Continuous Vacuum Foam Drying of Whole Milk Under Simulated Commercial Scale Conditions

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Abstract

This paper reports studies that tested the technical feasibility of vacuum foam drying of whole milk under simulated commercial-scale production. The tests showed that the scale-up ratio from pilot to commercial size is valid and that the feed nozzle will deliver a smooth and continuous ribbon of foam to the belt at commercial rates. They also showed that the agitated-film, vacuum evaporator will operate for at least 12 hours before shutdown for cleaning becomes necessary. A multiple-blade doctoring system was designed, built, installed and tested that permits satisfactory continuous removal of product from belt for at least five consecutive days. Other important observations were that temperature of the gas-containing concentrate and its dwell time from the gas disperser through the nozzle to the belt have significant effects on the behavior of foam as it leaves the nozzle and as it reacts to heat on the belt. It is concluded that insofar as a pilot-scale can predict, the vacuum foam-dried whole milk process is ready for commercialization.

Introduction

Vacuum foam-dried whole milk was invented (7) in 1960 at this Laboratory and it has been extensively and intensively studied since then. For example, the physical, organoleptic, marketing and storage properties have been reported (1, 2, 5, 6). Likewise, the process for preparing the dry milk has been advanced from a rather crude batch operation (6) to a sophisticated pilot-scale continuous process (4). Finally, the pilot process has been scaled-up on paper to commercial size and an economic analysis showed it to be economically feasible to operate (8).

The scale-up was based on two assumptions. The first was that the commercial dryer would produce 154 kg/hr (340 lb/hr) of dry product, and the second was that the plant would operate around the clock for five consecutive days without interruption. This paper reports research that tested the technical feasibility of the process under conditions of simulated commercial production.

Studies Concerned with Production Rate

Scale-up ratio. The key component of the pilot plant was a continuous vacuum dehydrator described as Model 1X2X2X9 (Chemetron Corp., Louisville, Kentucky)[1]. The model number represents, in feet, the width of a solid stainless steel belt; the diameters of heating and cooling drums over which the belt runs; and the distance between drum centers. The dehydrator envisioned for the commercial plant is described similarly as 4 × 8.5 × 8.5 × 36—a standard size. Referring to Figure 1, about 85% of the water is removed from the product in the radiantly-heated section between the feed nozzle and the heating drum (called the first drying zone). Thus, a reasonable scale-up ratio from the pilot to the commercial dryer was that of the respective areas of foam in the first drying zone at any given time. For the large-scale dryer this area was estimated to be 1.19 m wide by 9.60 m long, and for the pilot-scale it was measured as 0.27 m wide by 1.94 m long. Therefore, the scale-up ratio actually used to project the production rate data was 22:1 (11.43:0.52). To verify this projection the area of the first drying zone of the pilot dryer was increased by adding more radiators such that the length of the belt exposed to heat at a given instant could be as high as 78.3% of the drum center distance—up from the original 68.5%. Unfortunately, this new length only partially approached the length required in the 22:1 scale-up ratio. For full scale-up the radiating unit length should have been 87.5% of the drum center distance—impossible under spacial limitations in the pilot-scale equipment, but not in the commercial-scale. However, if production capacity increased in proportion to

[1] Use of a company or product name by the Department does not imply approval or recommendation of the product to the exclusion of others which may also be suitable.

