VERTICAL TUBE EVAPORATORS

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Summary

Multieffect evaporators with vertically oriented tubes make up by far the largest fraction of the world's evaporating capacity, being used in many large-scale industrial processes. Vertical tubes transfer heat from condensing steam or vapor to boiling liquid more efficiently than do horizontal tubes and this advantage is enhanced by the use of fluted tubes, which can more than double the rate of heat transfer. For seawater evaporation, a further important advantage is available through the addition of surfactants to the

boiling brine, producing thinner films and higher velocity foaming flow. In contrast to the multistage flash process, vertical tube multieffect evaporators for seawater are usually operated without recirculation and with a very small residence time for the brine within the process. These factors make the control of scale deposits much easier. For seawater, adding the make-up or feed to the high temperature end (forward feed) permits operation at higher temperatures and with higher recovery rates without risk of scale precipitation. Vertical tube desalination evaporators have been demonstrated in small units, which are usually arranged with the effects placed side by side. However, a recent study of a 75 mgal day^{-1} design showed that a vertical tower arrangement could drastically reduce the volume of the plant and the land required, with resulting lower costs.

1. Introduction

Multiple-effect vertical tube evaporators have been widely used for approximately 150 years. They were first developed in the sugar industry and then spread to salt refining, the chemical industry and petroleum refining. In desalination, vertical tubes were first adopted as an adjunct of vapor compression plants, which gave a high efficiency in a more compact system, but they were slow to be tried in thermal distillation seawater plants.

Although vertical tube evaporators were the standard and mainstay of the chemical and sugar industries, the great success of the multistage flash process in solving the scale-formation problem made the desalination industry wary of any other process.

In its broad-ranging research and development program, the US Office of Saline Water (OSW) finally built the first large multiple-effect vertical tube evaporator for seawater at Freeport, Texas in 1961. This 1 million gallon per day (mgal day^{-1}) (3800 m^3 day^{-1}) demonstration plant was proposed and designed by W.L. Badger Associates, Inc., an engineering firm specializing in evaporators for the chemical industry.

After the OSW had both its vertical tube and flash plant demonstrations running, they attempted to assess the two processes for their relative performance cost. This work was done by Bechtel Corporation, who reported that the flash unit was slightly superior. Later, after the OSW had decided to concentrate on flash plant development, a new analysis of the Bechtel report by the Oak Ridge National Laboratory (ORNL) showed that an error in arithmetic had actually reversed the standings of the two processes.

The OSW did not change its emphasis on flash units, but provided support for the ORNL to continue the technical development and systems analysis of vertical tube plants for several years. This work was published in a series of technical reports and led to some interest in industry. Six commercial vertical tube plants were built: three in the US Virgin Islands in 1968 and 1976, one in Japan in 1971, one in Gibraltar in 1973, and one in Abu Dhabi, UAE, in 1980. These plants were constructed using conventional practices of the chemical industry and did not make much use of the ORNL studies. Only lately has some of this advanced knowledge been put to use.

The OSW also supported work initiated in 1966 on vertical tube heat transfer enhancement at the University of California utilizing imposed vortex flow and induced foamy flow by the addition of a synthetic surfactant to increase the evaporation-side heat transfer coefficient substantially. This work led to the design, construction and testing of a 1.3 mgal day^{-1} prototype plant in 1983. Built in former West Germany, it was mounted on a sea-going barge and used several advanced concepts, including 24 upflow effects with double-fluted vertical tubes and surfactant-induced heat transfer enhancement.

1.1. Advantages of the Vertical Tube Process

All multiple-effect processes have a thermodynamic advantage over the flash process because the boiling brine does not change in temperature within the effect; that is, the temperature difference from steam to brine is constant everywhere. This contrasts with the flash process, where the brine being heated has a varying temperature difference from inlet to outlet of the stage.

Another multiple-effect advantage is that heat transfer coefficients are substantially higher. The overall coefficients for steam to thin-film boiling brine exceed those for steam to liquid-filled tubes of the flash process by 30-50 per cent, so that less heat-transfer surface is required. The use of surfactants (described below) markedly increases this advantage.

These processes are also capable of recovering as product a higher proportion of the incoming seawater than the flash process does. This means that the pre-treatment costs are lower. Vertical tube evaporators are usually operated once-through without recirculation, a valuable simplification. In turn, once-through operation produces another advantage: with forward feed (described below) the tendency to form destructive scale on the heating surfaces, which is a function of both temperature and concentration, is minimized throughout the plant.

