Chapter 22

Heat Integration of Evaporators and Dryers

22.1 The Heat Integration Characteristics of Evaporators

Evaporation processes usually separate a single component (typically water) from a nonvolatile material, as discussed in Chapter 9. As such, it is good enough in most cases to assume that the vaporization and condensation processes take place at constant temperatures.

As with distillation, the dominant heating and cooling duties associated with an evaporator are the vaporization and condensation duties. As with distillation, there will be other duties associated with the evaporator for heating or cooling of feed, product and condensate streams. These sensible heat duties will usually be small in comparison with the latent heat changes.

Figure 22.1a shows a single-stage evaporator represented on both actual and shifted temperature scales. Note that in the shifted temperature scale, the evaporation and condensation duties are shown at different temperatures even though they are at the same actual temperature. Figure 22.1b shows a similar plot for a three-stage evaporator.

Like distillation, evaporation can be represented as a box. This again assumes that any heating or cooling required by the feed and concentrate will be included with the other process streams in the grand composite curve. However, with evaporation, the temperature difference across the box can be manipulated by varying the heat transfer area. Increasing the heat transfer area between stages allows a smaller temperature difference between stages and hence a smaller overall temperature difference, and vice versa.

22.2 Appropriate Placement of Evaporators

The concept of the appropriate placement of distillation columns was developed in the preceding chapter. The principle also applies to evaporators. The heat integration characteristics of distillation columns and evaporators are very similar. Thus, evaporator placement should not be across the pinch (Smith and Linnhoff, 1988).

22.3 Evolving Evaporator Design to Improve Heat Integration

The thermodynamic profile of an evaporator can also be manipulated. The approach is similar to that used for distillation columns. The degrees of freedom are obviously different (Smith and Linnhoff, 1988; Smith and Jones, 1990).

Consider the three-stage evaporator against a background process, as shown in Figure 22.2a. At the chosen pressure, the evaporator will not fit against the grand composite curve. The most obvious possibility is to first try an increase in pressure to allow appropriate placement above the pinch (Figure 22.2b).

Now suppose that the required increase in pressure in Figure 22.2b would cause unacceptably high levels of decomposition and fouling in the evaporator as a result of the increase in temperature. The possibility of increasing the number of stages from three to, say, six could now be considered in order to allow a fit to the grand composite curve above the pinch (Figure 22.3a). The evaporator fits, but there still might be a problem of product degradation because of high temperatures. However, it is not necessary for all evaporator stages to be linked thermally with each other. Instead, Figure 22.3b shows a six-stage system with three effects appropriately placed above the pinch and three below. This could be either a conventional six-stage system in which the first three and last three stages are not linked thermally or,

