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Marijana Caric

Miloslav Kalab

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**EFFECTS OF DRYING TECHNIQUES ON MILK POWDERS QUALITY AND MICROSTRUCTURE:  
A REVIEW**

Marijana Carić and Miloslav Kaláb

Faculty of Technology, University of Novi Sad  
Veljka Vlahovića 2, 21000 Novi Sad, Yugoslavia  
and

Food Research Centre, Research Branch, Agriculture Canada  
Ottawa, Ontario, Canada K1A 0C6

Abstract

The quality of milk powders is markedly affected by the composition and properties of the milk, the manufacturing procedures, thermal processing during manufacture and, in particular, the drying technique itself. A variety of physico-chemical analytical methods, including scanning electron microscopy, has been used to obtain information on the effects of the various factors on the microstructure of the milk powders. Roller-drying, which has recently lost its commercial importance, produces a sheet of dried milk that is powdered in a hammer mill. The resulting powder consists of compact particles with sharp edges. Powders obtained by spray-drying are in the form of more or less regular globules which may have their surface convoluted to a varying extent. Inside, the particles are porous. Lactose present in the particles is in an amorphous glass form. In instant milk powders, the powder particles are agglomerated and lactose is partly converted into microcrystalline form.

Introduction

The technique of drying of milk was developed many centuries ago. Initially, the milk was dried primitively in the sun. One of the earliest reports was made by Marco Polo. In his 13th century journeys, he described the production of dried milk products and their subsequent rehydration and consumption [in reference 14]. However, industrial production of dry milk was initiated only in 1810. At that time, Nicholas Appert in France developed and described a procedure of evaporating milk to one third of its initial volume in an open vessel [14]. This product was made in a pill form and was air-dried to remove residual moisture [33]. The first commercial dry milk production was based on a British patent granted to Grimeade in 1855. Sodium or potassium carbonates and sucrose were used as ingredients in the dried milk [14]. The manufacture of a milk powder free from any alien ingredient was first reported in 1898 for which a number of patents was granted following extensive experimentation. Soon afterwards, in 1902, the first drum-drying equipment was designed and put into service. The development of spray-drying equipment and procedure can be traced to a patent granted to Percy in 1872 in the U.S.A. [in reference 30]. Improvements have been made since then.

The introduction of an instantizing procedure characterized by two-stage drying [18, 34-36] has markedly improved the drying technique and improved the quality of the milk powder. More recently, a three-stage spray-drying procedure is used to produce a superior product at a low energy consumption [2, 3, 8, 18, 24, 26, 30].

Under certain conditions, dried milk products have several major advantages over fresh milk products. These advantages include lower mass and volume than the fresh products which means that they may be stored in a smaller storage space with no special storage requirements, and may be transported more easily and at a lower cost.

Drying of milk balances the supply of milk with the demand for it. Dried surplus milk can be stored for long periods of time. Thus, it forms a stable food reserve for future use. The demand for dried milk is rapidly increasing in developing countries. There, the milk is reconstituted in recombining dairy plants and is used to combat malnutrition [11, 25]. Because dried milk products retain their high quality for a long time, they are irreplaceable in human nutrition in hot climates. They are also of importance in averting starvation in catastrophic situations such as earthquakes,

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Direct inquiries to M. Kaláb  
Telephone number: 613-995-3722 x7707

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epidemics, or wars. It is essential, of course, that the local population can digest milk. For those who cannot, it is possible to produce low-lactose milk powders. Thus, milk powders are used on a global scale to correct the imbalance between the need for high-quality nutrients and their temporary scarcity.

The drying technique markedly affects the physical, chemical, and microbiological properties of the finished product. The objective of this review is to compile information on the effects of the drying techniques most commonly used on the structure and related properties of powdered milk.

#### Principles and Techniques of the Drying of Milk

An objective of modern dairy technology is to produce high-quality milk powders. Following reconstitution, the products should closely resemble fresh milk particularly as far as nutritional and sensory properties are concerned. However, milk powders manufactured for various uses in the food industry may differ in quality parameters. The following powders are produced most commonly: skim-milk powder, partly skimmed milk powder, and whole-milk powder. Of the three types listed, skim-milk powder is the dairy ingredient most frequently used in the food industry. Thus, it represents the largest part of the milk powder production. There are several reasons for its popularity, all of which are associated with the absence of milk fat in the product. One reason is the resistance of the skim milk powder to the development of rancid off-flavour during long-time storage. Another reason is the easy recombination of the powder with vegetable fats which makes it possible to adjust the fat content in the reconstituted milk product to the desired level.

