Freezer which was developed principally for the freezing of bread and other bakery products and consists of a compact spiral conveyor that winds around refrigeration coils and fans located in the center of the unit.

The freezing methods and equipment discussed in this chapter are only a few of the many methods that have been developed, but they are representative of each of the three types of quick freezing.

FREEZE DRYING

Fundamentals

Freeze drying is the removal of water from a frozen wet solid, by sublimation. The principles of freeze drying were known for many years, but it was not utilized on a large scale until World War II when it was used in the dehydration of penicillin and blood plasma. Recently there has been a great interest in freeze drying as applied to the food industry.

The advantages of this method are: (1) moisture may be removed from heat-sensitive products at low temperature without affecting quality, (2) the freeze-dried product is extremely porous and rapidly absorbs water during rehydration, (3) the product may be stored and handled as any other packaged dry commodity without the use of refrigerstion and at a relatively low cost, and (4) weight savings are effected. The major disadvantages of this method is the high cost of removing the water during drying and the long period of time required for this operation. Also, information is still lacking as to the effect of this process on the quality of many foods.

At the present time, commercial freeze drying of foods is limited to shrimp, chicken for soups (primarily marketed in Europe), and small lot processing of beef for military evaluation. Much technical and economic study is being given to freeze drying in other fields, ranging from mushrooms to mink food to strawberries. Many of these technical and economic factors as related to final user cost were investigated in a recent study made for the U. S. Army Quartermaster. Using presently available techniques, processing costs of approximately 1 cent per 6½-oz serving (uncooked, wet weight, beef) were estimated for moderate production quantities.

Processing

In the freeze drying process, the initial feed material is first frozen, then placed into an evacuated chamber connected to a water vapor removal system. Heat is then added to supply the required heat of sublimation (116.5 Btu per pound for water), at a rate such that the vapor removal system can remove all the liberated water vapor at a pressure below the freezing point equilibrium pressure, thereby insuring that the food remains frozen.

Initial Freezing of Food. The initial wet product may be prefrozen by conventional means (cold storage chest, blast freezer, etc.) or by evaporative cooling. The former is preferred. In evaporative cooling, the wet non-frozen food material is placed in the vacuum chamber and the chamber is evacuated. As the moisture is removed, the heat required for its evaporation is supplied as a decrease in enthalpy of the remaining material, resulting in a drop in temperature. Although a large quantity of water is removed rapidly, and prior refrigeration is not required, the removal of liquid water from the outer layer of product prior to freezing usually results in collapse of the cellular structure, a condition called case hardening. Dried product with case-hardened sections inhibits subsequent drying and is almost impossible to reconstitute. Therefore, freezing prior to evacuation is strongly recommended.

The rate of product freezing may influence the quality of some foods. Quick freezing is desired primarily because of the reduction of bacterial, mold, and yeast growth that results.

Drying of Food. Cycle time is an important consideration in the drying process. Assuming ample water vapor removal capacity, the dehydration cycle time depends on the nature of the product—i.e., maximum allowable temperature, cell structure, fat content, and thickness. These factors determine the rate at which heat may be supplied as well as the diffusion rate of the outgoing water vapor.

Drying proceeds through three distinct phases. Initially the water is evolved at a rapid, *constant rate;* but, as the dry product-to-ice interface recedes within the product, this evolution decreases for the *falling* rate phase. When only a thin film of water remains on an otherwise cellular product structure, the desiccation phase begins, to continue until termination. The final moisture contents at the end of the cycle is less than 2–3 percent. In drying pieces of food, the cycle may range from 5 to 20 hr, with about 80 percent of the water removed in the first ½ to ⅔ of the cycle.

The rate at which heat is applied to the product is a function of method of heat transfer, maximum allowable dry product temperature, thermal conductivity of the dry product, and operating pressure (or vapor removal capacity).

The control of heat input for optimum cycle has been the object of much study. Although an improvement in control techniques is expected in the near future, reasonable control is currently obtained by the use of thermocouples imbedded in the frozen product, rate of pressure change, and trial and error.