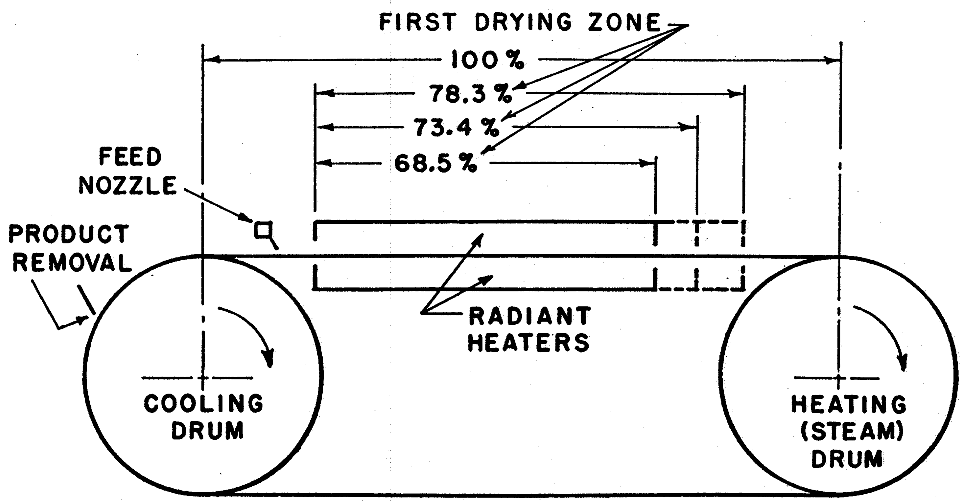

FIG. 1. Variation of first drying zone to test scale-up ratio.

this intermediate step, successful commercial production at the assumed rate could be anticipated with more confidence.

The research proceeded by determining the amount of water removed from the foam concentrate blanket in the first drying zone with three overall lengths of radiating units. As shown in Figure 1, the shortest length of heated belt was 68.5% of the distance between drum centers, the intermediate length was 73.4%, and the greatest length was 78.3%. The heating capacity of the radiating units per foot of length was constant along the whole heated length of belt. The width of the foam blanket was also constant. The feed rate to the dryer and the belt speed were adjusted proportionately with the stated percentages so that the belt loading (0.19 kg conc/m^2) and exposure time of foam to heat (24.2 secs) were the same at all lengths.

Moisture contents were determined on samples of partially dried foam removed from the belt at the end of the first drying zone. The data from 32 experiments analyzed statistically were used to develop a prediction equation relating amount of water driven off to area of foam in the first drying zone at the standard belt loading and residence time in the first zone. The prediction equation was: $y = (14.343\,l - 2.870)w$

where y = kg water removed per hour
l = length of first drying zone (m)
w = width of foam blanket (m)

Thus, if $l = 9.60$ m and $w = 1.19$ m, then 161 kg per hour water will be driven off in the first zone. This is equivalent to 157 kg per hour and compares favorably with the necessary rate for economic feasibility (154.4 kg per hr). Thus, it was shown that the scale-up ratio to project pilot-scale production rate to commercial-scale was valid. It was now necessary to determine any limitations in the feed nozzle or other parts of the plant that would prevent a commercial plant from operating at the projected production rate.

Plant performance at simulated commercial rates. According to the scale-up ratio just discussed, the belt of the commercial dryer must travel at five times (9.60/1.94) the speed of the pilot dryer if the heat exposure time in the first zone of each dryer is to be the same. As a result, the specific rate of feed to the nozzle (kilogram of concentrate per minute per centimeter of aperture length) must be increased five times. Since the concentrate-preparing part of the pilot plant was not large enough to produce five times the usual feed for the nozzle, the commercial condition was simulated by decreasing length of the nozzle opening by a factor of five while maintaining the usual concentrate rate. Tests under this condition showed that a smooth and continuous ribbon of foam could be applied to the belt at the required belt loading. Furthermore, when heat was applied in the first zone at the proper flux, the foam subsided five times as far from the nozzle as in the pilot tests. This occurred exactly where predicted by the scale-up ratio. These results indicated that the nozzle would perform well at five times the specific feed rate and that drying in the critical first zone would proceed as projected.

It is known that apparent viscosity and possibly surface tension of whole milk con-

