LOW ENERGY WATER REMOVAL FROM HEAT SENSITIVE LIQUID FOODS

Eugene O. Strolle
Eastern Regional Research Center
Science and Education Administration, USDA

We have recently started work on a project jointly funded by the U.S. Department of Energy and the U.S. Department of Agriculture to study water removal from heat sensitive liquid foods by various combinations of reverse osmosis, freeze-concentration and evaporation to determine which combination will use minimum energy without sacrifice of product quality. Hopefully, this combination will also represent the minimum cost.

Though our current research is concerned with skim milk, our project should be of interest to those concerned with whey, since the colligative properties upon which these three methods are based depend primarily on the lactose and mineral content; this is the same for both fluids. Though inherently less energy intensive, reverse osmosis and freeze concentration, because of high capital cost, high operating cost, product loss, and flavor loss, have not been able to compete with evaporation as a method for concentrating liquid foods. In addition, and probably of greatest importance, these two methods have been considered solely on an either/or basis. The fact that either of these processes can be used in conjunction with thermal evaporation has been ignored. They are ideally suited energywise in the initial stage of concentration where most of the water is removed. Also both are most efficient below 30-40% solids.

Currently, evaporation is carried out as the first step in drying (40-50% solids), to produce frozen concentrates, e.g., orange juice (ca 45% solids), or concentrated fruit juices of 65% used in jelly and candy making. These highly concentrated fruit juices are self-preserving and do not require refrigeration. Though drying may be a second step, evaporation is the major step in water removal. For example, if we concentrate skim milk to 40% solids before drying, we have to remove 85% of the water originally present. In fact, to go from an initial solids content of 9.1% to 16.7% entails a removal of 50% of the water.

Since 1973 the cost of steam has risen from $.50/1000 lb to around $4.00/1000 lb; hence, the Department of Energy has made evaporation a prime target for industrial energy conservation and has recently issued two publications (1,2) describing how to upgrade the energy efficiency of current evaporation systems requiring low, moderate, or large capital investments. Low investment improvements are nothing but good engineering practice, such as proper venting and prevention of leakage and fouling by operating at pressure for which the system was designed. Moderate investment improvements consist of adding heat recovery equipment and instrumentation. Large capital investment modifications involve installing additional effects and use of mechanical vapor recompression. The latter can also be used in tandem with existing evaporation systems.

There is no doubt that adding effects, if done properly, will improve energy efficiency. However, adding effects is not suitable for heat sensitive liquids (such as skim milk and fruit juices) for two reasons. First, to maintain capacity the temperature must be raised in the first effect (1,2). Second, the residence time in the evaporator will be increased (1,2).

Mechanical vapor recompression is also disadvantageous with heat sensitive liquids, not only because of the high capital investment required but also freeze concentration and reverse osmosis use less energy.

The spiraling energy costs and the inadequacy of the foregoing approach when applied to heat sensitive liquids have forced a reappraisal of reverse osmosis and freeze concentration. Because of recent technological advances, they are certainly back in the picture, especially when considered as part of the overall water removal scheme and not solely on an either/or basis. Let us review some of the more important developments. First, the developments in membrane technology leading to an ever increasing use of this technology on an industrial scale; this can only act as a catalyst for the further development of improved systems. Second, loss of flavor components; this was a serious defect of reverse osmosis. Recent theoretical developments have shown that separation of various substances can be predicted; the theory has been applied to the recovery of apple flavor components by reverse osmosis (3). The next three developments pertain to freeze concentration. For effectively preventing loss of solids in the washing step (a previous defect) large crystals are necessary. Research has demonstrated that this can be effected by separating the heat transfer step from the crystallizing step and allowing the crystals to grow in a tank (4). Another major development is the gravity wash column (5); this has eliminated the need for centrifuges, presses, and piston operated columns, reducing energy requirements as well as product loss caused by entrainment in the ice.

Finally, there have been other significant developments resulting from the desalination program which I describe in greater detail when I discuss our research plans.