Skim milk powder is graded according to the heat treatment of the skim milk during production. The amount of undenatured whey protein present in the powder, expressed in mg N/g of powder as the 'whey protein nitrogen index' (WPNI), is closely related to the heat treatment. In low-heat powders, WPNI exceeds the value of 6.0, in medium-heat powders, WPNI ranges from 1.51 to 5.99, and in high-heat powders, WPNI is below 1.5. Varying heat treatments impart various properties to the skim-milk powders produced. Low-heat powder is used, e.g., in recombined pasteurized milk and cream production because it ensures that the resulting products are free of a cooked flavour and thus resemble fresh milk products [44]. High-heat powder is commonly used as an ingredient in bakery products. Bread produced with this powder has an increased water-binding capacity and improved flavour and texture characteristics [13], with the loaf shrinkage considerably reduced. To produce reconstituted evaporated milk products from milk powders, the desired heat stability is achieved by high-temperature heat treatment of the skim milk prior to powder production [8, 44]. Thus, because of their functional and nutritional properties, various milk powders are used as ingredients in many foods. The reasons leading to the use of the powders in the foods have been discussed in greater detail elsewhere [13, 17, 24, 27-29, 31].

Functional properties of milk powders include emulsification, fat absorption, system stabilization, water binding, viscosity, gelation, texturization, consistency formation, plastic properties formation, fibrous structure formation, adhesion and cohesion, aeration, foam stabilization, flavour enhancement, and increased yield of the product. Because of these functional

properties, it is beneficial to use milk powders as ingredients in many foods to improve their quality and appeal. A wide range of applications of milk powders was recently reviewed by several authors [8, 9, 13, 17, 27-29, 31]. Milk powders are used directly or indirectly in foods made at home, in bakery products, confectionery products, meat products and meat substitutes, convenience foods, beverages, and dietetic products. They are also used in pet foods and animal feed.

Currently, there are several technological systems used in the dairy industry to dry milk:

##### Roller drying:

- Roller drying at atmospheric pressure
- Vacuum roller drying

##### Spray drying:

- Centrifugal atomization
- Pressure atomization
- Foam spray drying
- Steam swept wheel atomization
- Venturi spraying
- Two-stage spray-drying system producing non-agglomerated powders (1970)
- Three-stage spray-drying system producing either agglomerated or nonagglomerated powders (1980)

##### Foam mat drying

##### Freeze drying

Only systems which are commonly used in the dairy industry will be discussed in greater detail in this paper.

Spray-drying systems have been the subject of intensive research and development in the past few years although consideration has also been given to some other drying systems. However, these attempts failed. The current trend is to continuously modify and improve the spray-drying systems.

A decade ago, a two-stage drying system with an external vibrating fluid bed was developed for the production of non-agglomerated powders [39]. Using this system, processing has been improved economically and the products have attained higher quality because lower drying temperatures were used during the final phase of drying. This method is also used to produce milk powder which is less hygroscopic than regular milk powder.

The introduction of a stationary fluid bed integrated in the drying chamber is the most recent innovation of the spray-drying technique. The stationary fluid bed was developed and introduced in industrial use in the 1980's. This development makes it possible to maintain a higher moisture content in the milk during the initial stage of drying and is characterized by a lower outlet air temperature in comparison with the other spray-drying systems. This means that the economic as well as the quality parameters are improved and a free-flowing agglomerated powder is produced. The flow chart of this three-stage drying process is shown in Fig. 1.

The newest spray-drying procedure has been described in detail by several authors [1, 39, 40, 43] and the corresponding processing performances are presented in the technical documentation by the producers of the equipment [2, 3].

#### Effects of Drying Techniques on the Microstructure and Related Properties of Dried Milk

Initial electron microscopic observations of milk and milk products were made in Switzerland by Hostettler and Imhof [16] in 1952. Buma and Henstra [7] were the first to publish micrographs obtained by scanning

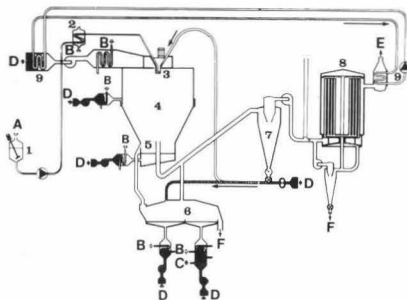


Fig. 1. Flow chart of the three-stage spray-drying process. 1: feed tank, 2: concentrate preheater, 3: atomizer, 4: spray-drying chamber, 5: integrated fluid-bed, 6: external fluid-bed, 7: cyclone, 8: bag filter, 9: liquid coupled heat exchanger, A: product inlet, B: steam, C: cooling water, D: air inlet, E: air outlet, F: product outlet. (Courtesy of APV Anhydro A/S).

electron microscopy (SEM) of spray-dried milk powders in 1981. SEM has been used more frequently [6, 7, 19-22, 38] than transmission electron microscopy (TEM) [5, 32] to study the structure of milk powders. This is because each electron microscopic technique provides a different type of information. SEM is appropriate to study the surface morphology as well as internal structure of the milk powder particles whereas TEM techniques such as thin-sectioning [32] or freeze-fracturing [5] make it possible to identify the individual powder constituents such as casein micelles and fat particles.