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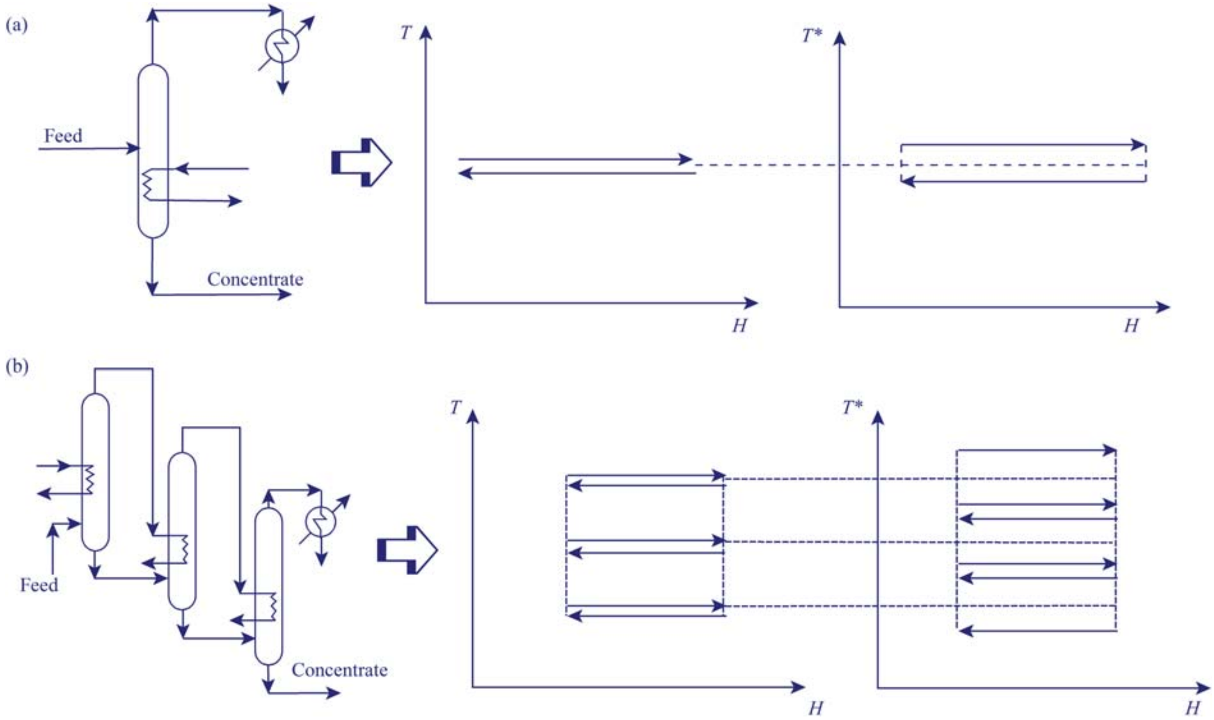
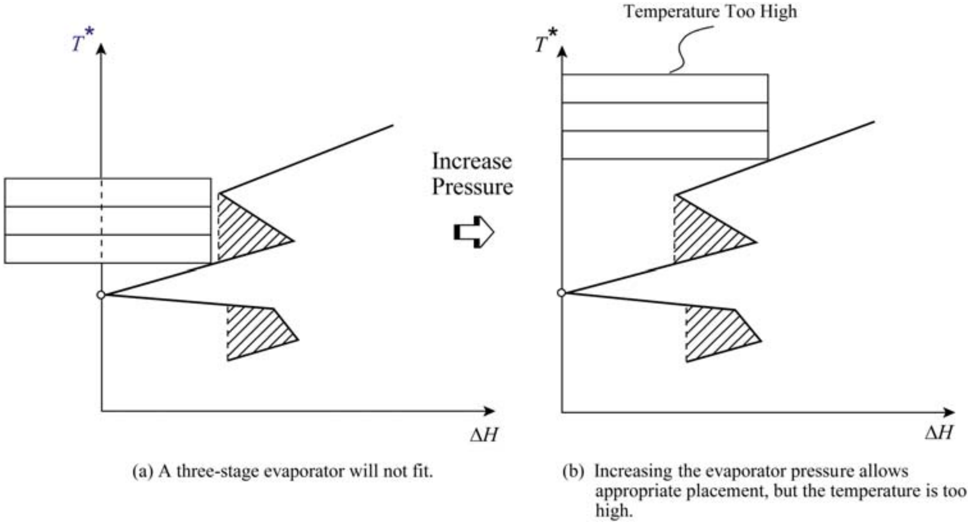


Figure 22.1

The representation of evaporators in shifted temperatures. (Reproduced from Smith R and Jones P.S (1990) The Optimal Design of Integrated Evaporation Systems, *J Heat Recovery Syst CHP*, **10**: 341, with permission from Elsevier.)

alternatively, two parallel three-stage systems, analogous to double effecting in distillation.

Yet another design option is shown in Figure 22.3c in which the heat flow (and hence mass flow) is changed between stages in the evaporator. Figure 22.3c shows an arrangement in which part of the vapor from the second stage is used for process heating rather than evaporation in the third stage. This means that more evaporation is taking place in the first two stages than the third and subsequent stages. It should be noted that even if the heat flow through the multistage evaporator is constant, the rate of evaporation will decrease because the latent heat increases as the pressure decreases.



(a) A three-stage evaporator will not fit.

