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Review

Spray drying of dairy products: state of the art

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Abstract – Milk is extremely perishable, and yet, for a number of reasons, it has to be preserved for later consumption. The removal of water prevents the growth of micro-organisms and facilitates preservation and storage of milk constituents. Spray drying is one of the most convenient techniques for producing milk powders and for stabilizing milk constituents. Before spray drying, the milk undergoes several processes (such as heat treatment, cream separation, membrane processes, vacuum evaporation and homogenization). The chemical, physical, technological, nutritional, functional and microbiological properties of final products are influenced by a number of factors such as operating conditions, properties of the dairy products and storage conditions. The aim of this review is to describe the process of spray drying of dairy products and to review the present and recent advancements of knowledge on the properties of spray-dried milk products, on modelling and water transfer simulation (drying and rehydration), dairy powders and the spray drying equipment and energy consumption.

Spray drying / milk

Résumé – **Séchage par atomisation des produits laitiers**. Le lait est extrêmement périssable, mais pour un certain nombre de raisons, il est souhaitable de le préserver pour une utilisation postérieure. L'élimination de l'eau (diminution d'activité de l'eau) empêche la croissance des micro-organismes et améliore la conservation des constituants du lait. Le séchage par atomisation est une des techniques les plus utilisées pour produire des poudres de lait afin de stabiliser les constituants de lait. Cependant, avant le séchage par atomisation, il est nécessaire d'appliquer successivement plusieurs opérations unitaires telles que le traitement thermique, l'écrémage, la filtration tangentielle, l'évaporation sous vide et l'homogénéisation. Les propriétés des produits finis (propriétés chimiques, physiques, technologiques, nutritionnelles, fonctionnelles et microbiologiques) sont influencées par un certain nombre de facteurs impliquant les conditions de fonctionnement, les propriétés des matières premières mises en œuvre et les conditions de stockage. L'objectif de cette revue est d'établir un état de l'art sur le séchage par atomisation des produits laitiers et de passer en revue les acquis sur les propriétés

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des produits laitiers déshydratés, sur la modélisation et la simulation des transferts de l'eau (séchage et réhydratation), sur les différentes poudres d'origine laitière ainsi que sur le matériel de séchage par atomisation et la consommation énergétique.

Séchage par atomisation / lait

1. INTRODUCTION

Dehydration of milk and whey is intended to stabilize these products for their storage and later use. These powders are used mostly in animal feeding. With changes in agricultural policies (like the implementation of the quota system and the dissolution of the price support system), the dairy industry was forced to look for a better use for the dairy surplus and the by-products of cheese (whey) produced from milk and butter milk manufactured from cream. Efforts have been made to reuse protein fractions whose nutritional qualities and functionality led us to believe that they could have multiple applications. The result has been a change in the nature of dairy powders over the last fifteen years [10, 11]. The total quantity of powder has not varied (about 1 400 000 t in 1986 and in 2000) but the amount of milk powder decreased by 40% between 1986 and 2000. This decrease was observed essentially for skim and fatty milk powders. The production of whole milk powder and whey powder, however, increased by 60% and 73%, respectively between 1986 and 2000. This increase was reflected in the types of whey and derived powders (protein concentrates) produced. This overall change may be explained by the quota system implemented, which gives a better control over dairy production. Cheese production from cow's milk having increased by 31% between 1986 and 2000, there was a corresponding increase in whey production and a decrease in milk powder production.

Since the 80s, the dairy industry has developed new technological processes for extracting and purifying proteins (casein, caseinates, whey proteins, etc.) [36, 49], such as dairy proteins and whey concentrates [9, 23, 44, 46, 50], micellar casein concentrates [18, 67], native phosphocaseinate suspension (NPCS) [56, 68], whey concentrates, selectively demineralized concentrates [29], and super-clean skim milk concentrates [57, 67, 78, 80], in large part due to the emergence of filtration technology (microfiltration, ultrafiltration, nanofiltration and reverse osmosis).

Most of these proteins, used either as nutritional or functional ingredients, are marketed in dehydrated form (Fig. 1). Milk "cracking" in different dried and stable forms led to a sudden increase in the use of intermediate dairy products. Many new uses of these constituents appeared with the manufacture of formula products, substitutes and adapted raw material.