Quality, i.e., a complex of physico-chemical and sensory attributes of the dried milk products, is influenced by the following factors acting on milk during the manufacturing process, or later, during storage:

- (a) chemical composition of the raw materials (high fat or protein content in the dairy product, presence of non-dairy ingredients),
- (b) manufacturing techniques and parameters (separation of fat, preheat treatment, homogenization, evaporation),
- (c) drying techniques and conditions (roller drying, various methods of spray drying, instantization, multi-stage drying),
- (d) storage conditions (packaging materials and methods, temperature and duration of storage, water activity in the product).

Of all the factors mentioned above, the drying techniques and conditions affect the microstructure (dimensions, shapes, and density of the particles) to the greatest extent. Main definitions and a possible classification of food powders according to their physical characteristics have been published in detail by Peleg [37]. Bulk properties of the powders are determined by their physical and chemical characteristics as well as by the processing system (Fig. 2) [30].

#### Roller Drying

Roller drying is accomplished by a direct heat transfer from a hot drum into a thin layer of evaporated milk. After the water present in the milk evaporates, the solids are scraped off and pulverized in a hammer mill. Consequently, the dry particles have a characteristic structure (Figs. 3 and 4). The irregular shapes and sharp edges of the particles reveal that the powder was produced as a result of crushing. The particles are compact and contain no occluded air. Even if some aeration takes place in the pipelines while evaporated milk is being conveyed to the drums, the air escapes from the milk during roller drying. The milk is

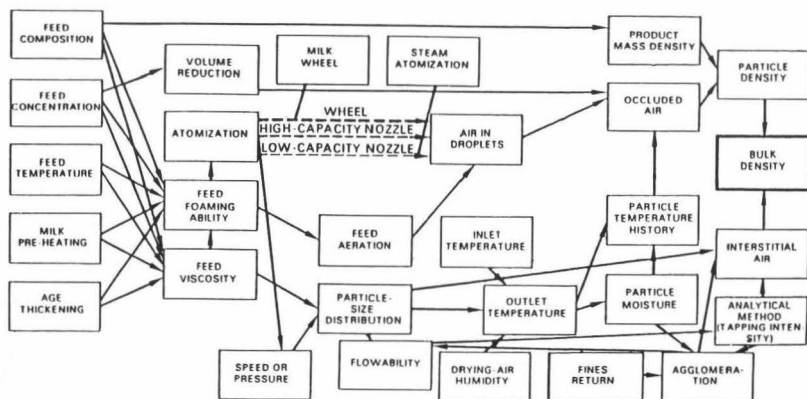


Fig. 2. Effects of various factors on the bulk density of spray-dried milk powders. Source: [30].

degenerated irrespective of whether the atmospheric pressure or the vacuum roller-drying procedures are used. This is evident from the equally compact structures of the resulting powders. Although the thickness of the evaporated milk layer on the hot drum may affect the particle size, the final dimensions of the particles are determined by the hammer mill.

Despite the compactness of the roller-dried milk particles, their irregular structure contributes to a low bulk density (i.e., mass-to-volume ratio) of the powder which is lower than that of spray-dried milk powder. Low bulk density is undesirable in milk powder because it leads to higher packaging, storage, and transportation costs per kg of powder. Bulk densities of non-fat milk powders produced by various processes are presented in Table 1 [14].

Table 1  
Bulk Densities of Skim Milk Powders  
Produced by Various Processes

Drying process	Bulk density (g/cm <sup>3</sup> )
Spray-drying	0.50 - 0.60
Roller-drying	0.30 - 0.50
Foam spray-drying [USDA*]	0.32
Spray-drying [commercial]	0.26
Instant spray-drying [commercial]	0.59

\* United States Department of Agriculture.

Source: Hall and Hedrick [14].

#### Spray Drying

Atomization of fluid milk into small droplets usually causes the spray-dried milk powder particles to be spherical with diameters in the range of 10 to 250  $\mu\text{m}$ . The particles contain occluded air in the form of vacuoles varying in dimensions. Some powders have a large central vacuole (Fig. 5) whereas in other powders, e.g., those produced by centrifugal atomization, small vacuoles are distributed relatively evenly across the particles (Fig. 6).