(b) Increasing the evaporator pressure allows appropriate placement, but the temperature is too high.

Figure 22.2

Integration of a three-stage evaporator.

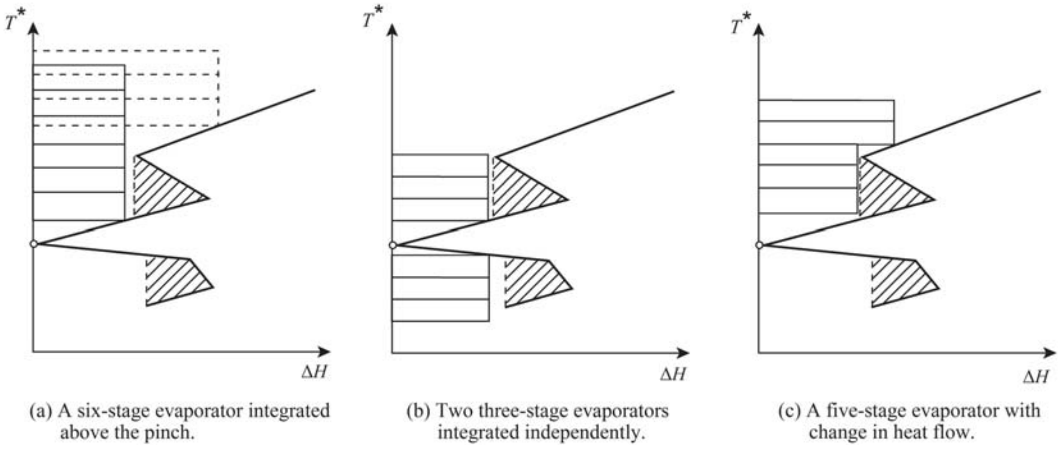


Figure 22.3

Evaporator design with the help of the grand composite curve. (Reproduced from Smith R and Linnhoff B, 1998, *Trans IChemE ChERD*, **66**: 195 by permission of the Institution of Chemical Engineers.)

If the evaporator cannot be integrated with the rest of the process because of the heat duty or constraints, another option is to use heat pumping. As with heat pumping in distillation, heat pumping of evaporators only makes sense if the evaporator cannot be integrated or must operate across the pinch. In practice, in many processes where there is a large evaporator duty, the pinch is caused by the evaporator vaporization and condensation duties. In such a situation heat pumping can make sense, because heat pumping around the evaporator also heat pumps around the pinch (see Case Study in Section 22.6). This will be most often vapor recompression, in basically the same arrangement as distillation. The evaporated vapor, which is very commonly water vapor, is compressed and used in the vaporization, as illustrated in Figure 22.4. Figure 22.4 illustrates a *mechanical vapor recompression*. For water evaporation, a steam ejector can also be used for the compression in *thermal vapor recompression*. Although Figure 22.4 shows a single-stage evaporator with a mechanical recompression, multiple stages can be combined with heat pumping and many different configurations are used.

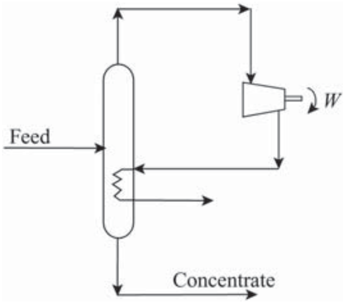


Figure 22.4

Evaporator mechanical vapor recompression.

22.4 The Heat Integration Characteristics of Dryers

The heat input to dryers, as discussed in Chapter 9, is to a gas and, as such, it takes place over a range of temperatures. Moreover, the gas is heated to a temperature higher than the boiling point of the liquid to be evaporated. The exhaust gases from the dryer will be at a lower temperature than the inlet, but again the heat available in the exhaust will be available over a range of temperatures. The thermal characteristics of dryers tend to be design specific and quite different in nature from both distillation and evaporation. Figure 22.5 illustrates the heat integration characteristics of a typical dryer.