The most frequently used technique for dehydration of dairy products is spray drying. It became popular in the industrial world in the 70s, but at that time, there were few scientific or technical studies on spray drying and none in particular on the effects of spray drying parameters and on the effects of the physico-chemical composition and microbiology of the concentrates on the powder quality. Manufacturers acquired expertise in milk drying and eventually in whey drying processes through trial and error. Today, due to the variety and complexity of the mixes to be dried, a more rigorous method based on physico-chemical and thermodynamic properties has become necessary. A better understanding of the biochemical properties of milk products before drying, water transfer during spray drying, the properties of powders and influencing factors has now become indispensable in the production of milk powder. The lack of technical and economical data and

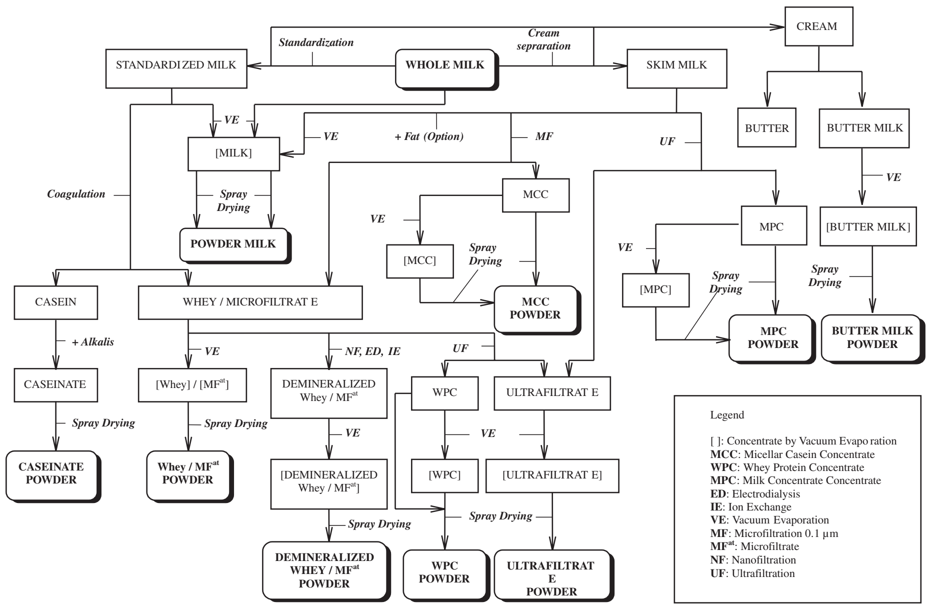

Figure 1. "Cracking" of milk.

of scientific methods, prevents the manufacturer from optimizing his installations in terms of energy costs and powder quality.

The aim of this review is to give a brief summary of the process of spray drying of dairy products and to review present knowledge on the properties of spray-dried milk products, on the modelling and simulation of water transfer processes (drying and rehydration), on dairy powders and on spray drying equipment and energy consumption.

2. PROPERTIES OF SPRAY-DRIED MILK PRODUCTS

A dairy powder is not only characterized by its composition (proteins, carbohydrates, fats, minerals and water) but also by its microbiological and physical properties (bulk and particle density, instant characteristics, flowability, floodability, hygroscopicity, degree of caking, whey protein nitrogen index, heat number, thermostability, insolubility index, dispersibility index, wettability index, sinkability index, free fat, occluded air, interstitial air and particle size) which form the basic elements of quality specification, and there are well-defined test methods for their determination according to international standards [1, 48, 61, 62, 64]. These characteristics depend on drying parameters (type of tower spray dryer, nozzles / wheels, pressure, agglomeration and thermodynamic conditions of the air: temperature, relative humidity and velocity) and characteristics of the concentrate before spraying (composition / physico-chemical characteristics, viscosity, thermo-sensibility and availability of water). Several scientific papers on the effect of technological parameters on these properties have been published [2, 5, 6, 15, 16, 24, 28, 34, 47, 48, 58, 59, 61, 79].

Water content, water dynamics, water availability is one of the most important properties (Fig. 2).

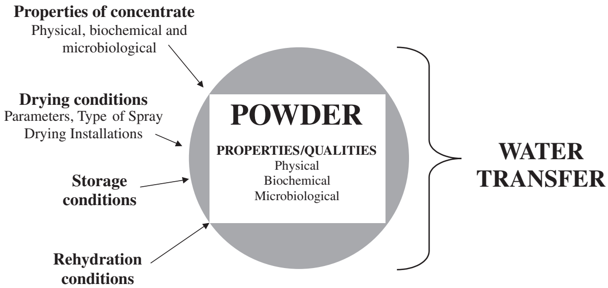

Figure 2. Properties and qualities of powders.

The nutritional quality of dairy powders depends on the intensity of the various kinds of thermal processing during the technological process. The thermal processing induces physico-chemical changes which tend to decrease the availability of the nutriments (loose of vitamins, reduction of available lysin content and whey protein denaturation) or to produce nutritional compounds such as lactulose [76, 77].

3. MODELLING, SIMULATION AND WATER TRANSFER DURING DRYING AND REHYDRATION OF DAIRY POWDERS

The physical and biochemical qualities of milk powder depend on the water distribution in the concentrate at the air/water droplet interface which depends on the composition of the concentrate [4, 21, 66–68, 70–73, 81]. Roos [65] describes the physico-chemical properties of pure and bound water and the effect of water on the physical state, transition temperatures, sticking temperature, reaction kinetics and stability of milk products. The emphasis is on the physical state of non-fatty solids and the effect of water and its physical state on physico-chemical changes, growth of micro-organisms and stability [22, 30–32, 38–43, 63, 74]. These articles and Vuataz's recent works [82, 83] demonstrate the role of water before concentration, during spray drying and after drying (stability and preservation). There are, therefore, some studies on water and protein [3, 12, 66, 68, 71, 72] and water and lactose interactions [7, 8, 12, 17, 30–32, 65, 70, 74, 82, 83] and their effects on the functional properties of powders [14, 28, 45, 73]. Several authors tried to model the mechanisms of water transfer and the kinetics of drying in a droplet [13, 20, 21, 76, 77]. However, the complexity of the mathematical models presented makes it difficult for manufacturers to put them into practice.