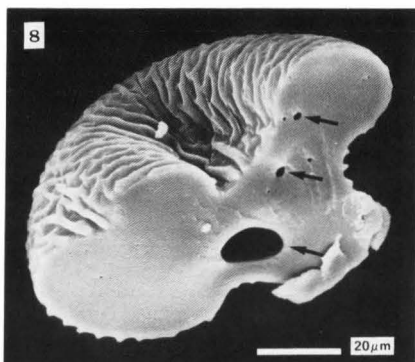
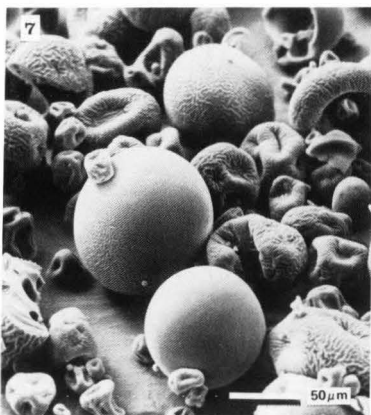
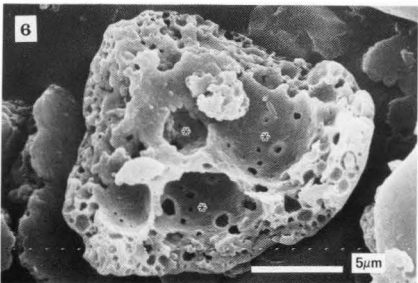
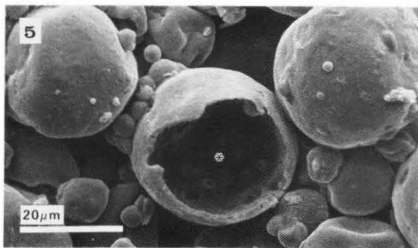
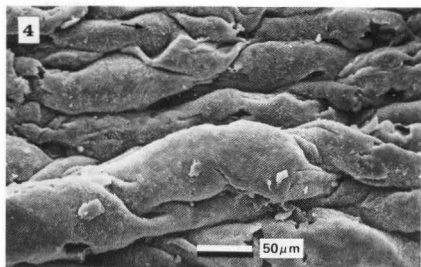
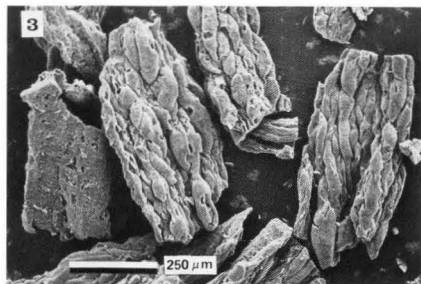
The surface of spray-dried particles is usually smooth but may also be wrinkled. The vacuoles in both the smooth and wrinkled particles occasionally contain minute dried milk particles. The external appearance as well as the internal structure of milk powders were studied by Buma and Henstra [7]. These authors used a nozzle atomization pressure of 7.85-9.80 MPa (80-100 kg/cm<sup>2</sup>). They found that even particles of the same powder, e.g., skim-milk powder, may have different superficial structures (Figs. 7 and 8). The presence of smooth particles as well as particles having severe surface folds in the same sample is attributed to the different drying conditions to which the individual particles were exposed. Buma and Henstra [7] have suggested that the formation of the deep surface folds in the skim-milk powder particles is caused by the presence of casein in the skim milk. This suggestion is based on a comparison of micrographs of a spray-dried skim-milk powder (Figs. 7 and 8) with those of a spray-dried whey powder (Fig. 9). As far as the drying conditions are concerned, there is a greater tendency to form wrinkles as the temperature of the inlet air is increased. Also, large temperature differences between

the hot air and the milk powder particles [15] contribute to the formation of the wrinkles. Generally speaking, centrifugal and nozzle atomization of milk destined for spray-drying result in the production of powder particles that have similar morphology. As far as the bulk density and the free-flowing characteristics of the powders are concerned, the nozzle atomization system appears to be preferred to the centrifugal disk atomization. On the other hand, higher feed concentrations may be used with the latter system. This means that the energy consumption is lower with the centrifugal disk atomization system [43] than with the nozzle atomization system.