Within the evacuated drying chamber, heat transfer is primarily by radiation. Heat transfer by conduction is of considerably less importance and heat transfer by convection is essentially non-existent. Most freeze drying is presently done on stationary heated shelves within the evacuated drying chamber. Under these conditions, the rate of heat input is often limited by the maximum allowable product temperature at the random points of contact (true even with very flat shelves) between product and shelf, rather than aided by the conduction heat transfer through these same areas. There are indications that shorter cycles can be obtained if the product does not touch the shelf at all, but is suspended above a shelf operating at a slightly higher temperature for radiant heating only. Vacuum drying cabinets have also been fabricated with movable heated shelves, with the intent of pressing the frozen food firmly between two heated shelves. Although conductive heat transfer was increased, the escape of the liberated water vapor was hindered.

A modification of the contact plate approach included spikes that penetrated the food for better heat input while still allowing vapor to escape. Still another modification uses an expanded metal sheet for the same reasons. After reconstitution the multitude of perforations were hardly noticeable. Although both of these methods did yield a shorter drying cycle time, they have met with only limited acceptance because of the increased cost and complexity of the equipment and the fact that the mechanism seems to reduce the drying cabinet capacity by a factor approximately proportional to the increased capacity resulting from the shortened cycle. A special rotary vacuum drum dryer has been used to successfully freeze dry small pieces of meat and vegetables. Short cycle times have been obtained because of the high heat input permitted by the short time the product contacts the heated wall. For certain products this offers an interesting approach with substitution of bulk handling for tray-loaded handling. A continuous freeze drying facility appears desirable at first thought for large-scale production rather than a multiplicity

of separate batch units. However, the concepts presented to date suggest little more than a tunnel in which the conveyed product travels over heated shelves. For a specified daily output the same amount of water vapor must be removed; and, since the same cycle times are involved, the same residence capacity must be provided as for conventional batch-type cabinet driers. Therefore, two doors with air locks, possibly with intermediate pressure differential stations, plus a conveyor system, are being substituted for the individual cabinet doors and multi-point loading. The estimated costs of these two facilities appear to be similar, and mechanical breakdowns in the continuous system endanger the entire production capacity.

Although heating of the outer layer of ice is relatively easy, as the ice-dry product interface recedes within the product, the already-dried product acts as a good insulator towards further heat. Because of the difference in dielectric constants between dry product and ice, it has been proposed that microwave energy be used to preferentially heat the ice. This has been successfully demonstrated but several difficulties make its future doubtful: (1) just as the dielectric of ice was more receptive to energy absorption than was the dry product, so too, water is more adsorbent than ice, and therefore, if a single drop of water is formed, melting occurs selectively at this point at an accelerating pace; (2) the cost of microwave energy is expensive compared to other forms; and (3) microwave generators are not expected to be available within the immediate future capable of supplying the energy levels required for other than laboratory efforts.

Water Removal. Absorption systems using chemical desiccants can be used in small laboratory units, with the desiccant reactivated by heating or replaced. Production absorption systems have been built using recirculating refrigerated brine such as calcium chloride. A portion of the recycle was continuously stripped of water by heat. Corrosion problems with the brine-water mixture caused severe maintenance conditions in at least one instance.

Pumping is another method of effecting water removal. At the vacuum used, water vapor occupies a very large volume (i.e., almost 28,000 cu ft of water vapor per lb compared to 0.016 cu ft liquid water per lb). In small units, a mechanical vacuum pump with the gas ballast feature (to prevent condensation of the water vapor in the pump oil) can be used. In larger sizes, mechanical blowers have been proposed (and tested in a laboratory scale). Steam ejectors have been used also, but often require 4 or 5 stages for this application, and it has only been quite recent that satisfactory results could be expected. Cooling water availability has a significant effect on the economic comparison of steam jets with other methods of water vapor removal.

A refrigerated surface can also be used to condense the water vapor so that only small vacuum pumps are required for the entrained air plus leakage. A static condenser may be located within the drying chamber if adequately baffled, or it may be in a separate chamber connected with short, large diameter manifold. Mechanical refrigeration systems, dry ice and acetone, and liquid nitrogen have all been used for cooling. The choice of refrigerant depends on economics, desired final moisture content, and operating pressure. However, as the layer of condensed ice becomes thicker, the outer surface of the ice (which is exposed to the vapor) is warmer because of the insulating effect of the ice. Although sufficient condensing surface can be provided on units of low capacity, another approach is preferred for production facilities. One company utilized a patented scraped-surface condenser for most of the penicillin and blood plasma plants installed during World War II, thus avoiding the buildup of ice on the condenser. These units, although high in initial cost, had low operating costs with easy removal of the condensed ice.