4. DAIRY POWDERS

The different processes of spray drying, associated with membrane filtration, also affect the physico-chemical environment, the purity and the biochemical properties of milk powders and produce a range of powders with different physical and functional properties, such as high milk protein powder [52–54, 68], whey protein powder [25], whole milk powder [27, 33, 51] and high fat powder [27, 55]. Now, physico-chemical indications help the dairy industry to optimize drying parameters and characterize these new dairy concentrates (except the dry matter and the viscosity). Methods generally used to analyze solubility, dispersibility and wettability of milk powders [1, 19, 26, 64] give inadequate results because they do not fully take into account the new functions [28].

5. SPRAY DRYING EQUIPMENT AND ENERGY CONSUMPTION

For more than thirty years, spray drying has been the most frequently used milk drying technique. It is also the most convenient technique for producing powders directly from pumpable feeds. Indeed, it is since the 70s that there has been an increase in the capacity of tower spray dryers (from 1 to 6 t of water drained per hour). Recently, tower spray dryers from 10 to 15 t of water per hour were installed in New Zealand and in Australia. The total capacity and the number of tower spray dryers have more than doubled in a short time in certain countries [60].

Spray drying involves atomizing the feed into a spray of droplets which are put into contact with hot air in a drying chamber. There are three modes of contact: co-current, counter-current and mixed flow. Sprays are produced by a rotary (wheel) atomizer or nozzle atomizer [48].

The tower is a one-stage spray drying unit which means that the processing time in the spray drying chamber is very short (20 to 60 s on average). So, there is no real equilibrium between air humidity and product humidity. Therefore, if the outlet air temperature of drying is raised, the energy efficiency of the unit decreases [37, 48, 75]. The two-stage spray dryer consists of limiting spray drying for longer processes, and is therefore closer to thermodynamics balance. On being discharged from the spray drying unit, the product should have a compatible maximal moisture with continuous evacuation. This brings about a significant lowering of the outlet air temperature, and an increase in the inlet air temperature. In order to get the required residual moisture, the final drying takes place in an external vibrating fluid or vibro-fluidizer in which the air flow and the treatment temperatures are lower than in the chamber and so better designed for qualitative preservation of the powder [37, 48, 75]. The two-stage dryer shows us how to reduce drying costs and improve the performance of units: by transferring most of the drying from atomization to the fluidization phase until the wet product begins to stick the walls of the chamber. This contact is inevitable considering the internal agitation necessary for the thermal exchange. Removing this limit would mean the complete overhaul of the spray drying phase. This study led to the three-stage dryer, the biggest breakthrough in this field since the emergence of spray drying. Because it is impossible to do away with the walls of the unit, we had to try to minimize any contact between the walls and the wet product. The latter was stabilized and dried in an internal fluid bed inside the spray drying chamber [37, 48, 60, 75].

There are other spray dryer designs, such as the tall-form tower, flat-bottom chamber, restricted-height chamber, high or extra high-temperature chamber, box dryer and integrated belt chamber (Filtermat®). The kind of tower spray dryer depends on the specific properties of the product to be dried (high fat content, starches, maltodextrin, egg products, hygroscopic products, etc.) [37, 48, 62] and the choice of the technology used depends on the thermal efficiency (calculated according to different methods [4, 35, 48, 69]), the qualities and properties of the product to be dried and the powders to be obtained.

Recommendations for fire prevention in spray drying of milk: fire in spray dryers for milk or milk products can lead to dangerous situations for the operators, and may cause serious damage to plants and buildings. Fire prevention in this area is primarily promoted through efforts to avoid situations involving a fire hazard. So, any situation that threatens to involve a fire hazard must be quickly detected, either through a system of recording and automatic alarm, or through visual inspection. In the event that in spite of all precautions, a fire should break out, provisions must have been made to prevent personnel injury and to limit material damage.

6. CONCLUSIONS

This review discusses the complexity of the spray drying process for dairy manufacturers who want to optimize their production. It is impossible to provide a simple mathematical model that takes into account all parameters simultaneously for complex processes in spray drying of dairy products [20].

Furthermore, the existing studies, essentially centered on skim milk, cannot be easily extrapolated to other dairy products. Study of more interaction processes, the production, and functions of dairy products is necessary in order to increase our knowledge of the mechanisms of water transfer, drying parameters, storage conditions and rehydration of dairy powders.

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