De Vilder et al. [45] studied the effect of the spray-drying conditions on the physical characteristics of whole-milk powder using the centrifugal atomization system. When the inlet air temperature was raised to 225°C from 155°C, the bulk density and the mean powder particle density were decreased whereas the vacuole volume was increased. This was evidently caused by rapid drying and moisture expansion in the powder particles. A similar finding was made earlier by the same authors [45] with powders produced by nozzle atomization. These authors also studied the effects of outlet temperatures varied from 70° to 105°C while the inlet temperature remained constant at 195°C. At a low (70° to 95°C) outlet air temperature, uniform drying was achieved throughout entire powder particles. Because there was little expansion of air at that temperature, the combined volume of the vacuoles was small. Higher outlet temperatures (95°C to 105°C) led to overheating of the milk, expansion of the trapped air bubbles, formation of cracks in the particle surface, a higher combined vacuole volume, and a low mean density of the powder particles. Consequently, the bulk density of such milk powder was low. High outlet air temperature may lead to high porosity of the powder particles if the concentration of total solids in the milk to be dried is low [11]. The fact that the outlet temperature has the greatest effect on the overall milk powder quality has been well known [8, 12, 26, 30, 38]. De Vilder et al. [45] also found that the bulk and mean powder particle densities were decreased as the number of the atomizer revolutions was increased.

Bloore and Boag [4] studied the effect of nozzle atomization on the quality of the resulting skim milk powder using an empirical approach. They reported regression equations for the solubility index, bulk density, powder particle density, and powder particle dimensions as related to operation variables of the spray-drying equipment used. The regression equations obtained were in the form of second-order polynomials having the following 5 variables: (1) the total solids content of the concentrate to be spray-dried, (2) the feed rate, (3) the atomization pressure and (4) temperature, and (5) the inlet air temperature. The authors concluded that a high atomization pressure was preferable.

Müller [32] studied the distribution of casein micelles in spray-dried milk powders and found that they retained their globular nature. This finding was confirmed for skim-milk powder by Kaláb and Emmons [21] who examined spray-, roller-, and freeze-dried skim-milk powders by TEM and found 3 kinds of microstructure present. They found that powder microstructure failed to reflect the differences in the preheat treatment of the milk destined for spray-drying. Low-heat, medium-heat, and high-heat powder particles appeared to be similar.



*Fig. 3.* SEM of a roller-dried skim milk powder shows irregular particles with sharp edges.

*Fig. 4.* Detail of a roller-dried skim milk powder particle showing minute lactose crystals (arrow) on its surface.

*Figs. 5 and 6.* Large central vacuoles (Fig. 5, asterisk) or evenly distributed small vacuoles (Fig. 6, asterisks) are present in spray-dried skim milk powder produced by centrifugal atomization of the skim milk.

*Fig. 7.* SEM of spray-dried skim-milk powder produced by nozzle atomization of the skim milk shows various extents of surface wrinkling. (Courtesy of T. J. Buma and S. Henstra [7]).

*Fig. 8.* Fractured particle of spray-dried skim milk. The interior of the particle is compact with a few small vacuoles (arrows). The surface of the particle is wrinkled. (Courtesy of T. J. Buma and S. Henstra [7]).

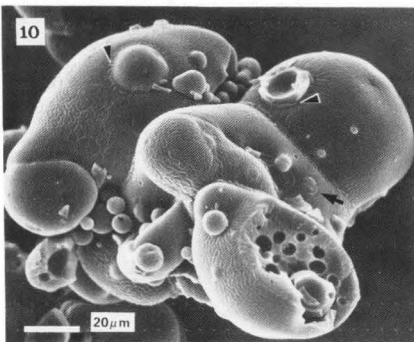
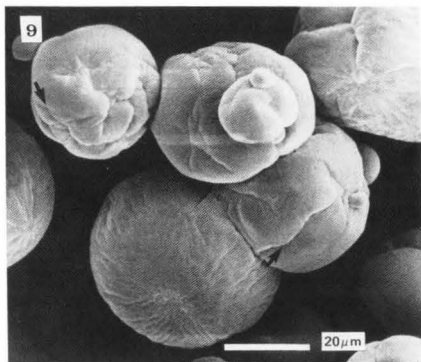
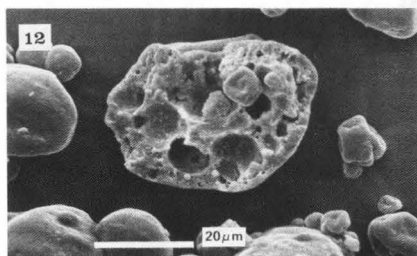
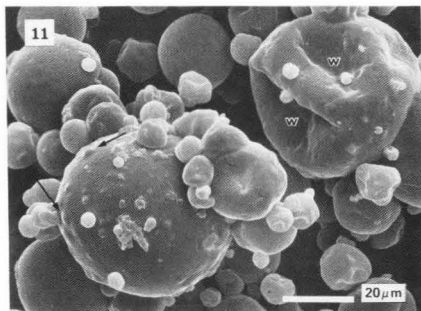


Fig. 9. Particles of spray-dried whey. The surface wrinkles (arrows) differ from those found in spray-dried skim milk. (Courtesy of T. J. Buma and S. Henstra [7]).

