlet to vent outlet, with no pockets of low velocity where noncondensible gases can be trapped, and no low resistance channels that can bypass steam directly from inlet to outlet.

6. Other Evaporative Methods

Solar evaporation, the first evaporative method developed, is in widespread use, primarily for production of salt from seawater (see Chemicals from brine). Evaporation rates vary widely with climate and can be predicted from weather data and the properties of the solution being evaporated (7). Evaporation rates of pure water are measured experimentally and are published by the National Weather Service. These are determined in small pans and must be reduced about 30% to yield rates experienced in large ponds or reservoirs. Rates must be reduced even further if the material has an appreciable BPR. For seawater saturated with salt, the resultant rate is only about half that of fresh water in small pans. This is of critical importance with substantial rainfall, because a net positive rate based on water in small pans may become a negative rate in large solar ponds containing brine. In solar salt plants the yield almost never approaches the yield expected from the evaporation accomplished. The principal cause is seepage of partially concentrated brine through the pond bottoms and dikes. This seepage has been the principal impediment to application of solar ponds to other uses, such as concentration of oil field brines and other waste streams. Laws require elimination of seepage to avoid groundwater contamination. The cost of providing the seepage barrier exceeds by far all other costs of solar pond development. Solar evaporation has also been used for the production of potable water from seawater. A barrier is required between the ponds and the atmosphere to admit the solar energy and to condense and collect the evaporated water. This barrier is even more expensive than a pond liner, making the method generally uneconomical. Yields are usually less than half the evaporation rates achieved in open ponds.

At the opposite extreme of fossil fuel usage are single-effect evaporative systems. Conventional steam-heated single-effect evaporators have been discussed. When the BPR is extremely high (as for manufacture of anhydrous NaOH), the evaporator may be heated by molten salt or other high temperature heat-transfer fluids instead of steam. The LTV-type evaporator is normally used in this service. Wiped-film evaporators also sometimes use these high temperature, low pressure heating media to achieve high ΔTs without need for very heavy heat-transfer wall thicknesses. The simplest single-effect evaporative method brings combustion gases into direct contact with the material being concentrated. A spray dryer can be used in this manner to concentrate liquids, and has been so used for high BPR liquids, such as $CaCl_2$. Less expensive in cost and more efficient in fuel consumption is the submerged combustion evaporator. In this case, the burner is immersed in the solution or slurry being concentrated and the combustion gases rise through the liquid to release almost all but the latent heat of the water in the combustion gases. Fuel may be either natural gas or the lighter distillate oils. Such evaporators are inexpensive and well adapted to handling corrosive and severely scaling liquids. They require no heat sink, but since the evolved vapor is mixed with large volumes of combustion gas they make it impractical to achieve much better than single-effect steam economy. These evaporators are impractical for all except very low capacities or the most refractory scale-forming or corrosive liquids.

Reverse osmosis (qv) is being used for some of the work previously only feasible by evaporation, such as concentrating dilute solutions that do not deposit solids on being concentrated. The limit is approximately that of recovering fresh water from seawater, where osmotic pressures to be overcome reach about 3600 kPa (520 psi). The choice here depends primarily on energy source. Reverse osmosis requires prime mechanical energy whereas evaporation systems frequently can make use of degraded energy, such as turbine exhaust steam. Evaporators have found applications at the other end of the spectrum, in concentrating waste streams to higher total solids contents and thus smaller volumes than possible by other methods, or to only solids, under the impetus of “zero liquid discharge” requirements. In some cases, this has required very large and efficient systems (6), but many waste streams are of such small volume that evaporators and solids handling techniques in use near 1900 are again appropriate.

Increasing energy costs have pushed optimum steam economy of evaporators higher and higher. This in turn has aided introduction of falling-film evaporators into more services because the heat-transfer performance does not degrade at the lower temperature differences then available. Higher costs of maintenance labor and demand for better onstream time have promoted use of more corrosion-resistant alloys. As an example, kraft-mill evaporators, which comprise a large share of the total steam-heated evaporation load in the United States, have gone from predominantly five- or six-effect mild steel LTV evaporators to eight- or nine-effect stainless steel falling-film evaporators, with appreciably higher single-unit capacities.

Some use is being made of lower grade heat sources, such as moist air from driers, and the construction of auxiliaries, such as condensers, integral with the evaporator body. A further step is elimination of the conventional condenser–cooling tower–vacuum pump circuit by recirculating last-effect liquor over the equivalent of a cooling tower built as an integral part of the evaporator body.

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16. N. Lior, ed., *Measurement and Control in Water Desalination*, Academic Press, Inc., New York, 1986.

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Related Articles

Dewatering; Drying; Heat-exchange technology; Steam