Some idea of the incentives for studying these two processes can be seen in the energy consumption for various processes shown in Table I. To have a common basis of comparison the third column gives the energy consumption on the basis of oil burned; for electricity the efficiency used was 35%, while for the thermal evaporators an 80% efficiency at the boilerhouse was used.

There are two types of freeze concentration processes listed. The direct freezing process or vacuum flash freezing is so termed because the refrigerant—in this case, water—directly contacts the liquid being concentrated. In the indirect method there is no contact and a heat exchanger is required.

The direct freezing process uses the least energy, almost ½ the amount used in the first indirect process listed and which was also developed in the desalination program (6). The figures for the indirect process are

TABLE I.--Energy requirements for various concentration processes

Process	KW hr/1000 gal	BTU/lb	BTU/lb (as oil burned)
Freeze conc.			
Direct	40	16.3	46.7
Indirect[1]	75	30.7	87.7
Indirect[2]	370	151.3	432
Evaporation[3]			
Single effect	-	1250	1562.5
Triple effect	-	417	520.8
MVR[4]	145	59.3	169.4
Membrane			
Reverse osmosis[5]	85.6	35.0	100

[1]Based on 25,000 GPD desalination plant.

[2]Does not include steam for melting ice.

[3]Does not include electricity for pumps, etc.

[4]Evaporating whey @ 120°F.

[5]Report 1977 DOE workshop on food processing RO = 10 effects.

based on data taken from a 25,000 GPD desalination plant (7). While not as good as the direct process, this indirect process is better energywise than any other concentration method including reverse osmosis. The other indirect process listed is a Dutch process currently used (8), with scraped heat exchangers and piston operated wash columns; ice is melted by external steam. The figures given here do not include this steam which would make its energy consumption pretty much the same as, if not worse than, the triple effect evaporators.

Consumption figures for the single and triple effect evaporators were based on the assumption that one pound of steam evaporates 0.8 lb of water per effect. The mechanical vapor recompression system in Table I was reported for a whey concentrating system (9). While more efficient than thermal evaporation, it uses significantly more energy than reverse osmosis or freeze concentration.

The figure for reverse osmosis was taken from a 1977 Department of Energy Workshop (10). In this report, reverse osmosis was stated to be equivalent to 10 effects. No other information was given, so I used a figure of 100 in the third column and worked back to the other numbers.

However, these figures should be used with caution. When first compared, freeze concentration wins going away. But let us remember these data are from different sources. Different starting materials were used. What works for sea water may not work for skim milk. This is particularly true for the gravity wash column. Cost factors must be considered. Finally, let us not lose sight of our research objective: What combination of methods is the optimum, costwise and energywise? Perhaps one method will prove to be the optimum. We really do not know. Hopefully, the research plan sketched here can give us the answer.

1. Reverse Osmosis

Table II shows our overall research plans. We have just purchased a reverse osmosis laboratory-size plate and frame unit which will be used to test membranes and to develop an appropriate cleaning regime for each liquid food we study. Our choice of the plate and frame type does not mean that we have ruled out the other configurations. However, one aspect of our research is concerned with membrane testing. Currently, a lot of work is going on in developing new membranes. The plate and frame configuration would simplify the problem of testing these membranes; all we will need is a sheet of the material. The other configurations would require the fabrication of the special modules that each configuration and make requires.

TABLE II.--Research plan

Reverse osmosis	Freeze concentration	Evaporation
1. Lab studies A. Membrane testing B. Cleaning regime	1. Lab studies A. Physico-chemical studies B. Develop process control methods	A. Assemble data for optimization B. Obtain some date in ED pilot plant
2. Pilot plant Obtain data for cost and energy optimization	2. Pilot plant	

Our objective in pilot plant studies is to obtain data so that a mathematical model relating concentration and quality to energy consumption and cost can be developed. An extended test under actual plant conditions will have to be made. As yet we have not developed a final plan for this phase and probably will not until we complete the laboratory studies.

2. Freeze Concentration

The laboratory studies have as their objective the determination of physicochemical data, such as the freezing point and phase studies, which will be used in the pilot plant study. For example, does lactose precipitate out? If so, in what range? Will the protein cause any difficulties? These are some of the problems we are now studying or thinking about.