Fig. 10. Particles of spray-dried buttermilk made from sweet cream are characteristic by the presence of shallow wrinkles, rims around small smooth globules emerging from the large particles (arrowheads), and crater-like scars (arrow).

Various dairy products, e.g., buttermilk, subjected to the same spray-drying technique were characterized by diverse morphological features (Fig. 10). Such differences may be used to detect adulteration of spray-dried milk products with less costly products [20, 21].

Ultrafiltration may be used to increase the protein content in milk destined for spray-drying. During ultrafiltration, milk undergoes membrane fractionation of the constituents and the chemical composition of the ultrafiltered milk (retentate) differs from that of the original milk. In our experiments, milk retentates

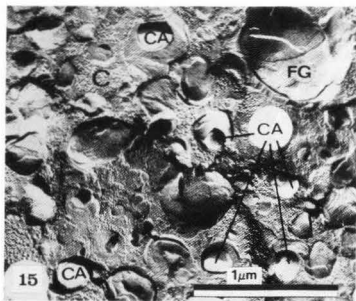
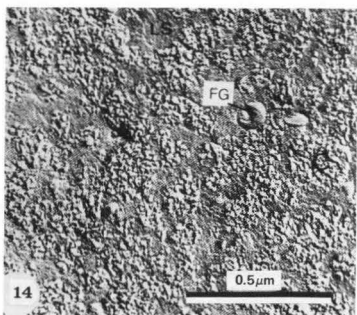
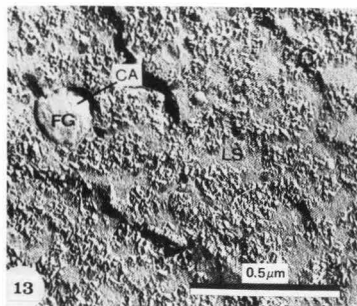


Figs. 11 and 12. Spray-dried milk retentates (centrifugal atomization, one-stage drying) resemble, in general, other milk powders as far as the surfaces and the internal structures are concerned. Occasionally, little bumps (arrows) appear on the surfaces. Deep wrinkles are noticeable (w) but shallow wrinkling is absent (Fig. 11). The particles are porous (Fig. 12).

containing 20%, 27%, and 34% of total solids were produced on a UF Module Type 35-GR-6-P (DDS, Pasilac, Denmark). The retentates were dried [47] in a spray-drier Type LAB 1 (APV Anhydro, Denmark) at an inlet air temperature of 220°C and an outlet air temperature of 90°C. Centrifugal atomization was used in conjunction with one-stage drying. SEM of the spray-dried retentates showed that they possessed all external (Fig. 11) and internal (Fig. 12) structural features characteristic of regular spray-dried milk powder particles and were indistinguishable from them.

Buchheim [5] freeze-fractured milk powders, replicated the fractures using platinum and carbon, and examined the replicas by TEM. Micrographs of low-heat (Fig. 13) and high-heat skim-milk powders (Fig. 14) and micrographs of whole-milk powder (Fig. 15) show casein micelles and fat globules as distinct entities dispersed in a lactose/salt matrix. The observations are in agreement with King's [23] finding that amorphous lactose partly forms the continuous phase in spray-dried milk powder particles. Although spray-drying is rapid, a small number of lactose crystals may be formed inside the powder particles. Warburton and Pixton [46]





Figs. 13 and 14. Freeze-fracturing reveals the internal structure and composition of skim milk powders: low-heat powder (Fig. 13) and high-heat powder (Fig. 14). C: casein micelles, CA: cavity in a fat globule, FG: fat globule, LS: lactose/salt matrix. (Courtesy of W. Buchheim [5]).

Fig. 15. Freeze-fracturing shows a high concentration of fat globules (FG) in whole-milk powder. C: casein micelles, CA: cavities in fat globules. (Courtesy of W. Buchheim [5]).

reported the presence of prism-shaped lactose crystals in freshly produced milk powder particles mounted in the Heinz fluid (Fig. 16). Saito [42] found no lactose crystals in freshly produced milk powders examined by SEM and X-ray diffraction analysis. However, he observed numerous prismatic and diamond-shaped lactose crystals after the milk powder particles were mounted in the Heinz fluid and concluded that the crystals developed during mounting. The presence of lactose crystals in milk powder is the sign of improper storage associated with exposure of the powder to high humidity.

