EXAMPLE 2 TAKING WATER OUT OF MILK AT THE FARM

Remote dairies in New Zealand can face major expenses in shipping their milk to a central processing facility, where the milk is largely made into cheese. These dairies would benefit from a method of concentrating the milk on the farm, removing only water. For a typical farm, this means reducing 4000 kg/day of raw milk to about 1000 kg/day of concentrate. How we might do so is the focus of this problem.

Our efforts to resolve this problem have focused on four unit operations: evaporation, absorption, spray drying, and reverse osmosis. Evaporation is the best established, and is used for products like "evaporated milk" and "condensed milk." It requires careful energy integration.

Absorption of water in inorganic or organic gels has significant problems. The inorganic gels which are selective require a lot of energy for the regeneration required for reuse. The organic gels – like polyisopropylacrylimide – are easily regenerated but are not sufficiently selective. Spray drying works well only with a feed of 50% solids, much more than that in raw milk. Reverse osmosis membranes foul too easily.

Thus, our best idea is evaporation. From an extensive energy analysis, not included here, we decide to run the evaporator at 60 °C, using 64 °C steam. The steam is produced by sending the 60 °C evaporated water through an electrically driven heat pump. (We should remember that a heat pump is approximately a Carnot engine run backwards, using work to move heat up a temperature gradient.) The use of a heat pump reflects the fact that hydroelectric power generation is common in New Zealand, and so electricity is relatively cheap.

Within our choice of evaporation, we have three possible forms of evaporators. The first is the conventional, falling-film unit, whose performance is well established and which is the sensible benchmark. The second is the centrifugal evaporator, which uses centrifugal force to stabilize thin milk films and hence improve evaporation efficiency. This method works well but the equipment is expensive. The third is a membrane evaporator, where the milk films are stabilized between membranes, which can impede evaporation. This membrane method has not been carefully explored and so has considerable risk.

Select which of these ideas is best.

SOLUTION

The solution to this problem implies a total of five steps. The first step is to determine the general specifications which any evaporator must meet. The next three steps are to find the size and cost for each of the three evaporators. The final step is to consider the risk, which in this case is largely associated with the membrane evaporator.

General specifications. We must first specify the general heat transfer characteristics of any successful evaporator. Doing so depends on choosing values for the physical properties of milk. Because the evaporation increases the concentrations of milk solids and non-volatiles, the viscosity increases from 0.9 cp to around 10 cp during evaporation. We will include this change in our calculations, but will assume that other properties of the milk remain close to those of pure water. Thus, the milk's density is taken as 1000 kg/m^3 and its thermal conductivity is about 0.60 W/mK.

The total heat transferred Q is proportional to the mass evaporated N_1:

$$Q = UA\Delta T = \Delta \hat{H}_{\text{vap}} N_1$$

where U is the overall heat transfer coefficient; A is the evaporator area; ΔT is the temperature difference, in this case 4 °C; and $\Delta \hat{H}_{\text{vap}}$ is the specific heat of vaporization at 60 °C, here about 2430 kJ/kg. Because N_1 is 3000 kg/day or 0.035 kg/sec,

$$UA = 21\,\text{kW/K}$$

But

$$\frac{1}{U} = \frac{1}{h_{\text{steam}}} + \frac{1}{h_{\text{wall}}} + \frac{1}{h_{\text{milk}}}$$

where h_{steam} is the individual heat transfer coefficient of the condensing steam, around 5000 W/mK; h_{wall} is that of the evaporator surface, typically 20,000 W/mK; and h_{milk} is that of the milk itself. We assume that this is given by

$$h_{\text{milk}} = \frac{k_{\text{T}}}{\delta}$$

where k_{T} is the thermal conductivity of the milk, and δ is the milk film thickness. Thus if we can estimate δ, we know h_{milk} and hence U, and so can find the area of a particular evaporator. This will be the key parameter in our selection.

Falling-film evaporator. The first unit we consider is the conventional falling film evaporator. In this unit, the film of milk must spread smoothly over the evaporator surface in order to use all of the surface efficiently. Such a smooth film means that the Weber number *We* must be greater than a critical value of 2:

$$We = \frac{\rho v^2 \delta}{\sigma} \geq 2$$

where ρ is the milk's density, v is its velocity, and σ is its surface tension. For a falling film,

$$v = \frac{\rho g \delta^2}{3\mu}$$

where g is the acceleration due to gravity and μ is the viscosity. Combining gives

$$\begin{aligned} \delta &= \left(\frac{18\mu^2\sigma}{\rho^3 g^2} \right)^{1/5} \\ &= \left(\frac{18\,(0.1\ \text{g/cm sec})^2\ 30\text{g/ sec}^2}{(1\text{g/cm}^3)^3\ (980\ \text{cm/ sec}^2)^2} \right)^{1/5} \\ &= 0.09\ \text{cm} \end{aligned}$$

To make sure we have a stable film, we assume we want about twice this value, or

$$\delta = 0.2\ \text{cm}$$

From the above, we then find that h_{milk} equals [(0.60 W/mK)/0.002 m], U is about 280 W/m^{2}K, and the evaporator area A is

$$A = 75\ \text{m}^2$$

This evaporator area, the benchmark for our selection, is large because the temperature difference is small (4 °C).

