Scaleup of Agitated Thin-film Evaporators

Process-design, mechanical-design and physical-property parameters must all be taken into account

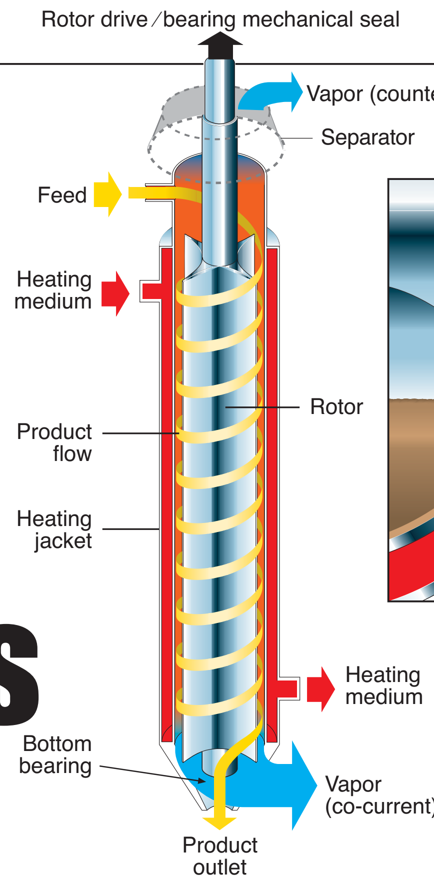

FIGURE 1. The key elements of a vertical thin-film evaporator are shown here

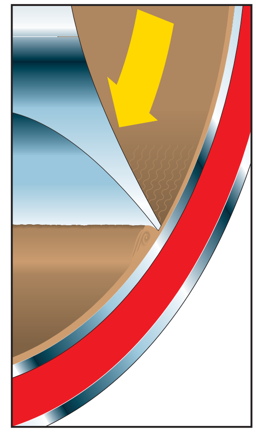

FIGURE 2. The rotor blades not only deposit the liquid on the wall, but also promote turbulence in the liquid layer

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Agitated thin-film evaporators are attractive for the concentration, distillation, stripping or deodorization of liquids in a broad variety of chemical-process-industries (CPI) applications where the process streams are temperature sensitive (and must have only brief exposure to heat), viscous, or tend to foul or foam. When this type equipment does seem to be the right choice in a given situation, the common, and sound, approach is to ask an evaporator manufacturer to conduct an evaluation and make an equipment quotation. The quality of such an evaluation will depend on the type and quality of the data that the manufacturer receives from the potential customer's engineers; and, perhaps to some extent, on those engineers' familiarity with the evaluation process itself.

The thin-film process

That familiarity begins with an understanding of what a thin-film evaporator is and how it works. A vertical thin-film evaporator consists of two major assemblies: a heated body and a close-clearance rotor (Figure 1). The process fluid enters the unit tangentially above the heated zone, and is distributed evenly over the inner surface of the body wall by a distribution ring mounted on the rotor. The rotor blades spread the product over the entire heated wall, and generate highly turbulent flow conditions in the thin layer of liquid (Figure 2).

The product spirals down the wall, while the turbulent conditions developed by the rotor blades generate optimal heat flux, rapidly evaporating volatile components. The resulting vapors flow upward through the unit into a centrifugal separator, which returns entrained droplets or froth directly back to the heating zone. Clean vapors pass through the vapor outlet ready for condensing or further processing. Meanwhile, the concentrated liquid stream leaves the evaporator through its bottom conical outlet. Continuous washing by the bow waves generated by the rotor (Figure 2) minimizes surface fouling of the thermal wall, where the concentrated liquid or residue is most prevalent.

Thin-film evaporators are commercially available in various basic or standard versions. They can have vertical or horizontal designs, with cylindrical or tapered bodies and rotors. The rotor can employ any of several zero-clearance designs, or a rigid fixed-clearance design, or an adjustable-clearance type. The basics for scale-up from the manufacturer's pilot testing program are the same or similar for all.

The evaluation procedure

The goals of a pilot testing program should include the maximum heat and mass transfer and product yield and quality (purity, color, other parameters), coupled with a minimization of operating cost (mainly energy consumption) and of capital cost (evaporator size). One key goal is to determine the minimum heat-transfer surface needed. The pilot-scale evaporator should be large enough for all the important factors to be evaluated, yet small and simple for economy.