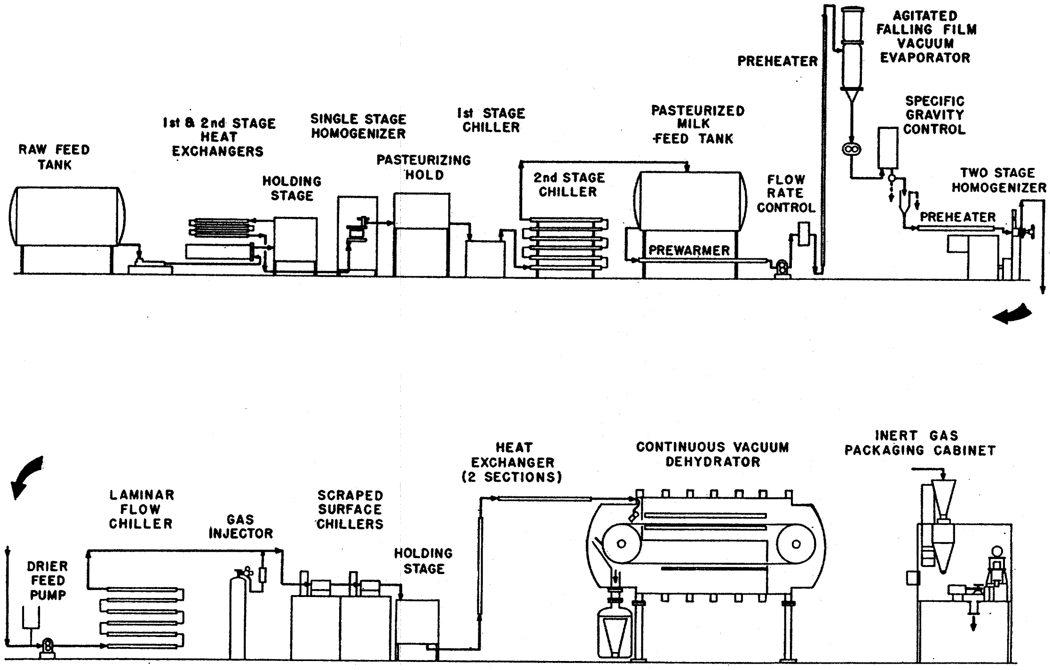

FIG. 2. Process flow diagram.

centrated as it was is time, shear stress, and temperature dependent. Both fluid properties have major effects on the properties of foams. Experiments were therefore run in which the residence time and temperature of the concentrate were varied between the evaporator and the dryer. Referring to Figure 2, the concentrate should be between 10 and 13 C on leaving the scraped surface chillers, that it should be held for at least 3 to 5 min between them and the nozzle, and that the ratio of the nozzle chamber volume to the specific feed rate should be at least 28 ml/(kg/min)(cm). If these conditions are not met, the foam will probably not flow smoothly from the nozzle, nor boil and subside satisfactorily in the first drying zone. In addition, there should be about a 30 mm Hg pressure drop across the orifices in the feed lines to the nozzle to prevent undesirable foaming of the concentrate in these lines.

Studies Concerned with Production Time

Another requirement for commercial scale operation is that a plant operate continuously for five days a week. Fulfillment of this requirement depended mainly on how long the evaporators could operate before they would have to be shut down for cleaning, and on how well a newly-designed multiple-blade doctoring system operated. Tests follow to answer these questions.

Evaporator fouling rate. The pilot-scale evaporator was a Model 1 Turba-Film Processor (Chemetron Corp., Louisville, Kentucky). The evaporation section was cylindrical, of 304 stainless steel, .516 cm thick, 20.32 cm inside diameter, 67.95 cm high, and 0.436 square meter heat transfer surface area. The rated capacity of the unit was 65.34 kg per hour of water evaporated.

In the usual pilot plant operation, fouling of the interior wall of the evaporator continued throughout an evaporation cycle, but its progression beyond six hours was unknown. A minimum necessary production cycle time for the evaporator in commercial operation was estimated to be 12 hr. Thus, a series of five 12-hr evaporation runs was made to determine fouling characteristics of the evaporator with time. For these tests, the feed was preheated to the vapor temperature (51.6 C). The feed was about 100 kg/hr and evaporation was about 73 kg/hr, which is somewhat above the design capacity. The milk was concentrated from about 12% solids to about 44.3%. The evaporator ran smoothly during the complete 12 hr of each run. To overcome fouling, the steam jacket pressure had to be increased from averages of 36.7 cm Hg (gauge) at the beginning to 82.8