The outstanding advantage of all, however, is unique to vertical tube evaporators, that is the ability to make use of fluted tubes. This innovation more than doubles the performance of the tubes, so that major savings are achieved both in heat transfer surface and in the evaporator shells that house them. This advantage is so compelling that it is unlikely that any new vertical tube plant will use smooth tubes. Recent work in both the desalination industry and in the chemical industry has demonstrated the performance and cost advantage of fluted tubes, so that the future is likely to see many new evaporator installations adopting this process. Because of their importance, fluted tubes are discussed in some detail in Section 4.

2. Feed Heating and Feed Control

2.1. Forward and Backward Feed

Of the energy required to produce distilled seawater, more than 15 per cent is used to heat the feedwater to the boiling point where evaporation can begin. In the chemical industry, where products much more valuable than distilled water are made, the custom is to heat the feed by letting it mix with the boiling charge in the evaporator and accept the loss in thermal efficiency that this entails. In desalination, where the product is worth only a few cents per ton, every opportunity to lower the energy consumption is explored, including regenerative heating of the feed. In an imaginary superefficient plant there would be an infinite number of effects and a tiny amount of steam would be taken from each effect in turn to heat the feed an incremental amount, starting at the lowest temperature effect.

In practice, of course, there are a finite number of effects and the feed is heated in bigger steps. The means for regenerative heating depends upon the type of feed flow chosen. There are two ways to add feedwater to a multieffect process, called forward feed and backward feed. In forward feed the seawater to be distilled is added to the highest temperature effect and proceeds to lower and lower temperature effects for partial evaporation in each. In backward feed the water is added to the lowest temperature effect and after partial evaporation is pumped to each higher temperature effect in turn. Figure 1 illustrates the flow arrangements for forward and backward feed.

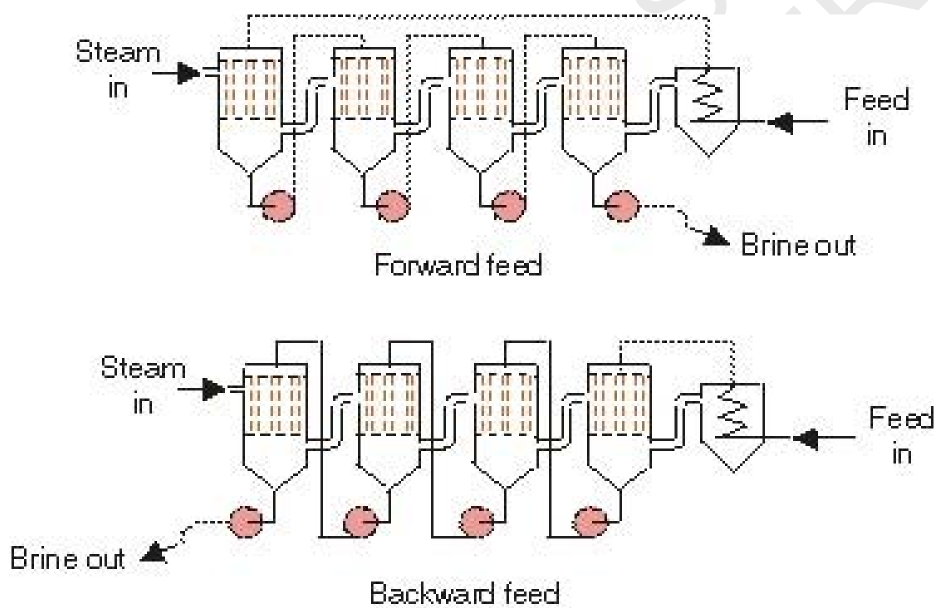

Figure 1. Types of feed for vertical tube evaporators.

Backward feed, particularly with a large number of effects, is a close approximation of efficient regenerative heating, in that the energy extracted to heat the feed is only slightly warmer than the feed it is heating. No special feed-heating equipment is needed, the required thermal energy being provided by increasing the capacity of the individual effect bundles by approximately 15 per cent.

To accomplish this same result in forward feed, the main bundles are not increased in size, but instead separate closed heat exchangers must be provided for each effect. This is always somewhat more costly to construct than the backward feed option, but there are important compensating advantages in desalination evaporators. Foremost of these is that, with forward feed and external heaters, the scale-forming tendency is minimized, since the seawater entering the highest temperature effect is at normal seawater salinity.

As the brine passes from effect to effect its concentration increases, but at the same time the temperature decreases. As will be discussed in Section 5, the result is to enable the process to operate at top temperatures that would be impossible with backward feed and yet stay comfortably clear of the region of scale formation.