22.5 Evolving Dryer Design to Improve Heat Integration

It was noted that dryers are quite different in character from both distillation and evaporation. However, heat is still taken in at a high temperature to be rejected in the dryer exhaust. The appropriate placement principle, as applied to distillation columns and evaporators, also applies to dryers. The plus–minus principle from Chapter 19 provides a general tool that can be used to understand the integration of dryers in the overall process context. If the designer has the freedom to manipulate drying temperature and gas flowrates, then these can be changed in accordance with the plus–minus principle in order to reduce overall utility costs.

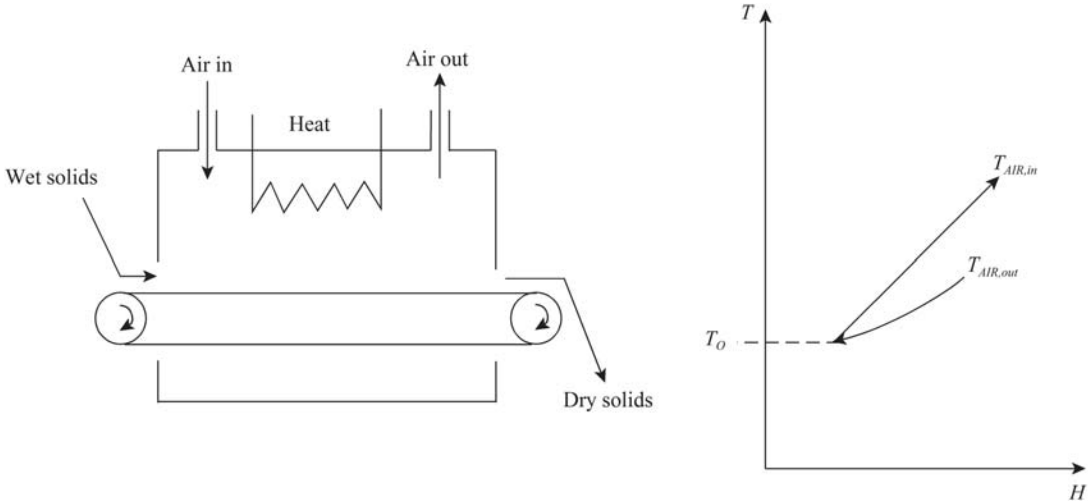
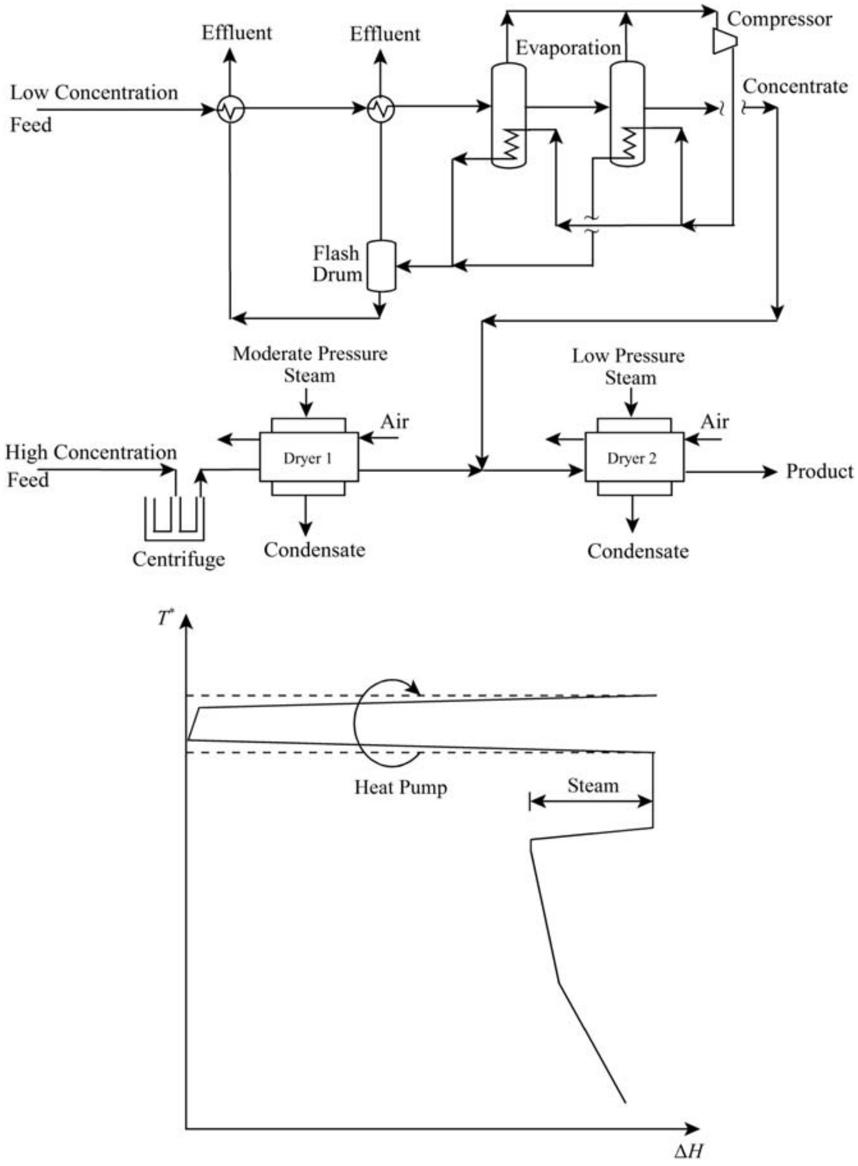