The other phase of the laboratory work is to develop appropriate process control methods. For example, we are considering the use of the refractive index in determining solids concentration. Crystal size is a critical factor in the washing step. For successful washing the size should be at least 200 microns in diameter. We are currently designing a monitoring system which will enable us to visually monitor the crystal growth development and also detect the precipitation of other compounds such as lactose.

The equipment we will use in our proposed pilot plant studies is shown in Figure 1. This is a schematic diagram of a 250 gallon per day pilot plant unit being built for us which embodies the latest developments of the desalination program. In effect, we are asking the question: Can we successfully transfer the desalination technology to the food concentration industry? This is an indirect cooling system in which the refrigerant does not come in contact with the liquid being concentrated. First of all, the conventional scraped wall heat exchanger is replaced by a shell and tube evaporator. The tube bundle is compartmentalized and operates cyclically, one compartment being on a thaw cycle to melt the ice which has built up on the inside of the tubes. Second, the refrigerant, before it goes to the condenser, is used to melt the ice which is then used for washing the slurry and precooling the feed. The net result is a significantly lower energy consumption than that of the Dutch process currently used in the food industry (8). The unit will also have provisions for bringing in fresh water for washing. Washing will be carried out in the gravity column.

Before I discuss the direct cooling unit in which the refrigerant water actually contacts the liquid which is being concentrated, I would like to discuss the physicochemical principles upon which the direct cooling system is based. Figure 2 shows the phase diagram for pure water and sea water (11). For pure water the three equilibrium lines intersect in (what is called) the triple point. Here, three phases, solid (ice), liquid, and vapor coexist at a temperature of 0.0100°C and a vapor pressure of 4.580 mm.

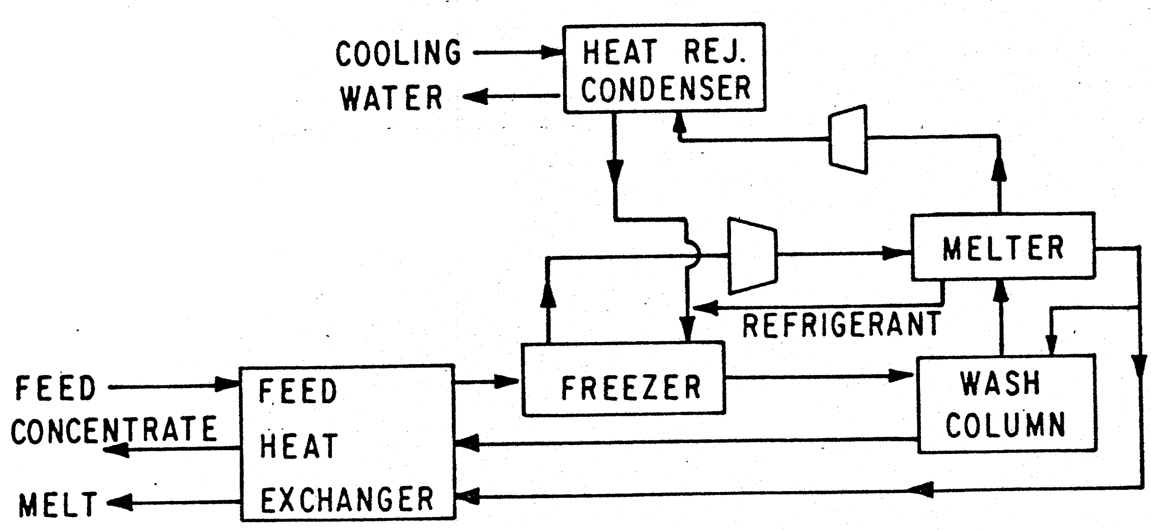

Figure 1.--Indirect freezing.

