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Xiao Dong Chen [a]; Kamlesh C. Patel [a]
[a] Biotechnology and Food Engineering Group, Department of Chemical Engineering, Monash University, Clayton Campus, Melbourne, Victoria, Australia

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Manufacturing Better Quality Food Powders from Spray Drying and Subsequent Treatments

Xiao Dong Chen and Kamlesh C. Patel
Biotechnology and Food Engineering Group, Department of Chemical Engineering,
Monash University, Clayton Campus, Melbourne, Victoria, Australia

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In this article three major aspects of spray-dried food powders are discussed. We first address several practical problems involved during spray drying that may greatly influence product quality. The second issue identifies how an accurate drying kinetics model can form a useful tool to predict changes in the physical and biological quality aspects and the microstructure of the particle during processing. Dryer-wide simulations using the accurate drying kinetics model can significantly reduce the number of experimental trials for optimizing the process. To date, such success has been restricted to production runs for pilot-scale or small-scale industrial operations. The final issue addresses some of the challenges encountered when evaluating the functionality of the spray-dried powders during their reconstitution. The superior functionality of the spray-dried food product needs to be established more scientifically, which can help commercial operations to achieve high-quality reconstitution.

Keywords Drying kinetics; Fluidized-bed drying; Functionality; Powder reconstitution; Product quality; Spray drying

INTRODUCTION

Food powders are one of the most important products in the food industry. Common food powders that are readily available in the market include baby food, cheese/whey products, coffee, coffee substitutes, tea extract, egg powder, flavors, honey powders, soup mixes, soy-based food powders, spices/herb extracts, sugar-based food powders, vegetable protein, vegetable powders, etc. Food powders are easy to store for long periods, transported locally and for export, and made into innovative formulations producing the widest possible range of food and beverages.

Spray drying and subsequent fluidized-bed drying operations are to date the most effective and economic ways of producing food powders of specific characteristics from concentrated liquid materials. Food powders are typically produced on the order of several tons per hour per dryer using large-scale equipment. A large group of spray-dried food powders contain dairy ingredients (skim milk powder, whole milk powder, whey proteins, lactose, cream powder, yogurt powder, ice cream mix, cheese powders, etc.) as constituents. Preserving the nutrients, deactivating undesirable microorganisms, achieving desired particle moisture content and functionality, and extending the shelf life of the product are the primary interests during manufacturing food powders. Modeling the details of various drying phenomena occurring in the spray dryer continues to pose a challenge due to the complexity involved with droplet–gas interactions, droplet size distribution, trajectories of the particles, and gas flow patterns. Similarly, modeling to evaluate the functionality of food or dairy powders during reconstitution has been a challenge due to the lack of a fundamental approach and suitable experimentation tools.

In this article, the main interest is focused at the manufacturing of food powders through spray drying and the associated processes. The key elements of the process and the product interactions are highlighted, and potential problems are identified by illustrating examples for spray drying of dairy materials. For understanding the particle formation process, predicting product quality and evaluating the behavior of spray-dried food powders during reconstitution, we suggest that following one droplet in a gas phase inside the drying chamber during drying and following one particle in a liquid phase during reconstitution could form a helpful approach. The types of functionality evaluations that should be considered during reconstitution of the powders are discussed using a more scientific approach. A future prospect is provided by giving reference to future improvements in research and development sponsored by or actually conducted in industry.

