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Modeling spray drying of dairy products – Impact of drying kinetics, reaction kinetics and spray drying conditions on lysine loss

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HIGHLIGHTS

- Coupling of drying and reaction kinetics with spray drying conditions.
- Model for drying kinetics of dairy powders.
- Computational fluid dynamics simulation of spray drying of dairy powders.
- Optimization of spray drying with regard to lysine loss.

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ABSTRACT

Lysine, an important nutrient in dairy formulations, is easily damaged during spray drying. The quality of spray dried dairy powders can be enhanced when lysine loss kinetics are coupled with drying kinetics and computational fluid dynamics of spray. Thin-film drying in a convective drying channel was applied to study the drying kinetics of the model dairy-formulation. The drying kinetics was modeled with the reaction engineering approach which was successfully implemented in the computational fluid-dynamics (CFD) simulation of spray drying. Lysine loss was modeled by reaction kinetics taking into account the temperature, water content and physical state of lactose. A 3D CFD model of spray drying was set up to determine the particle properties along their residence time. The model was validated with the experimental results of spray drying on a pilot scale. A good agreement between the experiments and the simulation was obtained. The reaction kinetics model was coupled with the particle properties along the particle tracks to create a predictive tool for the lysine loss. Thus, as it was hypothesized from the spray-drying experiments, the importance of the particle residence-time was highlighted. The following optimization study revealed potential strategies to ameliorate the spray drying process. In this context, the dryer geometry, air flow pattern and droplet atomization should be reconsidered carefully. The proposed approach can be transferred to other spray drying applications, e.g. for the targeted formation of microcapsules or to enhance the survival of microorganisms.

1. Introduction

Although spray drying is generally known to be a rather gentle drying process, sensitive products can be damaged when spray dried under inappropriate processing conditions (dehydration and elevated temperatures) (Fu et al., 1995; Anandharamakrishnan et al., 2007; Menshutina et al., 2010; Mestry et al., 2011; Tsotsas, 2012; Wijlhuizen et al., 1979). An example is the essential amino acid lysine in dairy powders which is an important nutrient that is necessary for the protein synthesis in the human metabolism, especially in the liver (Finot, 1983; Ferrer et al., 2000; Tome and Bos, 2007; Schmitz et al., 2011). The human body can only metabolize lysine if its ε-amino group is freely accessible (van Boekel, 1998; Meade et al., 2005; Moughan and Rutherfurd, 2008). This amino group is mainly blocked by the early Maillard reaction with the reducing sugar lactose in dairy products. To avoid this kind of product deterioration, product properties and process characteristics have to be harmonized. However, due to the short drying times, which hardly allow sampling at different drying stages, and the difficulties of taking representative samples inside the spray-drying chamber, this aim cannot be achieved easily.

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Spray drying belongs to the rather complex multiphase convective-drying processes which involve the atomization of droplets, particle transport, evaporation of droplets as well as the interaction between particles and/or droplets and/or dryer walls (Blei and Sommerfeld, 2011). For this reason, designing, optimizing or scaling-up spray-drying processes are complicated tasks which are often accomplished by time-consuming trial-and-error experiments. Computational fluid dynamics (CFD) can be an effective way to facilitate this process. Therefore, a lot of research is conducted on simulating spray-drying. Using CFD, Gianfrancesco et al. (2010) studied the stickiness of maltodextrin solutions during spray drying. They aimed at reducing wall deposition of particles and achieving a controlled agglomeration of particles. Rogers et al. (2012) investigated the formation of insoluble material during the spray drying of skim milk in a CFD-based study. In general, topics such as better understanding of the spray-drying process, particle history during spray drying and wall deposition have been widely studied using CFD. (Langrish and Zbicinski, 1994; Huang et al., 2003, 2005; Birchal et al., 2006; Zbiciński and Li, 2006; Mezhericher et al., 2009; Anandharamakrishnan et al., 2010; Mezhericher et al., 2010; Ullum et al., 2010). Although pilot-scale dryers were used in most studies, industrial-scale simulations were conducted, too (Straatsma et al., 1999; Lo, 2005; Huang and Mujumdar, 2007; Jin and Chen, 2009). It is generally accepted that special attention has to be paid to droplet-drying kinetics (Chen and Patel, 2008; Patel and Chen, 2008; Mezhericher et al., 2010; Putranto et al., 2011). Woo et al. (2008b) used two drying-kinetic models, the characteristic drying-rate curve and the reaction-engineering approach, in combination with a CFD simulation of the spray drying of a sucrose-maltodextrin mixture. They found no significant differences in the particle trajectories and outlet conditions although the predicted drying curves were slightly different. However, validating the simulation results is still a challenging task because detailed measurements of the flow field inside a spray dryer are hardly possible (Huang and Mujumdar, 2007). This, on the other hand, makes spray drying interesting for simulation studies.