The parameters to be considered during testing and scale up are those of process design (usually partially fixed by the end-product specifications), mechanical design (the physical configuratoion of the evaporator), and the physical properties of the process fluid. These parameters are interrelated: the value of a given parameter can affect the values of other parameters, as well as the overall performance of the evaporator.

The process design parameters include the degree of separation or concentration required, the feedrate and temperature, the operating pressure, and the type and temperature of heat transfer fluid (the heating medium).

The mechanical design parameters are the required materials of construction, material thickness, rotor speed, rotor clearance, body inside diameter and length, and liquid and vapor rates. Aso relevant here are the aforementioned operating pressure and type and temperature of the heating medium.

Among the needed physical-property parameters are the latent heat of vaporization, viscosity, thermal conductivity, specific heat and density, of both the heating medium and the process fluid. Additional process-fluid data needed are its solids content, fouling tendencies, thermal sensitivity, and foaming characteristics.

Either pilot testing or available data from already-operating plants is almost always required to determine the optimal heat-transfer area required. Typical variables investigated during testing are feed temperature, feed rate, internal operating pressure, rotor speed, and heating temperature. After a test run, product samples are taken and analyzed to see how well they conform with specifications. Once the conditions that give the required product specifications have been confirmed, the process can be scaled up to commercial requirements.

Heat transfer calculations

For that scaleup, the engineers need to know the overall heat transfer coefficients obtained in the agitated thin-film evaporator during testing. The process-related heat duty is first obtained, by calculations from the product properties and the test data. It consists mainly of the sensible heat needed to bring the feed to the initial boiling point, the latent heat needed to boil up the feed, and the superheat for any boiling-point rise as the liquid becomes concentrated. Next, the scaleup involves the basic equation for the transfer of heat by means of convection and conduction between two media separated by a wall:

$$Q = UA\Delta T_L \quad (1)$$

where: Q, the heat duty, is fixed by process requirements as just described; U, the overall heat transfer coefficient, depends on the physical properties of the process material and heating medium and the mechanical configuration of heat transfer device; A is the heat transfer area; and ΔT_L, the logarithmic mean temperature difference, is fixed by the inlet and exit temperatures. The value of ΔT_L is affected by the internal operating pressure (which changes the boiling points of the volatile materials) and the inlet and outlet temperature of the heating medium.

Likewise, based on Fourier's Law, U is a function of the resistances to the flow of heat from the heating medium to the product. These resistances generally consist of the inner product film, inner fouling factor, the metal wall of the vessel, the outer fouling factors, and the outer heating medium film. Proper design, plus the cleanliness of the heating-medium system and the cleaning effect of the agitated thin-film evaporator rotor, generally allows neglecting the fouling factors, so the relationships simplifies to the well-known equation:

$$1/U = 1/h_o + t/k + 1/h_i \quad (2)$$

As just discussed, the value of U can be calculated from data developed during the pilot plant testing. From the mechanical configuration of the test evaporator and the heating medium used, and from conventional calculations for fluid flow and heat transfer, the outside film coefficient, h_o, can be calculated. Since the thickness, t, and thermal conductivity, k, of the wall material are readily available, the inside heat transfer coefficient, h_i, obtained during pilot testing can be calculated straightforwardly from Equation (2).

From scaleup factors developed by vendors over many years of testing and operating commercial evaporators, the inside heat transfer coefficient, $h_{i,2}$, to be expected in the full-size evaporator can be calculated (the subscripts 1 and 2 refer, respectively, to the pilot-scale and full-scale evaporator):

$$h_{i,2} = fh_{i,1} \quad (3)$$

Finally, knowledge of the mechanical design of the larger evaporator and the heating medium to be used allows the calculation of the heating-wall resistance, t_2/k_2, and the outside heat transfer coefficient, $h_{o,2}$. From these values, U_2 for the full-scale evaporator can be calculated from Equation (2). Finally, with the use of U_2, the required area, A_2, for the full-scale evaporator can be calculated from Equation (1):

$$A_2 = Q_2/U_2\Delta T_{L,2}$$

The benchtop option

For commercial scaleup, the minimum size used for testing is conventionally about 0.1 to 0.13 m^2. In most cases, a unit of this size has the same physical configuration as, and is heated with the same heating medium as, the forthcoming full-scale plant. Feed rates for a pilot plant of this size are about 20–70 kg/h, and the units need many hours of running time to allow for stabilization between process changes, in order to get accurate prod-