SPRAY DRYING AND PRACTICAL ISSUES

The spray dryer mainly consists of three elements: the atomizer(s), the hot gas supply, and the chamber to mix the hot gas and liquid droplets. Modern spray dryers also

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Correspondence: Professor Xiao Dong Chen, Chair of Biotechnology and Food Engineering, Department of Chemical Engineering, Monash University, Clayton Campus, Building 36, Melbourne, Victoria 3800, Australia; E-mail: dong.chen@eng.monash.edu.au

have a secondary or an integrated fluidized-bed dryer to economically facilitate the final stage drying to produce agglomerates, to coat particles, and to cool the product to the appropriate packing temperature. The majority of the water is removed inside the drying chamber under high-temperature conditions. The design process of the drying chamber requires accurate drying kinetics data; product residence time data; position, type, and number of atomizers; number of drying stages in the chamber; as well as gas flow and product flow pattern for a given evaporation capacity. Because no accurate theoretical basis has been developed to date, the collection of drying kinetics data and product residence time data is still based on trial-and-error experimental procedures and previous experience. Typical geometries of current industrial spray dryers can be found at www.niro.com.

In the spray-drying process the concentrated liquid material is atomized into small droplets inside the drying chamber where the droplets come into contact with the hot air of over 150°C (up to 240°C depending on the feed characteristics).[1,2] Droplet formation enables very large surface area per unit volume of the liquid to promote quick water removal from the droplets (in a fraction of a second). Three types of atomizers are normally used in industrial spray drying: rotary wheel/disc, pressure nozzle, and two-fluid nozzle. When the droplet is detached from the atomizer, the droplet size and the size distribution are usually dependent on the feed rate and liquid surface tension, density, and viscosity. For the disk atomizer, the rotational speed is also an influential parameter. The required accuracy and indeed the availability of these parameters for rapid product development in today's market are in serious question.

In modern plants, the spray-drying process is often followed by static/vibrated fluidized bed(s) for further drying, classification, coating, and product cooling. Smaller particles (usually known as fines) are separated out using cyclones and filtration systems and sent back to the atomization zone on top of the spray dryer for agglomeration. Agglomeration creates larger particles or particle clusters, which enables good flowability and high packing densities and provides desired functionality for reconstitution. Extremely fine particles tend to be collected in the bag house and are considered as waste products.

The drying efficiency of the spray dryer greatly depends on the performance of the atomizer (i.e., ability to generate a desirable droplet size and size distribution), the liquid droplets spray pattern, the droplet–air interaction, and the air flow pattern. When mixing the countless number of liquid droplets with the hot gas inside the drying chamber, modeling the multiphase flow under the evaporation conditions poses a challenging issue. Furthermore, reliability of the droplet size and size distribution predictions for the large throughput atomizers to date remains a matter of doubt.

Carbohydrate-rich liquid materials form amorphous materials under rapid evaporation conditions, thus leading to glass-transition–related stickiness problems during processing.[3] Drying of high-fat products such as cream powder or high-sugar-content products such as lactose can be difficult due to the low-melting-point components or the amorphous nature of the material that can lead to massive deposition inside the drying facility (spray dryer walls, ducts, cyclones, bag house, etc.), preventing a cost-effective operation.

As an example of the spray–air interaction the cone-type spray pattern using a pressure nozzle is illustrated in Fig. 1. The hot air is made to penetrate the spray of small droplets. The liquid droplets that are in the middle of the spray-cone would take longer to dry due to the gas temperature distribution in the spray region. Ineffective mixing of air–droplet phases can lead to a wide range of functionality among the particles when collected as a product. The process of interaction between the spray and the hot air may also have a significant impact on the energy efficiency. Another aspect that affects the drying efficiency is the nature of the feed; i.e., solids concentration, feed composition, degree of protein changes, etc. To account for this so-called nonuniformity of the droplet characteristics, the one particle/droplet behavior in air approach may be used to predict the droplet or the particle's behavior inside the dryer in varying hot air conditions.