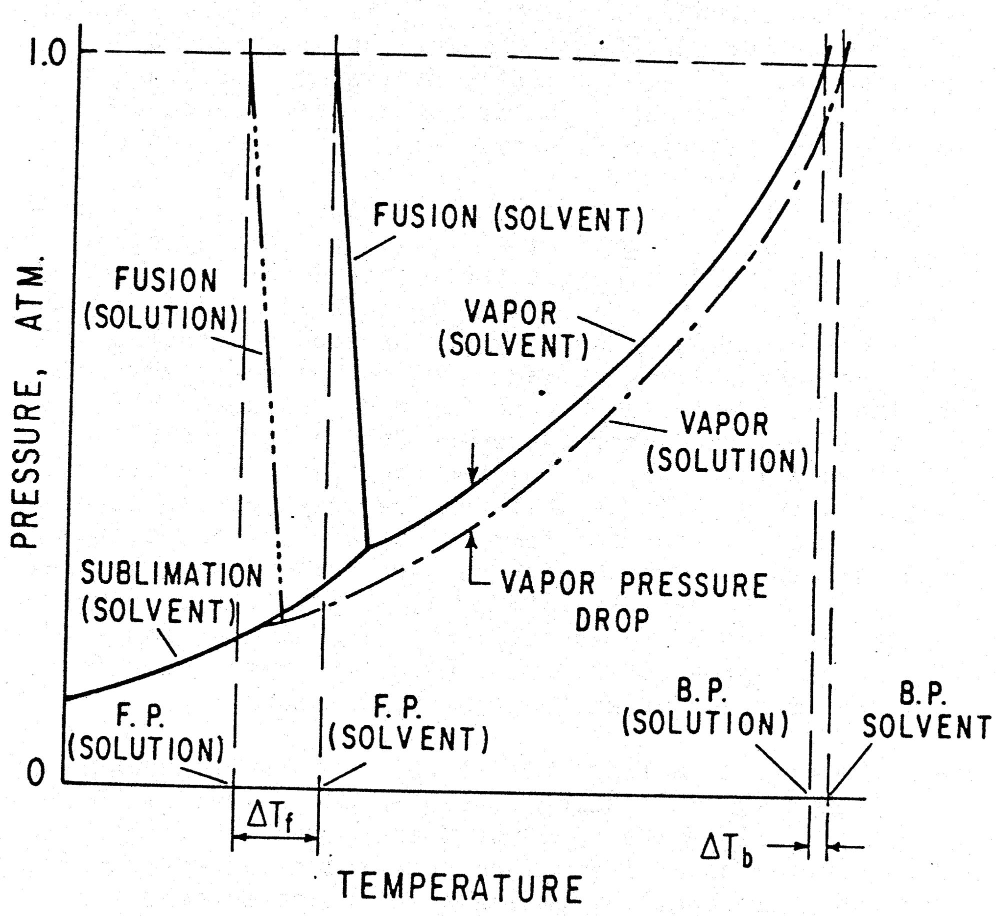

Figure 2.--Phase diagram for sea water and pure water

These conditions are invariant; in fact, units termed triple point cells are used to calibrate thermometers. The line below the pure water vapor equilibrium line represents the boiling point rise for a solution such as sea water for a range of pressures from atmospheric to below that corresponding to the triple-point pressure. The line to the left of the pure water freezing point line represents the freezing point line of the solution for the same range. It intersects the solution boiling point line at a unique point different from that of pure water. Obviously for a range of concentrations we will have a point for each concentration. The points, then, lie on a line which is the locus of all triple points for the given range of concentration. This means that if we bring feed in at a low concentration we can concentrate it to a solids content corresponding to the temperature and pressure of the triple point line if the equipment is being operated at these conditions. Furthermore, each pound of water evaporated removes 1000 BTU's from the solution; this freezes 7 pounds of water, since the latent heat of fusion is about 1/7 the heat of vaporization. In the direct vacuum freezing systems the vaporized water is considered the refrigerant and hence, instead of being removed by a vacuum pump, it is compressed (as any other refrigerant) and used to melt the ice from the wash column as in the indirect system. Since we are operating roughly between the freezing point of the solution and the freezing point of water, we approach the ideal refrigerating system for water, one that will require the minimum energy.

