SENSITIVITY ANALYSIS OF THE REACTION ENGINEERING APPROACH TO MODELING SPRAY DRYING OF WHEY PROTEINS CONCENTRATE

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Whey proteins concentrate (WPC) powder, which is an important protein source for human, is commonly produced from whey using a spray drying technique. It is important to predict several drying parameters and also parameters which govern the quality of the product before conducting real operations. Drying kinetics is an essential tool for predicting the drying rate and various parameters which are rate-dependent. There have been only little studies published previously on both modelling WPC drying and dryer wide simulations using different computational tools. In this paper, the application of a reaction engineering approach (REA) to modelling a droplet drying process is reviewed. Results based on dryer wide simulations using the REA are presented. Most importantly, a sensitivity analysis of the REA using drying of WPC and skim milk droplets is reported. This analysis will be helpful to select an appropriate drying kinetics model and to have a benchmark for the future WPC drying modelling work.

1. Introduction

Whey proteins concentrate (WPC) is widely used in food product applications due to its higher nutritional value and versatile functional properties compared to any other animal proteins [1]. Industries manufacture WPC with a few different grades which differ in its protein content, mostly varying from 35% WPC to 80% WPC. Preparation of WPC is well documented in the literature [1,2]. The manufacturing process involves ultrafiltration of raw whey, obtained from the cheese production with total solids content of 6 wt%, followed by evaporation and spray drying. High protein WPC requires additional water to be added in order to reduce the viscosity of the concentrated whey during ultrafiltration, now called diafiltration, which also removes the residual quantity of lactose and unwanted minerals. The trend today is to produce agglomerated instant whey proteins powders. Production of WPC is therefore now carried out using multi-stages drying with additional internal/external fluidized-bed dryers. Fluidized-bed drying is necessary for producing agglomerates of high proteins WPC as there is only a small amount of lactose present in the feed which acts as a binding agent.

Spray drying is a critical step during WPC production as it can seriously affect the physical form and the morphology of WPC particles as well as the native state and the stability of proteins. It is desirable to have drying kinetics information prior to the real operation in order to predict the effects of various drying and operating parameters on the physical and nutritional quality of the product during the spray drying process. A few models have been reported previously on drying kinetics of single milk droplets [3,4]. A commonly used model was the characteristic drying rate curve (CDRC) approach. However, a comprehensive mathematical model to formulate drying kinetics of commercial whey droplets is not reported in the literature.

A reaction engineering approach (REA) was successfully used to formulate the drying kinetics model for skim milk, whole milk and lactose solutions under a wide range of isothermal, non-isothermal and high-humidity drying conditions [5,6]. It was observed that the REA was more accurate under all drying conditions tested in the laboratory compared to the traditional CDRC approach. Recently, Lin and Chen [7] reported a detailed model established by measuring drying kinetics of single WPC droplets in the laboratory. Lin and Chen [7] used the REA to model the drying behaviour of the WPC droplets. Patel and Chen [8] successfully used this drying kinetics approach to conduct detailed spray drying modelling and dryer-wide simulation for the drying of the reconstituted lactose solutions. The REA was found to be useful to understand the variations in the product properties upon changing the drying parameters. The aim of this work is to assess the sensitivity of the REA during dryer-wide simulation for spray drying of WPC. Here, results are compared for drying of WPC and skim milk droplets to assess the trends and variations in predictions with respect to different drying and feed conditions.

2. Theoretical Model

Here, we have briefly presented a basis and key equations which describe the reaction engineering approach (REA). This approach assumes that drying is a competitive process between the evaporation reaction and the condensation reaction. The REA model is formulated based on a concept from reaction engineering assuming evaporation is an activation process that has to overcome an energy barrier for water removal during drying, while condensation is not an activation process [9]. Detailed information regarding the fundamentals involved, the model development and the experimental work are described previously [5-9]. The REA defined the driving force to facilitate drying using a droplet surface-bulk gas vapour concentration difference. Some fundamental equations including drop moisture concentration, diameter and temperature profiles for drying of WPC are expressed here:

$$\frac{dX}{dt} = \frac{A_d \cdot h_m}{m_s}\left(\rho_{v,sat} \cdot \exp\left(-\frac{\Delta E_v}{R_g \cdot T}\right) - \rho_{v,b}\right) \tag{1}$$

$$\frac{\Delta E_v}{\Delta E_{v,b}} \approx 1.335 - 0.3669\exp(X^{0.3011}) \tag{2}$$

$$\Delta E_{v,b} = -R_g T_b \ln\left(\frac{\rho_{v,b}}{\rho_{v,sat}}\right) \tag{3}$$

$$m_d Cp_d \frac{dT_d}{dt} = hA_d(T_b - T_d) + \Delta H_v m_s \frac{dX}{dt} \tag{4}$$

$$\frac{d}{d_0} = 0.873 + 0.127\left(\frac{X - X_e}{X_0 - X_e}\right) \tag{5}$$

where, X is the droplet moisture content (kg water/kg dry solids), T is the droplet temperature (K), m_s is the mass of solids in a droplet (kg), A_d is the droplet surface area (m^2), ΔH_v is the latent heat of vaporization (J/kg), R_g is the gas constant, Cp is the specific heat (J/kg·K) and $\rho_{v,b}$ and $\rho_{v,sat}$ represent bulk phase vapour concentration and saturated vapour concentration at the solid-gas interface, respectively. The parameter ΔE_v in Eq.(1) is an activation energy factor that represents the energy barrier for removing moisture from the liquid droplets under drying conditions. The energy factor is expected to increase during drying of droplets due to the greater obscurity in water removal at low moisture contents. The parameter $\Delta E_{v,b}$ in Eq.(2) is an equilibrium activation energy and obtained using the gas relative humidity ($\rho_{v,b}/\rho_{v,sat}$) and the gas temperature (T_b). The convective heat-transfer coefficient h and the mass-transfer coefficient h_m were estimated using appropriate Ranz-Marshall correlations [10]. In this work, a linear shrinkage model, which was worked out by Lin and Chen [7] and described by Eq.(5), was employed to estimate the change in WPC droplet diameter instead of a traditional ideal shrinkage model. The drying kinetics and shrinkage models for drying of skim milk are described elsewhere [5].

3. Results and Discussion

Simulation was performed for drying of reconstituted WPC and skim milk droplets using hot air. During simulation, a few assumptions were considered:

1. All droplets and formulated particles were spherical.

2. Temperature gradients within the droplets were considered to be negligible. This assumption was found to be reasonable considering small *Biot* numbers.
3. The drop was assumed to be a binary system (water and solids).