The predominant objective for any drying operation is to achieve the final water content of the product. This final water content varies with daily weather pattern each day

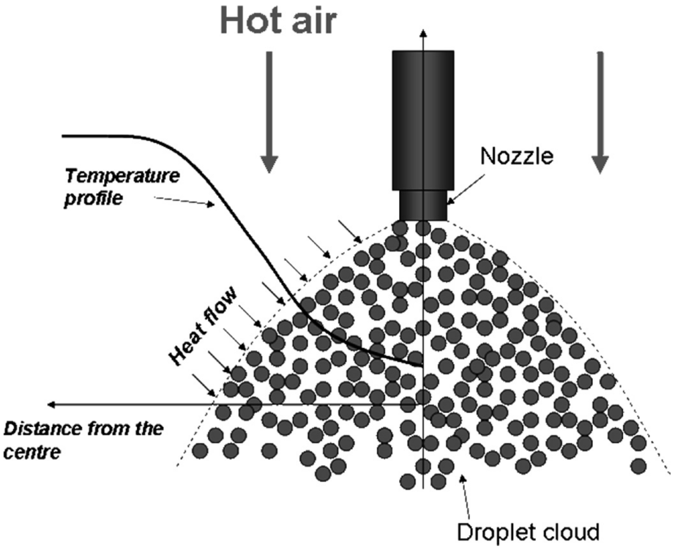


FIG. 1. Interaction of a spray of liquid droplets with hot air in the atomization zone.

while the dryer is operated. When a new formulation is dried, the final water content cannot be determined beforehand with respect to the different atmospheric humidity. Industries have to conduct many trial-and-error runs on large throughputs; for instance, as high as 10 tons of powder per hour. Wastage of the product can be huge during these experimental runs. When tuning the dryer to achieve the required water content and the high-quality product, the material wastage can be even higher. Spray dryer-wide simulations can significantly contribute to reduce the product development costs and can be used as a model control tool to adjust the plants to be operated at optimal conditions. These simulations may be carried out using computational fluid dynamics (CFD) programs or simple Microsoft Excel–based spreadsheets, depending on the depth of the information required and the permissible accuracy in predictions.

DRYING KINETICS AND QUALITY CHANGES

Spray drying substantially alters the physical and biochemical quality of food material during processing. Predicting the extent of alteration in the quality of the food droplets during a drying step is an essential aspect for optimizing the process. For instance, the surface properties of the particles are directly related to the microstructure and the stickiness and cohesiveness behavior of the product, which may lead to wall deposition and inferior product quality. Predicting the changes in the product quality has the prospect of being incorporated in the dryer suppliers' future capabilities, although this aspect has not yet been considered during design of the drying chamber. To follow the changes in the droplet/particle inside the dryer, a large number of particles have to be tracked to represent the size distribution and the residence time distribution under real spray-drying conditions.

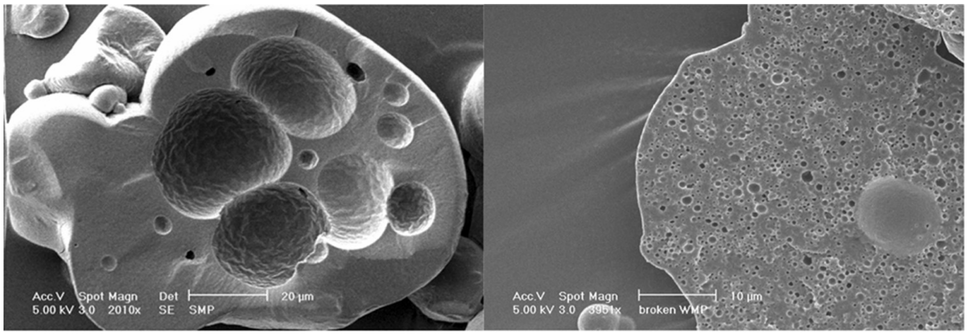
A simple approach for predicting the quality of the final powder is to understand (and accurately model) what a single droplet or particle actually experiences during its flight in the drying chamber regarding its temperature and moisture content and how a single droplet/particle may respond to these changes. Fluid-bed drying should also be followed closely for one-particle behavior as comprehensive as in spray drying.