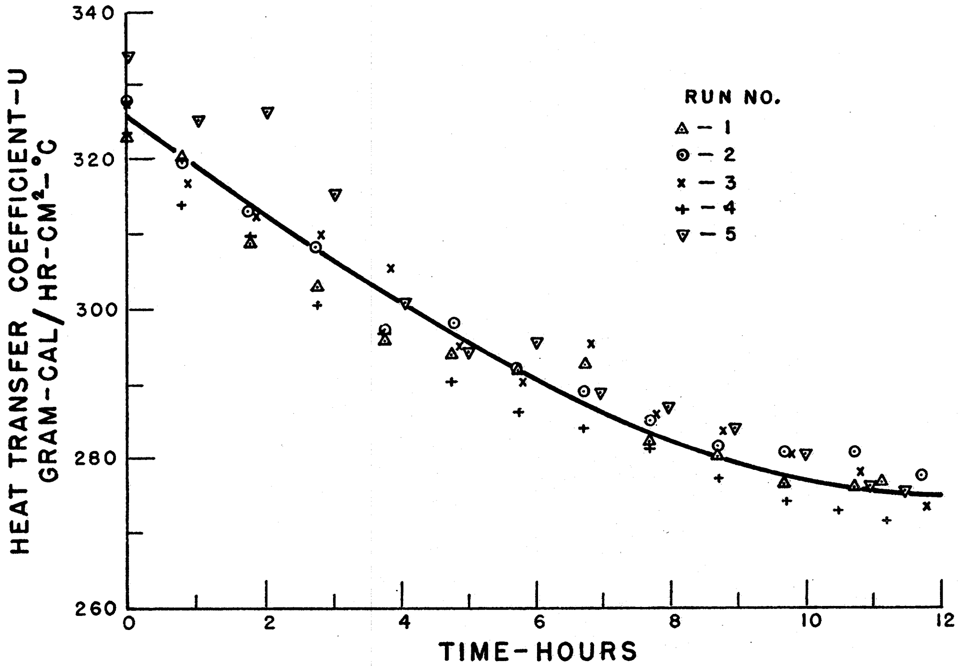

FIG. 3. Change in overall heat transfer coefficient during evaporation.

cm Hg (gauge) after 12 hr. Thus, when the evaporator is operated as reported here, it should be capable of running for at least 12 hr before it becomes necessary to shut down for cleaning.

Periodically, during each run, samples were obtained and an overall heat transfer coefficient (U) was calculated from the fundamental heat transfer equation: $q = U_i A \Delta t$

where U_i = overall heat transfer coefficient (g-cal/hr $\times$ cm^2 $\times$ C) based on inside wall area.

A = heat transfer area of evaporator (cm^2)

Δt = temperature difference driving force across the wall (C)

q = rate of heat transfer (g-cal/hr).

These overall heat transfer coefficients were plotted against time as in Figure 3. A curve was fitted to the experimental points by curvilinear regression and a statistical analysis showed it to be significant beyond the 99% confidence level. Figure 3 can be used to predict the performance of a larger evaporator of the same type operating with milk under the same conditions.

Multiple-blade doctoring system. On a pilot scale it had formerly been shown that a doctor blade made of Sandvik 11R51 stainless steel would clean the belt satisfactorily for the equivalent of five days, although these days were not consecutive. The belt in the projected plant, however, would travel at five times the speed of the pilot. Therefore, to clean five times as much belt with the same wear pattern would require five blades. To accomplish this a blade holder was designed and built in a rotatable turret with eight blades as discussed by Heiland (3). With this mechanism a dull blade could be replaced by a sharp one without interrupting the operation. Unfortunately, performance could not be tested at projected belt speed. For the blades to function properly the belt must be coated with dry foam and there was not enough heating capacity in the pilot dryer to accomplish this at five times the usual rate. It was confirmed, however, that the doctor blade would clean the belt satisfactorily for 120 hr. Furthermore, it was demonstrated that the multiblade turret successfully replaced a worn blade with a sharp one. Finally, if the blade wears at a higher rate in the commercial unit than anticipated, a holder with more than eight blades could be built.

Discussion

Commercial adoption of any process must ultimately depend upon its potential for profit-making and its technical feasibility. The process for manufacturing vacuum foam-dried whole milk was previously shown to have a good profit-making potential (8). The present work optimized the technical feasibility of the process by eliminating all foreseeable "bugs" that may arise when this is scaled-up to commercial size. This has been successfully accomplished. Thus, insofar as pilot scale work can predict, the vacuum foam-dried whole milk process is ready for commercialization.

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