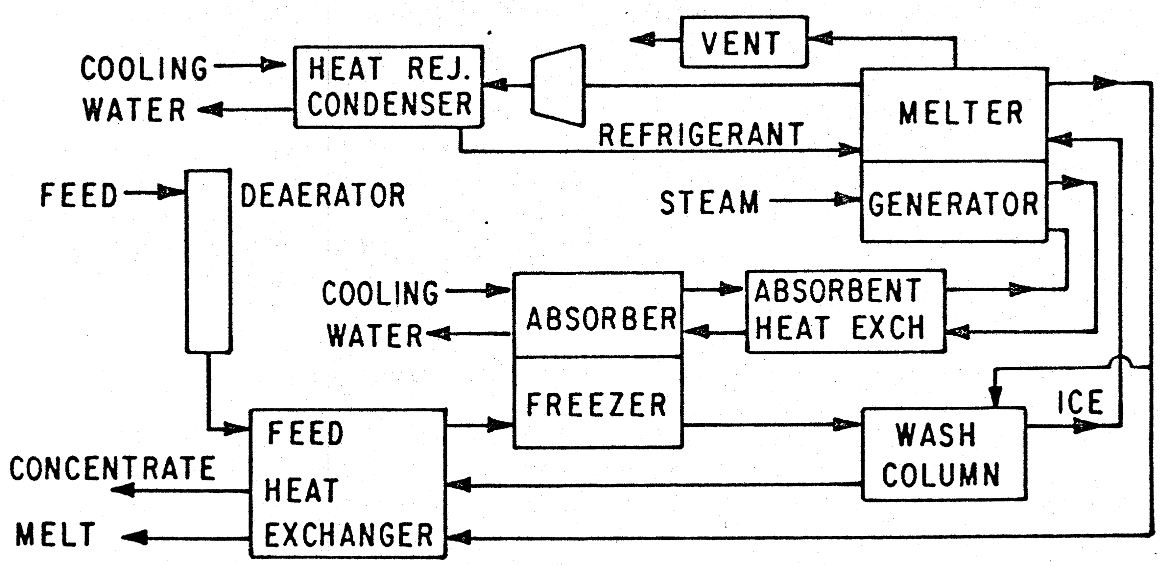

Figure 3.--Absorption freezing.

Figure 3 shows a schematic diagram of the direct freezing system being built for us but which will not be ready for at least another year. Conceptually it is similar to the system just described, with one major difference. Instead of a compressor to compress the water vapor, an absorption system is substituted. Hence, this system bears the same relationship to the vacuum freezing vapor compression system that ammonia absorption refrigeration bears to the vapor compression refrigeration system which is used in conventional refrigeration. It operates as follows. The entire system is under vacuum. Deaerated feed passes through a heat exchanger into the freezer. Water vapor from the freezer is absorbed by an absorbent which is a saturated solution of a salt such as LiBr or NaOH. This solution has a vapor pressure lower than that of the water at the prevailing pressure and temperature. Provisions exist for keeping it cool as it absorbs water vapor. The dilute solution passes through a heat exchanger countercurrent to the concentrated solution from the generator. It enters the generator, where it is then concentrated. The generator has an external source of heat such as waste steam, hot water, or even a heat pump. Part of the vapor evaporated in the generator melts the ice and is condensed. The excess water vapor is condensed by a refrigerating cycle. The condensed water vapor and melted ice are then used for washing the slurry. The refrigeration cycle can also be run as follows. The refrigerant passes through the absorber, cools it, and rejects its heat to the generator. The ice is melted by vapor from the generator. The refrigerating cycle can also be used to melt the ice. I have only briefly sketched out how the system works. Obviously, there are any number of heat transfer networks possible, either considering the system individually or as part of an overall water removal scheme involving other unit operations.

We decided to study both types of systems because each has its merits and demerits. The direct systems use less energy but are more complex. Additionally, if fruit juices are to be concentrated by the direct method, an efficient aroma recovery process has to be developed. Based on the opinion of experts in freeze concentration processes, the direct freeze concentration is more economical at rates greater than 200,000 gallons per day (GPD), while indirect freeze concentration is more economical at rates below 50,000 GPD. Since food processing plants handle between 50,000 and 200,000 GPD this is another question to which we need the answer in the freeze concentration studies.