2.2. Mixed Feed

In some evaporators mixed feed is used, wherein groups of effects are fed in parallel and their discharge pumped to another group. This is done primarily to reduce the number of pumps required. Another type of mixed feed, called split feed or tapered feed, has the purpose of achieving the highest possible thermal efficiency. This system is very similar to forward feed, in that the feed passes through heat exchangers exposed in turn to successively higher temperatures. The difference is that part of the feed stream is split off at each effect and added to the brine in that effect. The amount added is approximately equal to the amount that will be evaporated in that effect. In this way, all effects have the same amount of flow through the tubes and none of the feed has to be heated any hotter than the effect in which it will be evaporated. This is a closer approach to the thermodynamic ideal of a reversible system. The split feed system increases the yield of distillate from the same amount of energy and also requires less feed-heater surface. So far this is a theoretical concept, tested only with computer models. The gain in output is less than 4 per cent and the controls required are complex. Most of the gain is obtained with only one or two split feed points.

2.3. Feed Control

Controlling the feed is one of the most important functions in operating an evaporator. The feed rate to each effect must be maintained above the rate at which some tubes would be starved of liquid and would develop dry spots. These would pose an immediate danger of solid scale deposits, which are hard to detect and harder to remove. If not removed promptly they lead to corrosion and tube failure. At the other extreme, too great a feed rate wastes energy and pre-treatment chemicals.

The feed rate must be matched to the supply of heating steam sent to the first effect and to the amount of heat transfer surface installed, as well as to the salt concentration desired in the final brine discharge. Thus, feed control cannot be managed independently in normal operation. The objective is to maintain the brine concentration in each effect at a level that assures the solubility limit of calcium sulfate is not exceeded. In start-up and shut-down of the plant, however, the feed rate will have a different set of control parameters, as discussed below.

2.4. Feed Control during Start-up and Shut-down

A multiple-effect evaporator in steady operation represents a complex equilibrium between the heat flowing into the top effect and the cold seawater entering the bottom. The plant finds these equilibria easily and automatically without special controls, but the final conditions must be approached somewhat gradually at start-up, because little evaporation is occurring. In some plants, feed flows must be started well below the final value to prevent excessive brine levels. As start-up progresses with increased steam flow being applied, the feed flow is then progressively increased in order to maintain the residual brines in the series of effects within the calcium sulfate solubility limits.

During shut-down, steam flow is shut off, but the feed flow into the first effect is continued at decreasing rates to prevent excessive brine levels in the lower effects while still maintaining feed concentrations below the scaling limits.

2.5. Condenser Control

The source of feed in a desalination evaporator is usually seawater that has first been used to cool the final condenser. This saves energy since it already has one increment of heat added. In general, the condenser flow is kept somewhat greater than the feed flow desired, so that some of the condenser flow is discharged back to the sea and the remainder becomes the feed stream. This is done primarily to increase plant output, since the available heating steam is usually constant in amount and temperature.

The greater condenser flow lowers the bottom temperature of the effects and increases the available temperature difference across each effect. In some plants where a constant water output is desired winter and summer, the condenser flow is increased as the sea temperature rises in the summer, to counteract what would otherwise be a loss in production.

3. Upflow versus Downflow

The discussion of vertical tube evaporators has so far assumed that the brine is fed to the top of the tube and travels down the inside wall while boiling. This mode of operation is called downflow or "falling film" operation, with two ways of circulating brine. In once-through operations the entering feed is distributed and passes down the tubes once, usually with no pump required. In some cases a small pump may be needed to transfer the feed to the next effect. In the recirculation mode, a pump in each effect continuously transfers brine from a receiver below the tubes to the distribution plenum above them. Part of this flow is diverted to transfer feed to the next effect in line.

This falling film mode is the most common choice for seawater desalination. However, many evaporators in the chemical industry and some used for seawater are operated in upflow or "rising film" mode. In this arrangement there is no pump to deliver the feed brine to the top of the tube bundle. Instead the feed is delivered to the bottom of the tubes and pumps itself by using the vapor produced in boiling as a gas-lift medium.

In upflow, the feed is admitted to a water box located below the lower tube sheet of the evaporator bundle, enters the lower part of the heating tube, and boils as it passes upward to discharge from the top into a receiving chamber. The vapor and brine produced are separated and then treated just as in any other multiple-effect evaporator.

There are two ways of controlling a rising film effect. In one, the feed liquid is maintained at a constant level in the bottom of the evaporator, such that under a quiescent state approximately 20-30 per cent of the tube length is filled. As the warm wall heats the liquid, it begins to boil and fill with steam bubbles. The frothy vapor-liquid mixture expands rapidly to fill the tube. As it does, more heating occurs through the thin rising film and the tube "fires" or empties itself explosively into the chamber above the upper tube plate. More liquid enters the bottom and the process repeats. All the tubes thus fire randomly to produce an overall steady generation of vapor and a steady pumping of liquid uphill. The discharge chamber can be arranged so that liquid returns to the waterbox in a down-comer for recirculation or it is diverted to another effect.

