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CONTINUOUS VACUUM DRYING OF WHOLE MILK FOAM

SUMMARY

The principles developed on a batch scale for preparing vacuum foam-dried whole milk have been successfully applied on a continuous basis. An integrated pilot plant and means for creating a foam in vacuum and distributing it in a thin layer onto a moving belt are described. In the continuous process, pasteurized homogenized market milk is concentrated in an agitated, falling-film vacuum evaporator from 12% solids to a solids content (43% average) corresponding to a viscosity at 100 F of 32-43 centistokes. The concentrate is homogenized at 3,000-500 and 135 F. Nitrogen is metered into the concentrate stream and a scraped-surface heat exchanger then simultaneously chills the concentrate to 35 F and disperses the gas. Finally, within a drying chamber maintained at reduced pressure, the gassed concentrate expands to a foam which is applied and dried on a continuous solid belt.

Results of a study on the effects of process variables are reported and reproducible operating conditions are given for preparing products of excellent dispersibility and initial flavor. The study was restricted to dryer chamber pressures (9 mm Hg and below) found to preserve the foam integrity during drying (as in the case of batch drying). With this strict translation of the batch principles to a continuous operation, mass and heat transfer limitations were encountered, resulting in product rates which, when extrapolated to commercial scale operation, are considered too low to be of commercial significance. Thus, current work is directed toward improving product rate while maintaining product quality.

A broad research program directed toward developing an economically feasible process for preparing a dry whole milk of good flavor, easy dispersibility, and adequate shelf life is in progress at the Eastern Utilization Research and Development Division. The first significant findings in the Engineering and Development Laboratory were that concentrated whole milk dried as a foam under vacuum had unique dispersing properties superior to whole milk dried in other forms (13), and that it retained this property for at least 12 months at 73 F (4). Research carried out in the Dairy Products Laboratory has shown that important differences affecting dispersibility do, in fact, exist between vacuum foam-dried and spray-dried whole milk particles (7, 8, 9, 10). It now seems clear that from the standpoint of dispersibility whole milk should be dried as a foam.

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[1] Eastern Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture.

Flavor of the freshly prepared product is excellent, but it deteriorates on storage. Thus, another phase of the research program is devoted to extending the flavor shelf life of the product. Some results from this work have been reported. Craig et al. (3) found a significant relationship between the occurrence of 5-hydroxymethylfurfural in the product and its processing and storage history. Kliman et al. (11) reported that a good reciprocal relationship was found between the peroxide value and the flavor score of foam-dried whole milk stored in air at 55 F, but that no similar relationship could be found when the material was stored in nitrogen containing 0.1% oxygen. Tamsma et al. (14) reported that after storage at 80 F for six months a highly significant improvement in flavor stability was achieved by packaging in nitrogen containing 0.1% oxygen, compared with samples packed at 1% oxygen and air levels.

This paper discusses the translation of the essential processing principles of a batch vacuum foam-drying process (13) to a continuous operation.

DESCRIPTION OF INTEGRATED PILOT PLANT

The good initial properties of vacuum foam-dried whole milk are a consequence of drying an expanded, sponge-like structure at low temperatures in the substantial absence of oxygen. The batch studies reported previously demonstrated that for good dispersibility the whole milk concentrate should be dried in the form of a uniform, fine-grained foam. This dry structure was obtained by intimately dispersing a gas of low solubility, chilling to avoid stripping of the gas by flashing, applying a vacuum which caused the dispersed gas to expand the concentrate into the desired foam structure, and drying under conditions that assured maintaining the foam during the dehydration step. In contrast, drying a deaerated concentrate yielded a poorly dispersible product. An integrated pilot plant embodying the foregoing principles was designed and erected for the translation to a continuous process.

The integrated pilot plant being used to study the important process variables is shown schematically in Figure 1. Fresh pasteurized homogenized market milk (adjusted to 26% fat MFB) is concentrated in a single-pass, agitated falling-film vacuum evaporator to a constant apparent viscosity. Viscosity is the control variable because it is a prime factor contributing to the formation, characteristics, and stability of fluid foams and because in milk concentrates viscosity and solids content do not correlate well from one batch to another.