As in the reverse osmosis studies, our objective is to develop a mathematical model relating product concentration and quality to energy consumption and cost for both freeze concentration systems. Most of the data in optimizing the evaporation phase will be drawn from the literature and industrial sources. Some of the data on heat transfer coefficients can also be obtained in our pilot plant.

How are we going to handle these functions once we have developed them? At this point our mathematician and computer experts enter the picture. Accurate optimizing requires the proper mathematical model and computer program. One approach that we will try is the use of a new optimizing technique called geometric programming (GP) (12). This involves setting up a function, called the objective function which represents either total cost or total energy, i.e., the sum of the cost or energy function for each concentration method. Derivatives are taken and costs or energy are then distributed over the different concentration methods. The total cost or energy is then found. A policy is then developed to attain this total cost and total energy, i.e., a plant is designed for this cost or energy consumption.

Mathematics in many of its aspects is an experimental science. Hence, before we can start feeding pilot plant data into the computer, we have to test the proposed approach using data from the literature and any other available source to see if we can develop the appropriate model. If the GP technique fails, then we will go to the other more complicated models which we will be able to use, since we are currently expanding our computer capacity by tying into the large Washington, D.C., 370 computer.

If the rationale described is correct, and if our research plans succeed, just what can we hope to accomplish in conserving energy used in food processing? Right now, concentration of liquid foods uses 10 million barrels of oil annually. The new technologies proposed apparently are capable of reducing this. Today, everyone is keenly interested in preserving nutritional and organoleptic quality. These low temperature processes can certainly do this. How about cost? This is a gray area, though the engineers who are designing our equipment have presented a cost analysis showing that the indirect method is cheaper than triple effect evaporation (7). Since this was based on data extrapolated from a 25,000 GPD desalination plant, the cost still must be considered only an educated guess. Finally, if we can achieve the energy requirements realized in desalination we can save about 7.5 million barrels annually, a goal certainly justifying our efforts.

LITERATURE CITED

(1) Evaporation: Prime Target for Industrial Energy Conservation. Report COO/2870-1. National Technical Information Service, U.S. Dept. of Commerce, Springfield, Va., 22161.

(2) Upgrading Existing Evaporators to Reduce Energy Consumption. Report CO/2870-2. National Technical Information Service, U.S. Depart. of Commerce, Springfield, Va., 22161.

(3) Matsuura, T., Baxter, A. G., Sourirajan, S. 1975. Reverse Osmosis Recovery of Flavor Components from Apple Juice Waters. J. Food Sci. 40, 1039-46.

(4) Thyssen, H. A. C. 1974. Freeze-Concentration. Advances in Preconcentrating and Dehydration of Foods. Edited by Spicer, A., Wiley, New York, pp. 115-149.

(5) Shwartz, J. and Probstein, R. F. 1968. An Analysis of Counterwashers for Freeze-Distillation Desalination. Desalination 4, 5-29.

(6) Barduhn, A. J. 1975. The Status of Freeze Desalination. Chem. Eng. Prog. 71(11), 80-87.

(7) Harold Davis, Concentration Specialists, Inc., 204 Andover St., Andover, Mass., 01810. 1978 (Jan. 30). Personal communication.

(8) Van Pelt, W. H. 1975. Dutch Process Cuts Cost of Freeze Concentration. Food Engineering 47(11), 77-79.

(9) Slater, L. E. 1975. Low Energy Condensing System Makes Whey Recovery Profitable. Food Engineering 47(10), 63-68.

(10) Okos, M. R., Dept. of Ag. Engineering, Purdue Univ., West Lafayette, Ind., 47907. Dec. 15, 1977. Report of DOE Workshop on Food Processing.

(11) A. E. Snyder, Chapter 7. Freezing Methods. Principles of Desalination, Spiegler, K. W., ed., Academic Press, New York, 1966.

(12) Wilde, D. J. and Beightler, C. S. 1967. Foundations of Optimization. Prentice-Hall, Inc., Englewood Cliffs, N. J.