In a second method, the entrance to each tube at the bottom is partially constricted by an orifice. This has the effect of damping the violent, sudden discharge and instead creates a steadier foaming flow. This steady mode of boiling is desirable since all the tube length is receiving rapidly moving film flow all the time, instead of intermittently. The process is assisted by using forward feed, in which the entering liquid is slightly superheated and flashes as it passes through the constricting orifice. The presence of a synthetic surfactant further stabilizes this mode by imposing foamy vapor-liquid flow. The rapidly moving foam reduces the liquid hold-up in the tubes by approximately 80 per cent and increases the liquid-side heat transfer coefficient (HTC) as much as four-fold, as discussed below.

Both upflow and downflow modes of operation are quite efficient thermally and easy to control. The choice between them is influenced by several factors. The work done in pumping the liquid of course consumes energy, which shows up in a reduction of the available temperature difference within the upflow evaporator. Thus, the trade-off is in extra heating surface and thermal input against the capital cost and power used by an interstage pump. Unfortunately gas-lift pumping is not very efficient, but the simplicity of fewer moving parts can be important. The addition of a synthetic surfactant to induce foaming markedly improves the performance of both modes, as discussed below.

In cases where the feed must enter at a temperature below the boiling point (subcooled) or where the temperature difference per effect must be very small, the falling film system would be preferred. The upflow gas-lift may not be competitive with pumps in a dual-purpose plant, where steam is first used to generate power then used in series to heat the desalination plant. In such an arrangement, the pumping power is obtained at essentially 100 per cent efficiency. Another factor is that below approximately 65°C (150°F) the steady upflow mode is difficult to start and maintain and higher ΔTs (temperature differences) are required.

4. Fluted Tubes for Vertical Evaporators

Heat transfer engineers have long known that steam condenses much more efficiently on some surfaces than on others. Most ordinary metal surfaces are "wetted" by the condensate, so that a continuous film of liquid remains attached to the surface and is replaced even as it drains away. The thermal resistance of this condensate film is a substantial barrier to heat conduction into the metal wall. On some surfaces, however, the condensate does not form a film but collects in small droplets that coalesce and drain rapidly, leaving much of the surface bare. Many additives and surface treatments have been tried to make this "dropwise" condensation repeatable and reliable, but none that worked have seemed to be worth their cost.

In 1954 a Swiss engineer, R. Gregorig, published his studies of a new method for enhancing condensing surfaces (Gregorig 1954). He showed that merely adding vertical grooves to a vertical condensing surface would remove the film barrier through the use of surface tension. Further study has shown the details of this powerful mechanism (described in Section 4.2).

Gregorig (1954) studied only the condensing surface, using grooves machined into the wall of a flat plate or tube. With most metals, however, it is less costly to manufacture a fluted tube by pressing or forming waves into both sides, as shown in Figure 2. It was soon found that these inside flutes also improved evaporator performance, so that today a fluted evaporator tube usually has flutes or grooves on both the condensing side and the boiling side. It is called a "double-fluted" tube and was first produced commercially by the General Electric Company.

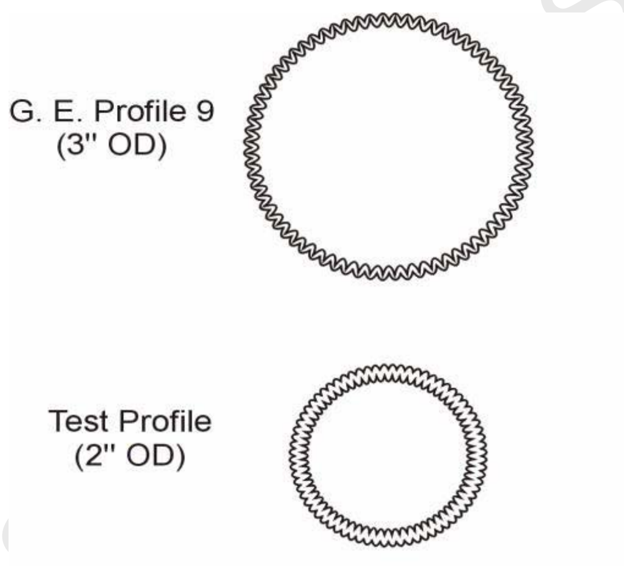

Figure 2. Profiles of fluted tubes.

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