Commercial Equipment

Freeze drying equipment is available commercially in the small laboratory and pilot plant sizes. In larger pilot plants and in production installations, custom engineering and fabrication is recommended to assure optimum performance with specific products.

A description of some of the available units suitable for both food and pharmaceutical products will illustrate the range of capacity and complexity.

1. One available unit consists of a chamber (a 12 in. dia by 12 in. high bell jar on a baseplate) from which vapor removal is accomplished by use of a rotary, gas-ballast, mechanical vacuum pump. Variable electric heating is provided. The capacity of the unit depends upon the size of the vacuum pump.
2. Another unit includes a chamber (30×42×42 in.) with steel cabinet shelves. Vapor removal is by means of a static surface cooled by a mechanical refrigeration system which is located behind baffles within the main cabinet. Heating is provided by a circulating fluid which is controlled to modulate the heat input. The capacity is 20 lb per hr for a total of 150 lb of water.
3. A third unit includes 3 steel chambers (49×89×53 in. high). Vapor removal is accomplished by means of 9 scraped-surface condensers with a mechanical refrigeration system. A circulating fluid is used with modulated heat input. The capacity of the unit is 225 lb per hr for a total of 2250 lb of water.

BIBLIOGRAPHY

C. F. Evers: The frozen food industry (*Industrial & Engineering Chemistry*, Vol. 40, 1948, p. 2251).

Freezers; Special Report: (*Food Engineering*, Vol. 29, 1957, p. 101).

H. C. Mannheim et al: Determination of enthalpies in food freezing (*Food Technology*, Vol. 9, 1955, p. 556).

G. W. Meek and V. R. H. Green: Evaluating food freezing methods (REFRIGERATING ENGINEERING, May 1947, p. 391).

W. R. Phillips: Freezing rates of fruits and vegetables at various air velocities (REFRIGERATING ENGINEERING, May 1947, p. 401).

H. E. Staph: Specific heats of foodstuffs (REFRIGERATING ENGINEERING, August 1949, p. 767).

H. E. Staph and W. R. Woolrich: Specific and latent heats of foods in the freezing zone (REFRIGERATING ENGINEERING, November 1951, p. 1088).

D. K. Tressler: Chemical problems of the quick freezing industry (*Industrial & Engineering Chemistry*, Vol. 24, 1932, p. 682).

D. K. Tressler: *Some Aspects of Food Refrigeration and Freezing* (UN Food and Agricultural Organization, Washington, D. C., 1950).

D. K. Tressler and C. F. Evers: *The Freezing Preservation of Foods;* Vol. I, Fresh Foods; Vol. II, Prepared and Precooked Foods (Avi Publishing Co., Westport, Conn., 1957, 3rd ed.).

W. H. Tucker and T. K. Sherwood: Vacuum dehydration using liquid adsorbents (*Industrial & Engineering Chemistry*, May 1948, p. 832).

A. L. Schroeder and H. W. Schwarz: Low temperature vacuum dehydration (*Chemical Engineering Progress*, June 1949, p. 370).

E. W. Flosdorf: Preservation by freeze drying (REFRIGERATING ENGINEERING, March 1954, p. 49).

H. P. Furgal: Progress in meat dehydration; freeze-drying (*Food Engineering*, September 1954, p. 74).

A. L. Tappel et al: Freeze-dried meat, I, preparation & properties (*Food Technology*, August 1955, p. 401).

Unit puts freeze drying right on production line (*Food Engineering*, November 1956, p. 40).

A. L. Tappel: Freeze-dried meat II, the mechanisms of oxidative deterioration of freeze-dried beef (*Food Research* 21, 1956, p. 195).

K. Neumann: Advances in the method and application of freeze drying (*Chemi-Ingenieur Technik*, January 1957, p. 267).

W. R. Smithies: New developments in the freeze-drying of meat (*Chemistry and Industry*, July 20, 1957, p. 1008).

C. L. Rasmussen et al: Latest dehydrofrozens cut costs (*Food Engineering*, December 1957, p. 117).

R. G. Tischer and M. C. Brockmann: Freeze drying ups quality of QM quick-serve rations (*Food Engineering*, January 1958, p. 110).