The concentrate is homogenized in a two-stage, single-pass, variable rate homogenizer operating at 3,000 and 500 psi. The function of the second homogenization is to reduce the fat particle size to below 2 μ. Homogenized market milk was used in these studies as a matter of convenience and, since normal homogenization practice for fluid milk does not give the desired fat dispersion, rehomogenization of the milk after concentration was necessary. Presumably, the desired fat dispersion could have been attained by adequate homogenization either before or after concentration, although this point has not been established. The homogenizer also acts as a pump that fixes the concentrate flow rate for gas dispersion. Nitrogen is metered into the concentrate stream just ahead of two scraped surface heat exchangers that simultaneously chill the concentrate to about 35 F and disperse the nitrogen to a bubble size of less than 75 μ. The gas-containing concentrate is then delivered to the dryer through a metering pump.

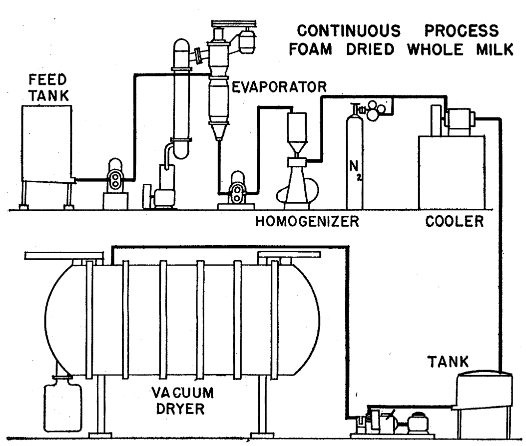

FIG. 1. Schematic diagram of continuous process for foam-dried whole milk.

The key piece of equipment in the pilot plant is the continuous vacuum dehydrator. A photograph of the dryer used in these studies is shown in Figure 2 and a functional drawing is given in Figure 3. The dryer consists of an endless solid stainless steel belt 12 inches wide, which alternately passes over heating and cooling drums. The drums are 2 ft in diameter and are spaced 9 ft between centers. Both vacuum and pressure steam can be supplied to the heating drum, and coolant at various temperatures can be circulated through the cooling drum. Heat can be applied to either side of the belt between the two drums by means of 19 banks of individually controlled electrical radiant heaters each rated at 2 kw. The whole apparatus is enclosed in a chamber where pressures can be maintained from 50 to 0.5 mm Hg absolute.

In this application, the gas-containing concentrate is metered to the dryer through the feed line which is jacketed by a cooling pipe. The feed temperature is adjusted to be below the flash point when it enters the drying chamber. The nitrogen in the concentrate expands in the nozzle and the resulting foam issues as a thin, uniform blanket or film. The belt carries the foam through the first drying zone (electrical radiant heaters) where the nitrogen expands further, around the second drying zone (heating drum), and through the third drying zone (electrical radiant heaters). The belt with dried product then passes between the cooling drum and a crushing roll that breaks the friable blanket. An oscillating doctor blade at the cooling drum removes the residual dried product from the belt. The product drops into a screw conveyor and is carried to one of two receivers.