Selection of an appropriate drying kinetics model for modeling spray-drying operations is an important step because predictions of various drying parameters and hence dryer designing and scale-up are directly related to the accuracy of the drying kinetics model.[4] In the literature, many studies have been published to formulate drying kinetics models for spray drying of various food materials. Sano and Keey[5] and Cheong et al.[6] adopted a comprehensive transport phenomena approach by incorporating coupled heat and mass transfer equations. Langrish and Kockel[7] and Jannot et al.[8] used a characteristic drying curve (CDC) approach assuming that the drying rate is a first-order and linear function of the particle's free moisture content. This approach has been widely used in CFD programming for characterizing industrial spray drying operations.

Chen and Lin[9] proposed a reaction engineering–based drying kinetics model for drying of small droplets or thin-layer materials. Their drying kinetics model was found to be useful for predicting the behavior of single milk droplets during drying under industrial drying conditions.[10] The majority of the drying kinetics models published in the literature were validated using lab-scale drying of single, suspended, and large droplets (2–10 mm). Certain drying parameters that are difficult to obtain during real spray-drying operations could be qualitatively evaluated using drying of one-droplet experiments. A simple trajectory spray dryer is necessary to progress further with this kind of modeling.

The microstructure of the particle is the link between processing and functionality. A typical microstructure formed during spray drying is drying rate dependent and affected by drying conditions such as gas temperature, humidity, and velocity and feed conditions such as liquid concentration, composition, and temperature. Typical microstructures of industrial skim milk and whole milk particles are illustrated in Fig. 2 using scanning electron microscopy images. The whole milk particle (WMP) was observed to be more porous compared to the skim milk particle (SMP). The transport of key constituents in the droplet/particle, for instance, migration of lactose, fat, proteins, and water molecules when drying of milk droplets, may be helpful to understand the fundamental process behind how a typical microstructure forms during spray drying. When drying the skim milk or whole milk, the size and surface activity of the basic molecules such as lactose (0.8 nm), fat (0.5–10 μm), and protein (soluble globular proteins: 2–10 nm, casein: 50–500 nm) may play an important role during transport of these molecules. The transport of molecules inside the droplet under solid formation conditions is still somewhat unclear, and hence the solid formation or the pore formation processes are not well modeled to date. The droplet size, shape, and solids distribution make the modeling for the solid formation process more difficult. In such scenarios, the one droplet behavior during drying approach may be used to model the solid and pores formation processes.

Understanding the transport of basic molecules is especially useful to determine the surface properties of the dried particles. When studying the surface composition of SMP and WMP, a higher fat content was observed on the surface of the WMP.[11] Surface composition may severely affect the powder's functionality (wetting and dispersion) and stability as well as stickiness and cohesiveness. Characterizing the particle structure and the surface



(a) skim milk particle (b) whole milk particle

FIG. 2. SEM images of cross sections of two typical industrial milk powder products.

composition is relatively easier these days due to great advancements in various techniques such as SEM, ESEM, AFM, XPS, FTIR, NMR, DSC, etc. However, the real challenge lies in interpreting the information obtained from various techniques to favor the higher quality product.

Solubility index or insolubility index is usually considered as a postdrying property of food powder.[12] Insolubility index is considered to be an indicator of formation of insoluble materials in the particle/powder. This property is often used by commercial milk powder manufacturers as a criterion to indicate the quality of milk powders. The insolubility index can be related to the feed composition (mainly the protein content) and may affect the reconstitution property of powders in an aqueous medium. The rate of insoluble material formation during drying largely depends on the temperature and moisture content profiles of the droplet in the drying chamber. Straatsma et al.[13] proposed a zero-order kinetic model to determine the insolubility index for milk powders assuming that the insoluble material forms only when the particle moisture content is between 10 and 30 wt%. This model may be used to describe the solubility behavior of individual droplets when combined with the drying kinetics model. This requires the insolubility kinetics to be established for a wider range of products, which has not yet been done.