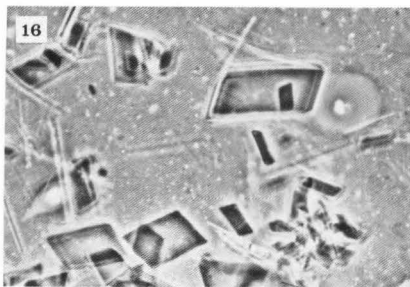


Fig. 16. Light microscopy of prism-shaped lactose crystals in freshly produced spray-dried milk mounted in the Heinz fluid. (Courtesy of S. Warburton-Henderson [46]; copyright Slough Laboratory; magnification not shown).

Roetman [41] studied lactose crystal formation in spray-dried milk powders and the effect of lactose crystallization on the milk powder particle structure based on experiments with spray-drying various model solutions. His electron micrographs showed that crystalline lactose present in the milk powders was either 'precrystallized' (i.e., the crystals originated in the milk concentrate prior to drying) or were 'postcrystallized' (i.e., the crystals developed after spray-drying). The origin of the crystals was reflected by their shapes. Precrystallization resulted in a tomahawk form of the lactose  $\alpha$ -hydrate. Needle-like crystals of the lactose  $\beta$ -anhydride were formed in postcrystallized products.

In spray-dried whole-milk powder, fat is present both at the surface of the particles in the form of pools and inside the particles in capillary pores and cracks. The portion of the which may be reached by fat solvents was called extractable fat by Buma [6] who studied it in greater detail. Another portion of the fat, which is present in larger amounts in homogenized than in nonhomogenized milk, is encapsulated in the powder particles where it is complexed with milk proteins; it cannot be extracted easily and is resistant to oxidation [6]. Because homogenization stabilizes the fat in this way, it is an important step in the production of spray-dried whole-milk powder; it is not, ordinarily, a required step in the processing schedule.

Dimensions of the spray-dried particles are influenced by the temperature of drying, concentration, and viscosity of the milk to be dried, and the atomizing system used. Foam spray drying produces the largest



Table 2.  
Characterization of Spray-Dried Skim Milk Powders

Atomization method	High- single nozzle	Medium- capacity* multiple nozzles	Low- multiple nozzles	Steam-swept wheel	Rotary wheel		
					A	B	C
Feed conc. [% total solids]	42	44	42	45	46	50	50
Inlet air temperature [°C]	195	170	170	180	200	200	250
Moisture content [%]							
in the powder	3.2	3.6	3.4	3.7	3.8	3.6	3.9
Bulk density of powder							
tapped 100x	0.62	0.72	0.72	0.79	0.62	0.76	0.71
tapped 1250x	0.65	0.76	0.77	0.83	0.65	0.80	0.74
Solubility index [mL]	0.3	0.8	0.2	0.3	0.1	0.05	0.1
Vol. of vacuoles [mL/100 g]	26.0	13.5	4.0	5.5	21.5	11.8	14.3

\* A limited number of samples was available from commercial production. The listed operating conditions and other results may not represent the optimum.  
Source: Plšeký [38].

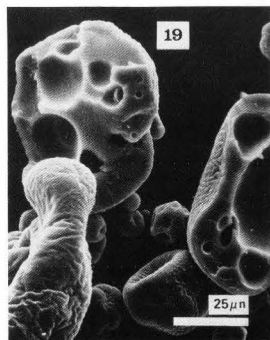
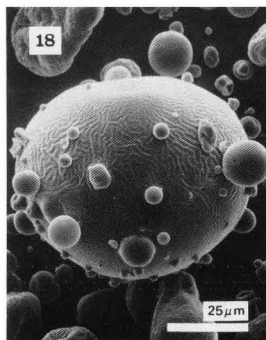
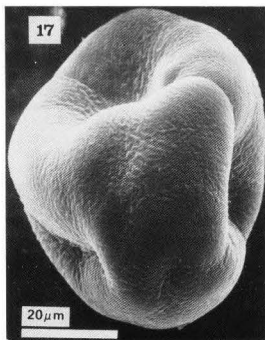
powder particles. They are followed, in size, by particles obtained by centrifugal atomization. The nozzle atomization system produces the smallest powder particles.