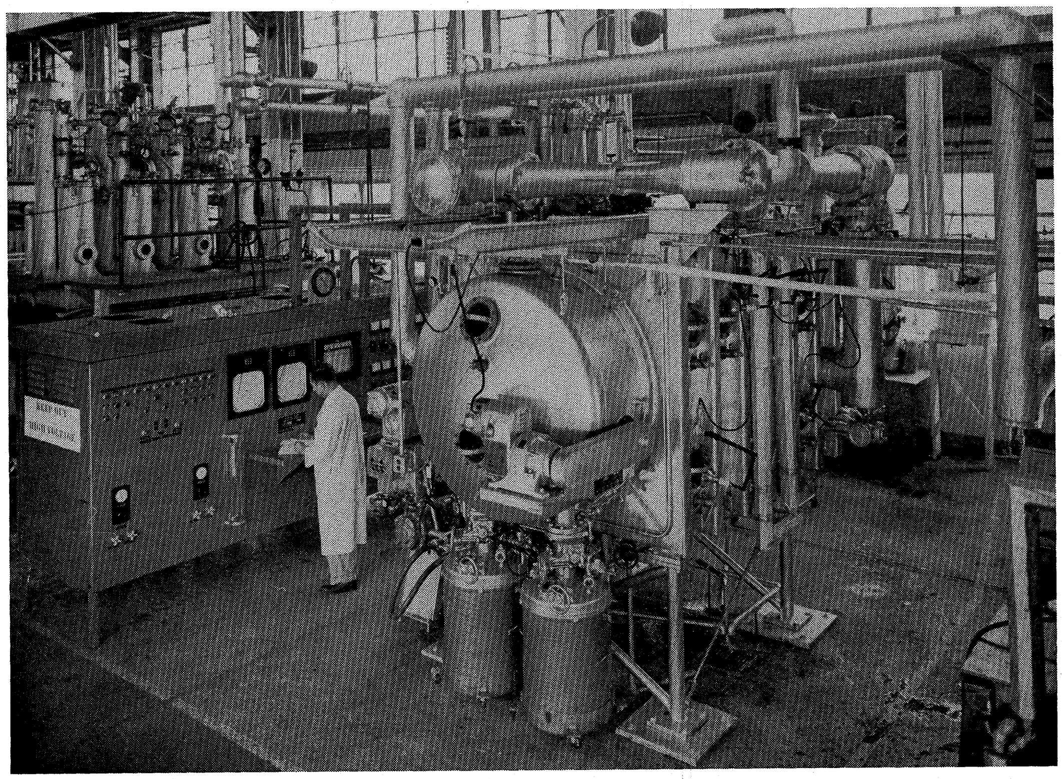

Fig. 2. Pilot-plant scale continuous vacuum dryer.

RESULTS OF RESEARCH

(a) *Design of the feed nozzle.* This pilot-plant dryer is essentially a small-scale model of a unit used to dehydrate citrus juices and coffee on a commercial basis (1, 2, 5, 6). The major difference is the manner in which the material to be dried is applied to the belt. In the commercial drying operations the material is applied to the underside of the belt by means of a feed roll. A level of material is maintained in a feed pan through which the feed roll rotates. When operated in this manner a puffed structure may be formed by the evolution of water vapor. The earlier work (13) showed, however, that for whole milk this type

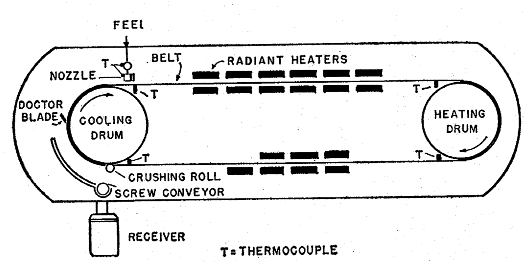

Fig. 3. Functional drawing of continuous vacuum dryer.

of structure is distinctly inferior to the fine-grained, uniform foam obtained by the expansion of finely dispersed nitrogen within the concentrate. Applying a foam to the underside of the belt by means of a feed roll would obviously be difficult if not impossible. For this reason it was necessary in these studies to design an apparatus that would create and apply a foam to the top of the belt. The final result was a nozzle that is illustrated in Figure 4. The nozzle is in effect a rectangular chamber the front face of which is adjustable with shims to give the desired opening. The gas-containing concentrate enters the chamber where it begins to expand and continues to expand as it passes through the aperture. Upon leaving the aperture the foam has been formed into a thin uniform blanket due to the action of the reduced pressure in the drying chamber and nozzle. Figure 5 is a photograph of foam being applied to the moving belt. The nozzle is housed to prevent heating due to radiation.