NOMENCLATURE

Q = Heat transfer rate (duty), W
U = Overall heat transfer coefficient, W/(m^2)(K)
A = Heat transfer surface (wall) area, m^2
ΔT_L = Log mean temperature difference between process and heating streams, K
h_o = Film coefficient for heating medium outside wall, W/(m^2)(K)
h_i = Film coefficient for process fluid inside heating wall, W/(m^2)(K)
t = Heating wall thickness, m
k = Heating wall thermal conductivity, W/(m)(K)
f = Scaling factor for h_i

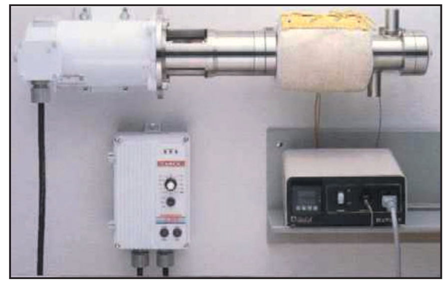

FIGURE 3. Small-scale benchtop evaporators, such as this one, have several advantages (as well as some limitations) for testing and scaleup

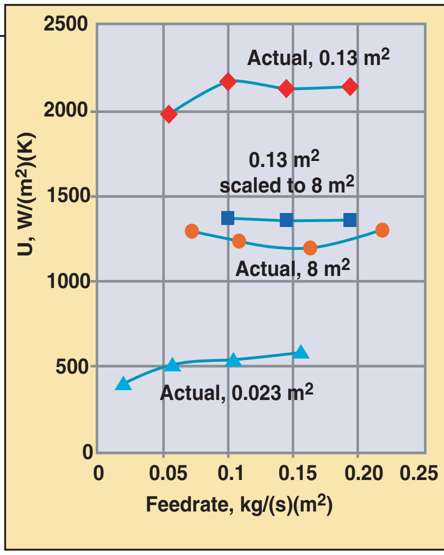

FIGURE 4. Here are heat-transfer coefficients with water as the feed, determined on benchtop, pilot-plant and full-scale commercial thin-film evaporators

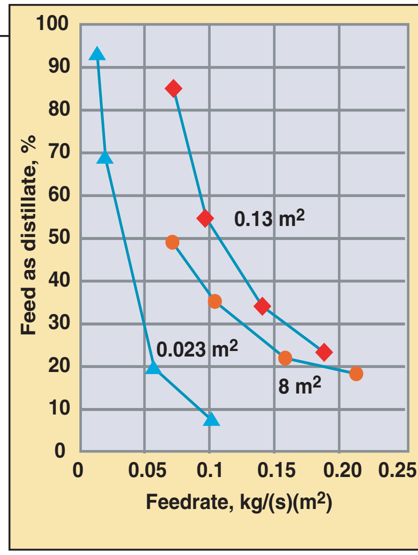

FIGURE 5. Confirming the conclusion conveyed by Figure 4, the concentration ratios on identical feed differ across benchtop, pilot and full-scale units

uct samples. This sequence requires a large amount of feed.

Nowadays, however, the need for such pilot-scale (not to mention fullscale or semiworks) testing is undergoing much more scrutiny, due to: the escalating costs of equipment and its installation and operation, today's ever-shorter business and time-to-market cycles, and environmental compliance. Companies have become much more selective about how, when, and to what degree their processes should be pilot-plant tested. The type of the process, type of product, available data, and experience with similar processes usually dictate the amount and type of testing needed to provide enough information for a process design and scaleup.

If a project is at a preliminary stage and only its feasibility is in question, a benchtop-sized thin film evaporator can provide much information. One such unit appears in Figure 3. This unit has 0.023 m^2 of heat transfer surface, is heated electrically by a resistance type heating mantle, and requires only 1 to 7 kg/h of feed.