Figure 22.5

The heat integration characteristics of dryers.

Figure 22.6

A plant for the production of animal feed. The heat pump encroaches into a “pocket” in the grand composite curve. (Reproduced from Smith R and Linnhoff B, 1998, *Trans IChemE ChERD*, **66**: 195 by permission of the Institution of Chemical Engineers.)



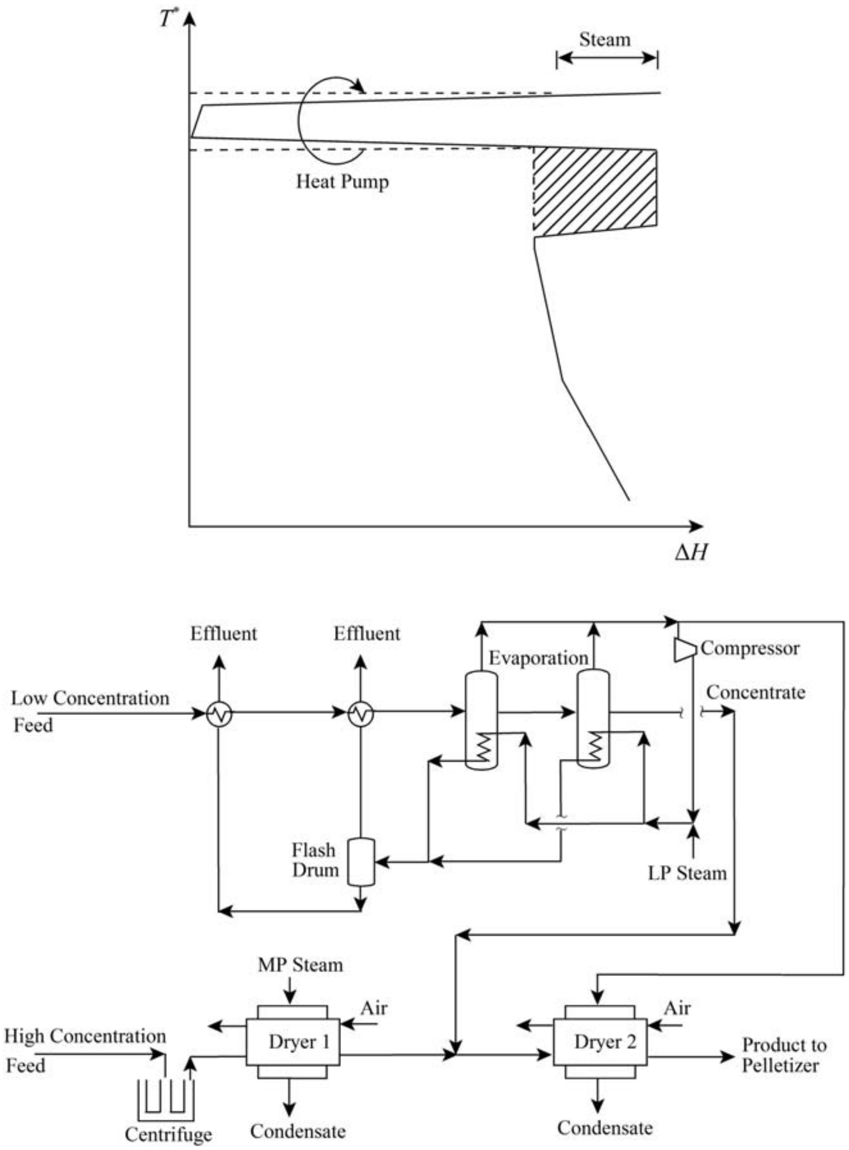


Figure 22.7

A simple modification reduces the load on the heat pump, saving electricity. (Reproduced from Smith R and Linnhoff B, 1998, *Trans IChemE ChERD*, **66**: 195 by permission of the Institution of Chemical Engineers.)

22.6 A Case Study

Figure 22.6 shows a plant for the production of animal feed from spent grains from a food process. The plant has two feeds, one of low and one of high concentration solids. Water is removed from the low concentration feed by an evaporator, followed by a rotary dryer. Water is removed from the high concentration feed by a centrifuge, followed by two stages of drying in rotary dryers. As is usual with this type of plant, the evaporators and dryers have been designed on a stand-alone basis without consideration of the process context. Optimization of the evaporator on a stand-alone basis has indicated that heat pumping using a mechanical vapor recompression system would be economic.

Figure 22.6 shows the grand composite curve for this process and the location of the evaporator heat pump. The heating duty for the first dryer has been omitted from the grand composite curve, since the required temperature is too high to allow integration with the rest of the process. The heat pump can be seen to be appropriately placed across the pinch. However, the cold side, below the pinch, encroaches into a pocket in the grand composite curve. If the design of the heat pump is changed so as not to encroach into the pocket, the result shown in Figure 22.7 is obtained. The resulting steam consumption is virtually unchanged, but energy costs will be lower. This results from the reduced load on the heat pump leading to a reduction in electricity demand.