The important design features of the nozzle are as follows:

(1) The large rectangular chamber. This provides negligible pressure drop in distributing the foam across the inner lips of the aper-

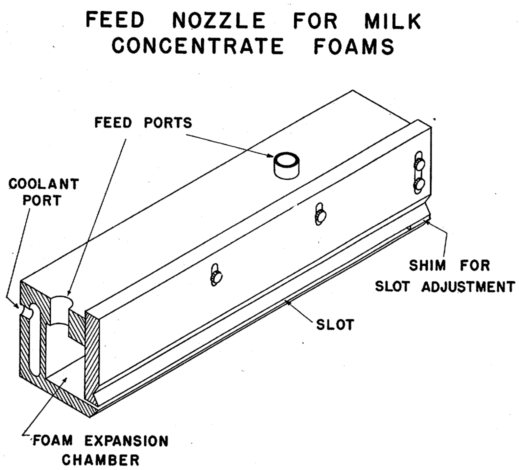

FIG. 4. Feed nozzle for milk concentrate foams.

ture compared to the pressure drop through the aperture, resulting in uniform thickness of the foam blanket as it issues from the nozzle. This consideration is similar to the design of distributors (12).

(2) The lips of the aperture. These must be parallel to insure a blanket of uniform thickness. They also must have a significant dimension (land area) from the inner to the outer edge so that they may impart a single direction across the width of the foam blanket as it issues from the nozzle. The lips of the present nozzle are ½ inch wide. The outer edges of the lips should also be bevelled, to prevent the foam from clinging to the face of the nozzle.

(3) The coolant core. This is necessary to prevent the concentrate temperature from rising above the flash point.

(b) *Effects of drying variables.* Ideally, for best product quality and highest dryer output, the foamed concentrate should be uniformly applied in as thin a film as possible and be well bonded to the belt throughout the drying cycle. The important variables that affect product quality and dryer output through their influence on foam thickness, foam behavior, and the degree of foam-to-belt bonding are dryer chamber pressure, rate of heat application, nozzle aperture, viscosity and gas content of concentrate and belt temperature at point of foam application.

(1) Chamber pressure. This directly affects drying temperature, foam stability, and heat transfer between the drums and the belt. In

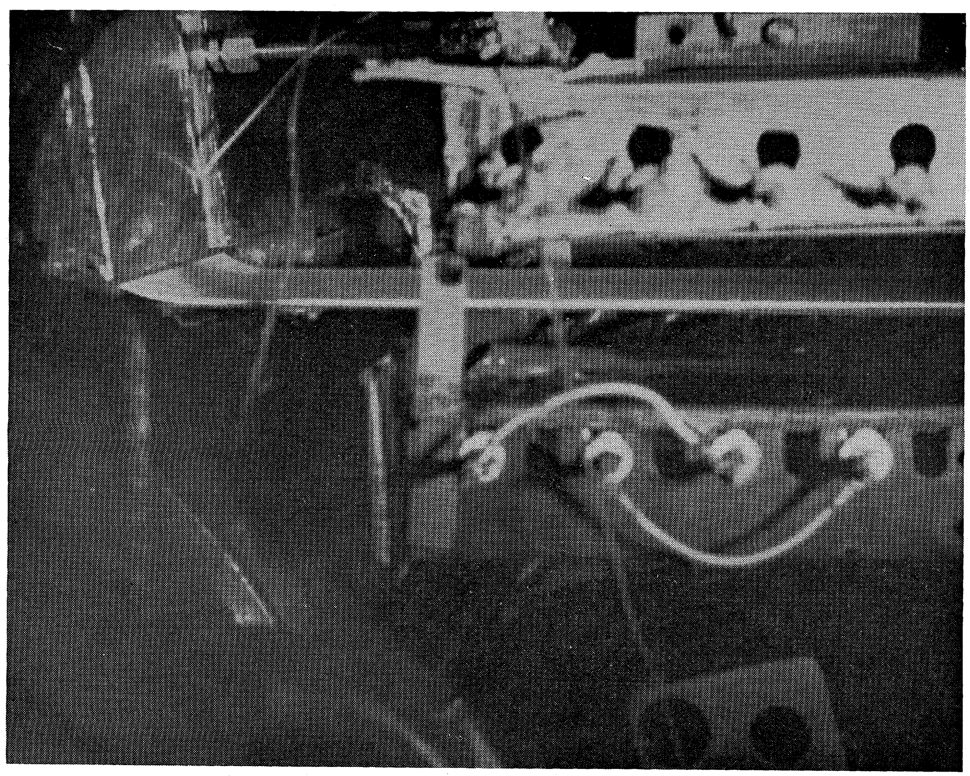

FIG. 5. Whole milk foam being applied to moving belt.