Benchtop equipment can be installed relatively inexpensively in a small area. Other major advantages include these:

- Only minimal feed needed for testing (this feature is particularly attractive during initial development, when only laboratory-produced quantities may be available)
- Little labor needed to operate the system
- Minimal production of byproduct waste material
- Faster installation of the test system
- Faster development of the process
- Ability to provide initial operational parameters
- Ability to demonstrate the process feasibility
- Ability to uncover some process limitations

On the other hand, there are also some limitations of benchtop evaporators, especially when processing viscous, fouling, foaming, temperature-sensitive, or high-boiling products:

- Optimization of a process may not be practical from the benchtop data
- The scaledown of equipment to miniature size may distort critical operating behavior; examples include vapor/liquid flow, heat transfer and pressure drop
- Care must be given as to how any developed information is interpreted, and how it is used to predict behavior of larger pilot plant, semiworks, or commercial scale processes
- Lines might plug when tubing or very-small-diameter pipe is used.
- Lines may freeze up, because tracing or insulation is in many cases difficult or impractical
- Materials transport at small scale is difficult
- Instrument scaledown is difficult, and errors in measuring devices can be significant.

Besides these general limitations, additional cautions with benchtop units should be kept in mind when the purpose of the full-scale plant involves either distillation or liquid concentration:

- The heat flux is restricted to the maximum electrical rating of the heating mantle and/or the inability to effectively trace or jacket small surfaces.
- Heat transfer coefficients are reduced by the air-gap/contact area of heating mantles
- Liquid and vapor flow restrictions are greatly increased, due to the mechanical design limitations with getting an agitator into the small diameter of the heating zone. Such restriction can affect the hydraulic capability and limit the internal operating pressure
- Power-consumption predictions can be skewed, due to the relatively high ratio of no-load to full-load power (This limitation relates to such designs as those of bearing and seals.)
- During scaleup, the limitations in mechanical or process design may affect the interdependence of the length-to-diameter ratio, rotational speed, residence time, Reynolds number, surface fouling, fluid velocity and pressure drop

Some benchtop results

Even though they have their limitations, benchtop units can, under the right conditions as noted above, give reliable predictions as to the feasibility of a process, and allow for a go/no go decision for continuing to develop a process. A sense of the kind of information obtained from benchtop evaporators appears in Figure 4, which compares the heat transfer coefficient obtained from tests in the aforementioned 0.023-m^2 benchtop unit with those from a pilot plant (0.13 m^2 of heating surface) and from a full-size commercial (8-m^2) unit when heating and distilling water. The benchtop unit was heated with a 1,500-W heating mantle whereas the pilot plant and commercial units were heated with steam in jacketed heating zones.

The overall heat-transfer coefficients (U) developed in the 0.13-m^2 evaporator, when corrected using conventional heat transfer equations, corresponded well with the actual coefficient obtained under plant conditions in a similar 8-m^2 evaporator. On the other hand, because the heat flux in the 0.023-m^2 benchtop unit was limited by the capacity and contact efficiency of the heating mantle, its heat transfer coefficient was not optimized and could not be scaled up with confidence to a larger commercial process.

Another illustration of the results from benchtop units appears in Figure 5, relating to the concentration ratio of an aqueous feed (the percent of feed that appears in the distillate). A particular process required the concentration of an aqueous solution of a pharmaceutical from 20% total solids to 60%. This requires that 67% of the feed be distilled off. As can be seen in Figure 3, all three evaporators can achieve the desired result, but the obtainable feed rates on a per square meter basis cover a wide range. This illustration supports the axiom that while bench-size testing equipment is excellent for demonstration of feasibility, care must be given when using data for scaling and optimizing the operating parameters.

In short, use bench-scale testing for what it is: an excellent tool for obtaining a relatively quick and inexpensive determination of the feasibility of a process or a process step, and a cost-effective technique for confirming that you are on the right path to success before taking the next step of testing. For obtaining accurate numerical scaleup information, however, the use of full scale pilot plant evaporator is instead recommended.

Finally, be aware that for quick, accurate scaleup information, many suppliers of agitated thin-film evaporators will operate their own pilot facilities. This option makes sense for a customer, in light of the high cost that the customer would incur by buying, and operating such system itself, especially if for one-time use. ■

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