A high quantity of occluded air in spray-dried milk particles is undesirable because it results in low bulk density of the powder. The quantity of occluded air is about the same in milk powders obtained by centrifugal and high-capacity pressure atomization. However, the bulk density of powders obtained by nozzle atomization in low-capacity plants is higher and this is evident from Table 2 [38]. Vacuoles in spray-dried milk particles originate as the result of air incorporated in concentrated milk prior to spray-drying and during the drying process. Evaporation acts like a deaerator, while atomization during spray-drying introduces air into the milk. Plšeký et al. [38] designed a special atomizer called a 'steam-swept wheel'. Here, steam is introduced into the atomizer and, consequently, the air-liquid interface is replaced with a steam-liquid interface. The effect of atomization on the

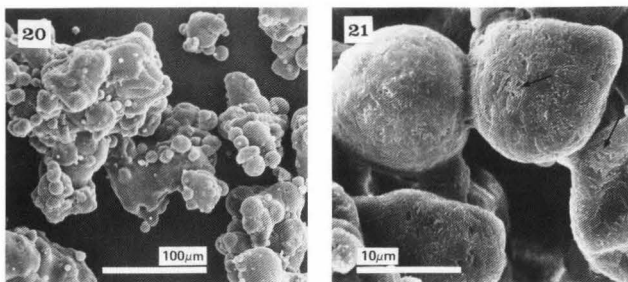
shrinkage of the milk particles is evident from Figs. 17 to 19 and from Table 2. A two-stage spray-trying system has a similar effect on particle shrinkage.

So-called instantation of milk powders is an additional development in the drying of milk. The objective is to agglomerate the primary milk powder particles in order to make their dissolution in water easier. Agglomeration changes the microstructure of the powders (Figs. 20 and 21). Partial conversion of the amorphous glass form of lactose into a microcrystalline form also takes place as the result of instantation. This is accomplished by maintaining a higher moisture content in the powder particles during the two-stage drying process. This moisture is removed following the agglomeration of the powder particles.

Milk powders produced in the three-stage spray-drying system are similar in appearance [1-3, 39, 40, 43] to instant powders obtained in the two-stage system (Figs. 20 and 21). The primary powder particles are agglomerated to a varying extent depending in the equipment and the drying process used.



Figs. 17-19. SEM micrographs showing the effect of atomization on the appearance of skim milk powders. Fig. 17: Steam-swept wheel atomization. Fig. 18: High-capacity nozzle atomization. Fig. 19: Medium-capacity nozzle atomization. (Courtesy of J. Plšeký [38]).



Figs. 20 and 21. Powder particles are agglomerated in instant milk powders. Microcrystalline lactose (arrows) is noticeable at a higher magnification on particle surface (Fig. 21).

### Conclusions

Modern, sophisticated dairy technology makes it possible to dry milk in powder form. Nutritional and sensory properties of the reconstituted products resemble fresh milk very closely. However, the quality of the final product is affected by a number of factors such as the chemical composition of the raw milk and its treatment, drying techniques, and storage conditions. The most recent developments in the spray-drying technology are aimed at producing a wide variety of milk powders at a low energy consumption and capital costs as low as possible. The powders produced should have excellent properties (free-flowing property and solubility) and retain high quality during storage.

Although many effects are interrelated, the drying conditions affect the microstructure and related properties most severely. SEM has been used more frequently than TEM to investigate the microstructure of the milk powders. Particle dimensions, shapes, and densities as well as the presence of lactose crystals can be easily evaluated by SEM. TEM is more suitable to identify the particular powder constituents. TEM studies have shown that casein micelles and fat globules are dispersed in an amorphous matrix composed of lactose, whey proteins, and salts. In whole-milk powders, fat is present both at the surface and in the capillary pores as well as in cracks inside the powder particles.

Spray-dried particles are mostly spherical and contain vacuoles of occluded air inside. The surface of spray-dried particles is usually smooth with a high occurrence of wrinkles and deep folds. The tendency to form wrinkles is greatest at high inlet air temperature and also when large temperature differences occur between the hot air and the milk particles. Centrifugal atomization as well as nozzle atomization, followed by spray-drying, produces powder particles of similar morphology. Steam-swept wheel atomization leads to particle shrinkage and a high bulk density of the powder. Physical characteristics of the powder particles such as vacuole volume, bulk density, free-flowing properties etc. are closely correlated with the particle microstructure. In contrast to spray-dried powders, roller-dried milk powder particles are compact and have characteristic irregular shapes with sharp edges.

Powder particle dimensions are influenced by the concentration and viscosity of the milk, the atomizing system, and the temperature of drying. Foam spray-dried particles are largest, particles obtained by centrifugal atomization and smaller and particles produced by nozzle atomization are smallest.

With instantization and integrated fluid bed technologies well established, it is assumed that the future trends in milk powder production will be in the modification of processes and equipment used. Electron microscopy will be a tool to evaluate the effects of the

innovations. It will continue to provide information about the microstructure of the powders as related to their other physical properties.

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*Editor's Note: All of the reviewers' concerns were appropriately addressed by text changes, hence there is no Discussion with Reviewers.*