these studies the chamber pressure was restricted to a range that would insure that the foam structure was maintained during drying. That range was determined to be below 9 mm Hg as foam structures were partially destabilized at higher pressures. Absolute pressures below 2.0 mm Hg caused the nozzle to operate poorly because the foam was partially frozen. Heat transfer between the two drums and the belt improved at 3.0 mm and above. It was found that 3.0 mm Hg was optimum in these studies, because the foam expanded to a lesser degree in the first drying zone.

(2) Rate of heat application. During the initial drying stage (constant rate period) in vacuum drying the foam temperature can be expected to be at the boiling point corresponding to the chamber pressure. For this reason heat can be applied rapidly without danger of damage to the product. A limiting factor, however, is maintaining good foam-to-belt contact. If heat is applied too rapidly to the belt in the first drying zone, the foam will lift from the belt in the form of large balloons, thus substantially reducing the subsequent heat transfer area for conduction between belt and foam. These balloons are undoubtedly caused by the release of water vapor at the belt-foam interface. Under these conditions the water vapor forms faster than it can escape through the foam. Some balloons can be tolerated if they are transient, but in instances where they persist, less drying is accomplished by increasing the heat input in the first zone. Ballooning can also occur on the heating drum (second zone) unless the foam is relatively rigid through drying in the first zone.

During the final drying stages (falling rate period) the temperature of the product will rise above the boiling point, and excessive temperatures can result in damage to product quality. Using the criterion of product quality as evidenced by the formation of hydroxymethylfurfural (HMF) (3), indications are that the falling rate period commences before the foam leaves the second zone. For example, maintaining all factors constant but the heating drum temperature, the HMF of resulting products increased as heating drum temperature increased. Thus, temperature of the heating drum has a profound effect on product quality. The same is true in the third drying zone. Relatively low levels of heat input in these two zones are thus mandatory. The maximum heat levels that could be applied with limitations imposed by heat and mass transfer and product quality considerations are given in Figure 6.

(3) Nozzle aperture. Drying theory indicates that drying time is proportional to between the first and second power of film thickness. Hence, thinner films could be expected to lead to higher product rates. They also contribute to uniform product moisture. In these studies it was found that film thickness is influenced by nozzle aperture down to an opening of 0.04-0.05 inch. When the nozzle opening is less, the films become thicker. This phenomenon is probably associated with pressure drop across the aperture. It appears likely that if the pressure drop is too great the foam will continue to expand significantly close to the outer edge of the aperture, permitting expansion to occur in all directions.

(4) Viscosity of concentrate. This influences the behavior of the foam on the belt as well as foam thickness. The apparent viscosity of the concentrate changes at it passes through the processing line from the evaporator to the dryer. This difference is due to the thixotropic nature of the concentrate in addition to temperature reduction and gas impregnation. These changes, however, were found to be reproducible, and hence the apparent viscosity of the gassed feed for the dryer is maintained by controlling the viscosity of the concentrate at the evaporator.

If the belt speed is greater than the speed of the foam blanket issuing from the nozzle, the foam blanket under certain circumstances can be made to stretch. It was found that the apparent viscosity of the gas-containing feed

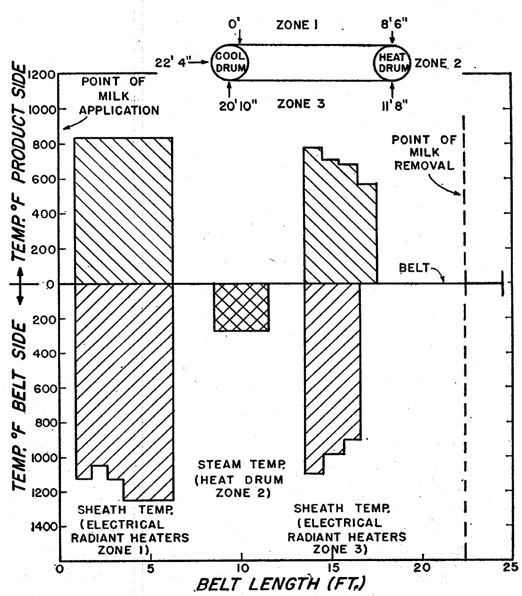

FIG. 6. Temperature profile for the continuous vacuum foam drying of whole milk.