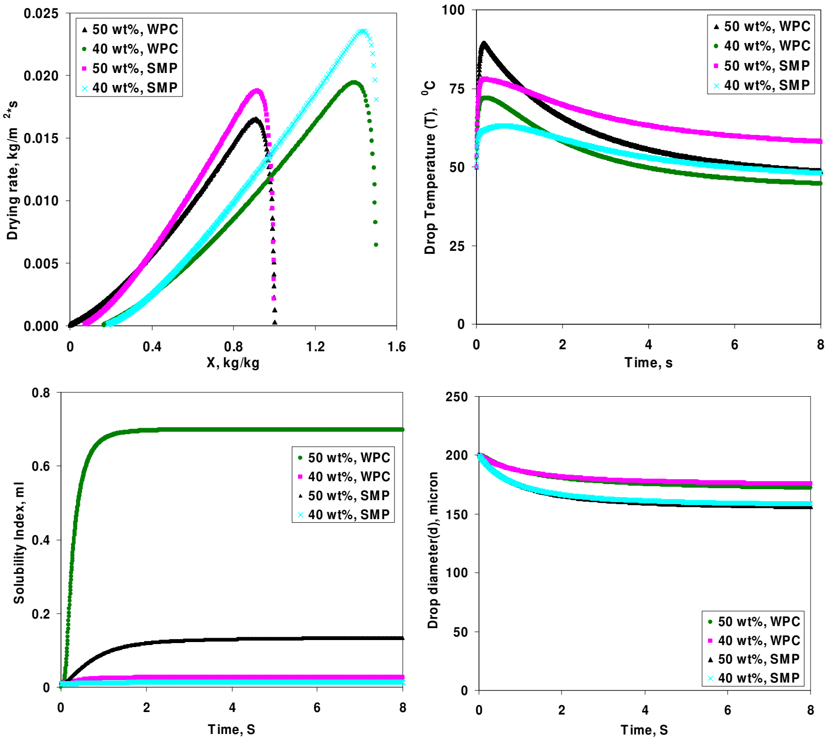

Figure 1: Comparison of drying rate and droplet characteristics profiles for the aqueous WPC and SMP droplets of 40 and 50 wt% (dry basis) initial solids content.

Required thermo-physical properties of the liquid feed and air streams were estimated using appropriate correlations. All the drying and operating parameters were made to be time-dependent. Formulated models and other equations were simultaneously solved using Microsoft Excel spreadsheet programs with a time-step of 0.01 second. The diameter of a cylindrical drying chamber was assumed to be 10 m during simulation. The first run of simulation was conducted for drying of aqueous WPC droplets of 200 µm initial diameter. The feed temperature and flow rate at the inlet of the dryer were 50ºC and 10,000 litre/hour. The air conditions include 180 ºC inlet temperature, 200,000 kg/hour flow rate and 5 g water/kg dry-air inlet absolute humidity. These conditions are typical of an industrial operation in Australia and New Zealand dairy plants.

Same conditions were used for drying of skim milk powder (SMP). Results were produced for two different initial solids concentration, 40 wt% and 50 wt%. Droplet's drying rate, temperature, solubility index and diameter profiles for WPC and SMP using the above conditions are depicted in Fig.1. Unfortunately, time-dependent experimental data for industrial drying of WPC and SMP are not reported in the literature, therefore validation of models was not possible. Emphasize is given here at the sensitivity and the trends of several parameters predicted by the REA model.

It can be observed from the Fig.1 that the drying kinetics model is sensitive to the initial solids content of the liquid feed. The drying rate profiles showed that the drying rates with 40 wt% and 50 wt% WPC were lower compared with those of SMP of same concentrations during earlier stages of drying. Due to different drying profiles with WPC and SMP of same concentrations, a large deviation in the final particle temperature was observed. The overall shrinkage with WPC droplets was observed to be lower for both solids concentrations. The average final particle diameter for WPC was noted to be 170 micron, while it was about 150 micron for SMP. This is because the WPC forms a thin shell more quickly during drying and restricts the shrinkage. The average drying time to reach the final moisture content of 3.5wt% was noticed to be 8 second and 12 second for WPC and SMP, respectively for the 50 wt% initial solids content materials. Average drying time differences for the 40 wt% WPC and SMP were even larger. The solubility index profiles demonstrated that the final solubility index of WPC was higher compared to that of SMP for both solids concentrations. Materials with higher protein concentrations and total solids content had greater values of solubility index as expected. Simulation was also performed with varying inlet air temperatures, inlet feed temperatures, inlet air humidity, initial droplet sizes and inlet air flow rates (results are not shown here due to space constraints). The drying kinetics model based on the REA was found to be sensitive to each parameter and provided correct trends for each prediction. Inlet air temperatures, feed temperatures and initial droplet sizes had big impacts on the overall drying rate, and hence the overall product quality.

4. Conclusion

Results from the dryer-wide simulation showed that the drying kinetics model based on the REA has delivered right trends for each droplet characteristics in spite of several simplifying assumptions. The model reflected well to variations for important drying and droplet parameters. This approach can be successfully used to predict important drying parameters for large-scale whey proteins drying operations. This simulation technique and drying kinetics model can be further used to predict important physical and nutritional parameters of the products such as density, glass-transition temperature and residual activity of biological species. This sensitivity analysis could be of significant importance to decide key process variables, to control the protein denaturation and other physico-chemical processes, to produce the pre-requisite quality product and to optimize the operation for an improved economy. Recently, the research work is under progress within the same research group for incorporating the REA-based drying kinetics model into computational fluid dynamics (CFD) programs for detailed analysis of drying parameters such as droplet trajectory and residence time distribution of the droplet.

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