Another surface property of interest that may be related to the stickiness behavior of the powder is the glass-transition temperature, which is a characteristic property of an amorphous component of the food material. When the droplet/particle temperature rises above the glass transition temperature, the amorphous material of a glassy state transforms itself into a rubbery state. The sticky-point temperature, which is considered to be responsible for caking and wall deposition inside the dryer, is generally 5 to 20°C higher than the glass-transition temperature.[14] In the literature, the glass transition temperature of the food material was estimated using a Gordon-Taylor equation or its modified expressions, considering the glass transition temperature of individual components and average water and solids fractions in single droplet. Since predicting the glass-transition temperature during drying requires temperature–time and moisture content–time profiles of single droplets, an accurate drying kinetics model has to be combined with the glass-transition kinetics model.

Liquid food material typically contains many heat-sensitive biological compounds such as proteins, vitamins, enzymes, probiotics, etc., which may provide nutrients and other health benefits to the consumers. Food materials may also have some harmful microorganisms, which may be responsible for deterioration of the food and causing severe diseases. The fundamental understanding and keeping a good balance between inactivation of useful and harmful bioactive substances can help to improve the overall quality of spray-dried products.

Drying involves removal of excess water from the food matrix until a safe moisture content is achieved that does not permit any physical, chemical, and microbiological reactions to occur in the food matrix. The removal of water from the food material during drying may cause irreversible changes in the structural and functional integrity of the bacterial membranes and configurations of the proteins. Furthermore, the exposure of materials to high temperatures may cause damage to the protein and enzyme structures and also reduces the viability and activity of microorganisms in the dried product. Predicting the survival/activity of microorganisms and bioactive compounds during drying is necessary for ensuring the high retention of bioactivity and also for optimizing and scaling up or scaling down of the overall process.[15] These predictions require good understanding regarding how drying and operating parameters are correlated with the rate of inactivation during processing. Chen and Patel[15] reviewed several commonly used inactivation kinetics models in context to drying operations. For dryer-wide simulations it is essential to couple the inactivation kinetics model with a suitable drying kinetics model in order to accurately predict the survival of microorganisms. This inactivation process could be qualitatively and quantitatively studied by following one droplet and tracking its temperature and moisture content history during drying.

In general, combining the drying kinetics model with the one droplet behavior in the dryer approach may be very useful to predict the changes in the overall quality and the surface properties of the particles. The surface temperature and moisture concentration of the particle should be used when evaluating the surface properties of the particle, such as glass-transition temperature.

FUNCTIONALITY AND TESTING

Modern food powder plants that utilize spray drying as a key technology are designed to aim at the lowest energy consumption while achieving the highest product quality. Usually it is not possible to achieve both criteria together; therefore, a compromise has to be made considering the top priority and the overall objective of the production. An intelligent decision (often with predictive tools) can be made based on a limited number of plant trials. Response surface or multivariable regression methods have often been used when no predictive models were available; however, only a limited number of plant trials were made to optimize with regression methods.

In the food industry, ingredients in a powder form are commonly used to design the final food products. The physical and biochemical properties of these powders determine the quality of the resulting food products. Dissolution of food powders is of particular importance both to the manufacturers and to the consumers, being one of the critical benchmarks of the food powder quality for consumption. An example is reconstituted milk, where it is important for the powder to dissolve instantly to form a stable colloidal suspension of fat and protein, thus leaving little or no visible residue suspended in water or on the container surface.[16] One-particle behavior may again be very helpful to understand the performance of the product in the liquid solvent. To form a one particle behavior in liquid approach we now consider how one particle behaves in the liquid medium (e.g., water, tea, coffee, etc.) upon mixing.