concentrate can be used as an indication of this property. When measured at the feed temperature, the foam is quite elastic if the gasified concentrate viscosity is between 180 and 340 centistokes. Above and below these values the foam blanket tears readily. However, it was also found that the balloons formed in the first drying zone are less permanent with viscosities in the low end of the range. Thus, the best viscosity compromise for the gas-containing feed concentrate was found to be about 200 centistokes when measured at the feed temperature to the dryer.

(5) Gas content of concentrate. This variable influences such factors as the type of foam structure and the thickness of the foam film. When operating at the low chamber pressures (9.0 mm and below) a minimum of about 40 ml of gas (corrected to 0 C and 760 mm Hg) per liter of ungassed concentrate is required for foam formation. However, considering the above factors, 100 to 140 ml/liter of gas was found to be the optimum range. Higher gas contents, e.g., above 200 ml/liter, yield thick films resulting in slower drying rates and more bulky products.

(6) Belt temperature. The belt temperature at the point of foam application must be below the flash point of the foam. If it is above, the foam will flash as it contacts the belt, resulting in a poor bond between the foam and the belt.

(c) *Optimum drying conditions.* In the batch process the foam was first created by expanding well dispersed nitrogen in the concentrate through the application of vacuum, and then drying that foam without altering its structure. The present work has demonstrated that this can be done continuously. The optimum conditions, within the chamber pressure range for accomplishing this, are listed in Table 1. The applied temperature profile is shown in Figure 6. The properties of the dry whole milk obtained under these conditions are given in Table 2.

TABLE 1

Conditions for the continuous vacuum foam-drying of whole milk

Viscosity of concentrate [a] from evaporator (gas-free; 100 F)	32-43 centistokes [b]
Gas content of concentrate	100-140 ml/liter
Viscosity of concentrate to dryer (gassed; 34 F)	190-240 centistokes [c]
Feed temperature	28 F
Feed rate	0.40 lb/min
Belt loading	0.052 lb/ft²
Nozzle aperture	0.047 inch
Belt temperature at feed nozzle	< 29 F
Chamber pressure	3.0 mm Hg (flash temperature for concentrate 29 F)
Belt speed	9.3 ft/min
Drying time	2¼ min
Cold drum temperature	−5 F
Product rate	10.7 lb/hr

[a] Corresponds to approximately 43% total solids.
[b] Viscosity measured by Saybolt Viscosimeter, using a Universal tip.
[c] Viscosity measured by Saybolt Viscosimeter, using a Furol tip.

DISCUSSION

Because of the unique properties of the raw material and the nature of vacuum foam-drying, translating a batch operation into a continuous one entailed far more than streamlining and achieving continuity of operation. For example, the expansion to a foam in the batch dryer can be done as slowly as desired. Also, applying heat in the platens can be done at such a rate that moisture is evolved gradually without actual ebullition and collapse of the foamed structure. The drying time may be more than 1 hr. In contrast, the continuous process entails introducing the gasified concentrate into an existing high vacuum, where expansion is instantaneous and where the drying has to be accomplished in 1 to 3 min without destruction of the foam or impairment of flavor. The introduction of a gassed concentrate into an existing vacuum, the creation of a suitable foam and its distribution in a thin, uniform layer onto a moving belt, were made possible by the development of the nozzle.