Centrifugal evaporator. The centrifugal evaporator uses centrifugal force to keep the milk film smooth, thin, and stable. As the milk film moves outwards on the centrifuge discs, its higher viscosity caused by evaporation is more than balanced by the increased centrifugal force. While the details of the fluid mechanics are beyond the scope of this book, the result is that the average film thickness is about

$$\delta = 25\ \mu\text{m}$$

Parallel with our earlier arguments, we now find that h_{milk} equals [(0.60 W/mK)/ 25×10^{-6} m], U is about 3400 W/m^2 K, and the evaporator area A is

$$A = 6\ \text{m}^2$$

Using a centrifugal evaporator cuts the surface area required for evaporation by over ten times.

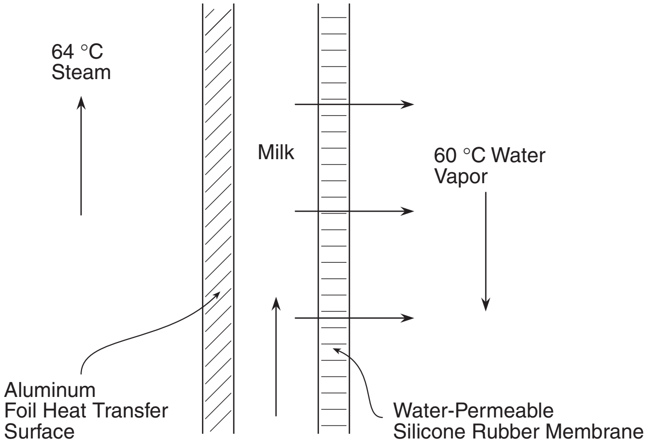

Figure 1 *Membrane evaporator* Water in warm milk evapo-rates across the thin membrane shown. Because the membrane is selective, volatile flavors are not lost.

However, this dramatically reduced area is dearly purchased. The only serious estimate which we could obtain for building a centrifuge like this was over $50,000. This seems too expensive for most farmers. As a result, we turn to the third method for evaporation.

Membrane evaporator. Like the centrifugal evaporator, the membrane evaporator can sustain very thin, stable milk films during evaporation. As shown in Figure 4.4–1, the thin films are now sustained not by centrifugal force but between two thin membranes. One of the membranes is a metal foil which transfers heat from the 64 °C steam to the 60 °C milk. This membrane has a heat transfer coefficient around 20,000 W/m^2 K.

The other membrane, which separates the 60 °C milk from the 60 °C steam produced by the evaporation, is the barrier for the evaporation. Interestingly, its heat transfer resistance and mass transfer resistance are predicted to be negligible under these conditions. If this is true, then the significant resistance to heat transfer must be the film of milk itself. In many membrane devices like this, the two membranes are held apart by a spacer, which fixes the thickness of the milk film. Typically, the thickness δ of this spacer is

$$\delta = 600\,\mu\text{m}$$

By the same arguments as before, h_{milk} is $[(0.60\ \text{W/m}^2\ \text{K})/6 \times 10^{-4}\ \text{m}]$, U is about 800 W/m^2 K, and the evaporator area A is

$$A = 26\,\text{m}^2$$

This is one third the area of the falling-film evaporator, but four times the area of the centrifugal evaporator. Significantly, membrane experts agree that membrane modules like this can be built for about \$10/m^2, independent of the chemical structure of the membrane used. Thus, we should be able to build a membrane evaporator for less than \$1000. Such a system is attractive commercially.

Table 1 ***Risk assessment for the membrane evaporator.***

Risk	Probability	Consequence	Risk level	Mitigation
1. Difficult to make heat transfer membrane	0.1	0.5	0.05	Use parallel heat exchange technology
2. Difficult to make evaporation membrane	0.3	0.5	0.15	Existing data suggest, at most, required membrane area doubles.
3. Cannot easily manifold the module	0.5	0.2	0.10	Can mitigate with larger steam channel.
4. Evaporation flow is slow	0.5	0.2	0.10	Use larger membrane spacer in steam channel.
5. Cannot sterilize effectively	0.3	0.9	0.27	Chemical cleaning preferred, but requires no dead spots.

Risk assessment. The three evaporators discussed above show a vivid contrast of advantages and disadvantages. The traditional thin-film evaporator has the largest area because it operates with the thickest milk film. The centrifugal evaporator has a very small area but a very high price. The membrane evaporator has a moderate area and a very low price, but it may not work. Using the membrane evaporator is risky.

Five of the major risks of the membrane evaporator are shown in Table 4.4–4. The first, that we have trouble making the heat transfer membrane, is unlikely because there are already foil-based heat exchangers on the market. The obvious strategy is to use the manufacturing procedures of these foil exchangers as a guide. The second risk, that the membrane across which evaporation occurs offers a major mass transfer resistance, is more serious. While such trouble would be inconsistent with earlier studies of membranes with high permeability, we suspect that the membranes used in those studies may be difficult to make in the large, flat sheets needed here. However, even if the water permeability is only 20% of that reported earlier, the membrane area required increases only slightly.

The other risks depend on the design of the evaporation module. The third risk concerns the design of the inlets and outlets, and should not be especially difficult to resolve. The fourth risk reflects the concern that the evaporated water will not easily flow out of the module. This is easily mitigated by using a larger membrane spacer in the steam channel. Sterilization of the milk channel is the most severe risk. While the membranes may not be able to stand high temperature, most farms use chemical cleaning anyway. We must ensure that sterilization is complete, without any dead spots. Even this risk, scored as the most serious, does not seem crippling. We should build a prototype and show by experiments if this new but risky idea merits selection.