Reconstitution or dissolution of food powder can be considered to have four steps:

1. Wetting of powder particles
2. Particles sinking into solution
3. Particles dispersing evenly in solution
4. Solid particles dissolving completely

The dissolution procedure should take place in the above sequence. However, there are times when different phases overlap each other.[17] This sequential process leads to four reconstitution properties of food powder: wettability, sinkability, dispersibility, and solubility, respectively. The steps of dissolution are difficult to study independently. As soon as a particle is immersed in the liquid phase, the one particle behavior in liquid becomes a key phenomenon of interest (following on from the one droplet/particle behavior in air). Drying of one droplet in a gaseous environment and reconstitution of one particle in a liquid medium are schematically illustrated in Fig. 3.

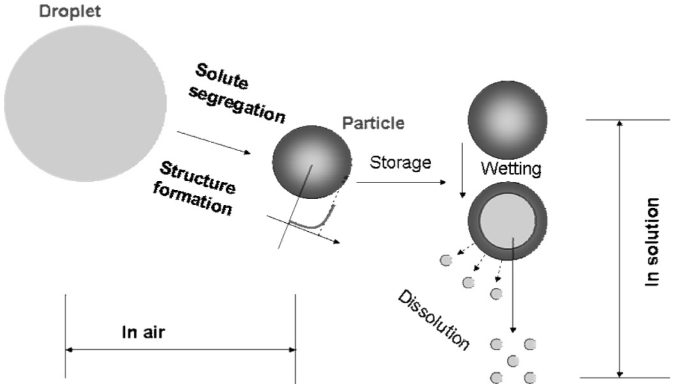


FIG. 3. A schematic diagram of the droplet drying process in the dryer and the particle reconstitution process in the liquid medium.

Solubility, which is the final step of the dissolution process, appeared to be a more reliable criterion to evaluate the powder's behavior in the aqueous phase.[18] Insolubility index is commonly used to evaluate the solubility of the powders after manufacturing or during reconstitution. When producing protein-rich materials such as high milk protein powders, whey protein powders, and casein-rich powders, the insolubility index is an important property that relates the functional behavior of proteins with the solubility property. Solubility of proteins is significantly affected during spray drying because protein molecules may face emulsion, foaming, and gelation during processing, leading to the denatured state of proteins. The ability of proteins to dissolve in the liquid medium depends on their native or denatured state inside the particle and also on environmental factors such as temperature and pH of the liquid medium. Unfavorable changes in pH or temperature disrupt a normal folded structure into a random shape unfolded structure, which is a biologically inactive or denatured state. The unfolded protein structure allows cross-linking interactions to occur between two protein molecules and also other electrostatic, hydrogen-bonding, and disulfide interactions.[19] It is important to recognize that denaturation of proteins alone is not significant to cause a measurable loss of solubility, as proteins must also aggregate, coagulate, and finally precipitate.[20]

CONCLUDING REMARKS

Understanding and quantifying the one droplet/particle process could form an important tool for producing high-quality spray-dried products and achieving an improved economy. No comprehensive mathematical tool has been established (except perhaps the software developed at NIZO, The Netherlands) to cater for a large number of operating parameters to account for many important physical phenomena involved during processing. Furthermore, there is no simple-to-use software developed for large plant applications at the operator level so that the plant settings can be predicted before commencing the large throughput production (the second trial for the same product). In the industry, engineers and technologists are often interested in observing the trends or changes in the particle characteristics or the drying parameters when changing in the process conditions. This curiosity may be fulfilled if predictive models are available in a simple-to-use form with reasonable accuracy. The corresponding parameters for predicting the functionality are often more difficult to obtain compared to the drying kinetics and are unlikely to be determined comprehensively for each formulation. Furthermore, there is not any accurate shrinkage model as a function of product composition, which warrants further investigation. On the other hand, simple yet accurate drying kinetics models (e.g., lumped kinetics) can be established and may be most effectively used to optimize cost-effective plant operations. It remains to be a challenge when the spatial distribution of water content inside the particle becomes critical for determining the changes in the quality of the dried products. Unfortunately, there is no accurate laboratory data available for the moisture distribution profiles within the micron-size particles to back up modeling attempts.

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