In this study we link food technology (reaction kinetics, stability concepts) to process engineering (spray drying, drying kinetics, computational fluid dynamics) in order to gain a deeper understanding of the mechanism of lysine loss during spray drying and to derive optimization strategies. A stepwise approach is chosen: we have determined the kinetics of thermally and dehydration induced lysine losses in a model dairy-formulation at conditions relevant for spray drying (Schmitz et al., 2011) and have described the kinetics by a reaction-kinetics model (Schmitz-Schug et al., 2013d). The impact of the physical state and of molecular mobility on lysine loss was investigated (Schmitz-Schug et al., 2013c) as well as the impact of the spray drying conditions (Schmitz-Schug et al., 2013a). This paper focuses on drying kinetics and computational fluid dynamics in order to complete our study on the mechanism of lysine loss during spray drying. Thin-film drying is used to measure the drying kinetics which is modeled using the reaction engineering approach. The reaction kinetics model and the drying-kinetics model are integrated in a computational fluid-dynamics simulation of the spray-drying process that is validated by spray-drying experiments in pilot scale. Thus, critical regions can be identified and process optimization with regard to the loss of available lysine can be achieved. To sum up, the quality of spray-dried powder can be ameliorated using the approach of this study by linking the particle properties to the reaction kinetics of undesirable reactions.

2. Materials and methods

2.1. Preparation of the model dairy-formulation

The model dairy-formulation was prepared by reconstituting skim milk powder (22.2%), whey protein isolate (8.4%), lactose (68.3%), potassium citrate (1.0%) and disodium phosphate (0.1%) in deionized water to 20% dry matter. The model dairy formulation was characterized by a protein-lactose ratio of 1:5 and a whey protein-casein ratio of 60:40.

2.2. Spray drying

Spray drying trials were performed with a short-form co-current pilot scale spray dryer (PRODUCTION MINOR^{TM}, GEA Niro, Søborg, Denmark) which was equipped with a two-fluid nozzle that works with compressed air as atomizing device. Air inlet-temperatures were in the range of 160–200 °C, the air volume-flow rate was 411 $m^3\,h^{-1}$ and product mass-flow rates were in the range of 11.0–18.7 $kg\,h^{-1}$. The dried powders were recuperated and analyzed for their water content, water activity and available lysine.

2.3. Thin-film drying

The drying kinetics of the model dairy-formulation was determined by thin-film drying experiments. The drying channel (Figs. 1 and 2) had a height of 20.3 mm and a width of 50 mm. Compressed air at 2 bar was used as drying-air supply. The drying air was heated to temperatures of 80–120 °C and the relative humidity was adjusted to 0–20% by injecting and evaporating water in the dry air stream using a controlled evaporator mixer (W101A, Bronkhorst High-Tech B.V., Ruurlo, the Netherlands). Air velocity was set to 0.15–0.30 $m\,s^{-1}$ with the aid of two dosing valves (EL Flow Select and Liqui Flow, Bronkhorst High-Tech B.V., Ruurlo, the Netherlands). The drying channel was surrounded by a second pipe with an insulating air flow that was heated using an electric pipe heater (type 5000, Herz GmbH, Neuwied, Germany). The temperature of the insulating air was adjusted depending on the experimental conditions in order to obtain a stable temperature in the drying channel. Before starting an experiment, the drying channel and the sample holder were equilibrated at the desired temperature for 30 min. All parameters were controlled and recorded using a Labview automatic control system. The relative humidity of the air was not measured continuously but before positioning the sample in the drying channel. The sample holder which formed the bottom of the drying channel had a cavity with a diameter of 40 mm and a depth of 0.6 mm into which 1000 μl of the sample were filled as thin film. To determine the drying kinetics, i.e., the weight loss over time, the sample holder was taken out of the drying channel after discrete time steps and put on a precision balance (WZ64S, Sartorius AG, Göttingen,

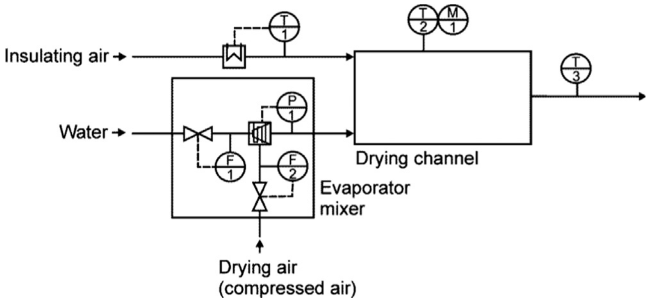

Fig. 1. Experimental set-up of the drying channel.