22.7 Heat Integration of Evaporators and Dryers – Summary

Like distillation, the appropriate placement of evaporators and dryers is that they should be above the pinch, below the pinch, but not across the pinch. The grand composite curve can be used to assess appropriate placement quantitatively.

Also like distillation, the thermal profile of evaporators can be manipulated by changing the pressure. However, the degrees of freedom in evaporator design open up more options.

Table 22.1

Problem table cascade for the background process.

T^*(°C)	ΔH(kW)
211	0
191	2800
185	3280
171	2580
125	4880
105	2880
95	2680
80	4330
60	4930
51	4480
45	3580

Dryers are different in characteristic from distillation columns and evaporators in that the heat is added and rejected over a large range of temperatures. Changes to drier design can be directed by the plus–minus principle.

22.8 Exercises

1. Table 22.1 presents the problem table cascade data for a process for $\Delta T_{\text{min}} = 10\,°\text{C}$.

   An evaporation process is to be integrated with the process. The evaporator is required to evaporate $1.77\,\text{kg·s}^{-1}$ of water. The latent heat of vaporization of the water can be assumed to be $2260\,\text{kJ·kg}^{-1}$ and to be constant. Cooling water is available at 25 °C to be returned to the cooling tower at 35 °C. Suggest an outline evaporator configuration that will allow heat integration of the evaporator with the background process.

References

Smith R and Jones PS (1990) The Optimal Design of Integrated Evaporation Systems, *J Heat Recovery Syst CHP*, **10**: 341.

Smith R and Linnhoff B (1988) The Design of Separators in the Context of Overall Processes, *Trans IChemE ChERD*, **66**: 195.