The principles developed on a batch scale for preparing vacuum foam-dried whole milk have been successfully applied on a continuous basis. Moreover, products excellent in dispersibility and initial flavor and high in bacteriological quality have been reproducibly prepared

TABLE 2

Properties of continuous vacuum foam-dried whole milk

Moisture content	3-4%
Solubility index	< 0.25
Dispersibility rate (hand stirring in water at 38 F)	> 98% in 100 sec
Typical bacterial estimate	< 20,000 per gram
Typical coliform estimate	< 70 per gram

by a continuous process. However, it has been shown that continuous drying under conditions to preserve the integrity of the foam as applied to the belt, product rates are too low to be considered economic. Referring to Table 1, the product rate of 10.7 lb/hr, when extrapolated to existing commercial scale designs, would correspond to approximately 40% of the minimum economical rate. Thus, current work is directed toward increasing the product rate consistent with maintenance of product quality, and providing engineering information for improving dryer design to increase its efficiency for foam-drying whole milk. Increased product rates can be expected if, for example, methods could be found for maintaining good heat transfer contact between belt and foam by the elimination of persistent balloons and by providing thinner drying films. Present indications are that these ends may be obtainable by alteration of foam behavior during drying. With respect to dryer design, present indications are that modifications can be made that will yield a more favorable ratio of capital cost to unit capacity.

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REFERENCES

(1) Anonymous. Speed-Dries Heat Sensitive Liquids. Food Eng., 26, 1: 36. 1954.

(2) Anonymous. Superior Dehydrated Juices from Continuous Vacuum Process. Food Eng., 27, 3: 71. 1955.

(3) Craig, J. C., Jr., Aceto, N. C., and Della-Monica, E. S. The Occurrence of 5-Hydroxymethylfurfural in Vacuum Foam-Dried Whole Milk and Its Relation to Processing and Storage. J. Dairy Sci., 44: 1827. 1961.

(4) Eskew, R. K., Aceto, N. C., Sinnamon, H. I., and Schoppet, E. F. Dispersibility of Foam-Dried Fat-Containing Milk Products. J. Dairy Sci., 41: 753. 1958.

(5) Fixari, F., Conley, W., and Bard, G. Continuous High Vacuum Drying Techniques. Food Technol., 3: 217. 1959.

(6) Fixari, F., Conley, W., and Viall, G. K. Continuous Vacuum Dehydration Reduces Costs. Chem. Eng. Progr., 53, 3: 110. 1957.

(7) Fox, K. K., and Pallansch, M. J. Effect of Moisture on the Physical Properties of Milk Powder. Proc. Fourth Milk Concentrates Conf., p. 22, Michigan State Univ., East Lansing, Mich. March 23-24, 1960.

(8) Harper, M. K., Fox, K. K., Holsinger, V. H., and Pallansch, M. J. The Reconstitution Rate of Milk Powders After Wetting. Abstr. Papers, 138th Meeting, ACS, New York. p. 4A. September, 1960.

(9) Holsinger, V. H., Fox, K. K., Harper, M. K., and Pallansch, M. J. The Spatial Distribution of Milk Constituents in Powders Made by Different Drying Techniques. Abstr. Papers, 138th Meeting, ACS, New York. p. 3A. September, 1960.

(10) Howard, N., Fox, K. K., Holsinger, V. H., and Pallansch, M. J. The Specific Surface Areas of Milk Powders Produced by Various Drying Methods. J. Dairy Sci., 44: 1155. 1961.

(11) Kliman, P. G., Tamsma, A., and Pallansch, M. J. Peroxide Value Flavor Score Relationships in Stored Foam Dried Whole Milk. Abstr. Papers, 138th Meet., ACS, New York. p. 5A. September, 1960.

(12) Richardson, D. R. How to Design Fluid-Flow Distributors. Chem. Eng., 68, 9: 83. 1961.

(13) Sinnamon, H. I., Aceto, N. C., Eskew, R. K., and Schoppet, E. F. Dry Whole Milk. I. A New Physical Form. J. Dairy Sci., 40: 1036. 1957.

(14) Tamsma, A., Pallansch, M. J., Mucha, T. J., and Patterson, W. I. Factors Related to the Flavor Stability of Foam-Dried Whole Milk. I. Effect of Oxygen Level. J. Dairy Sci., 44: 1644. 1961.