Journal of Food Engineering 116 (2013) 37–44

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Shrinkage behaviour of skim milk droplets during air drying

Nan Fu [a,b,*], Meng Wai Woo [b], Cordelia Selomulya [b], Xiao Dong Chen [b,c,*]

[a] College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou City, Jiangsu 215123, PR China
[b] Department of Chemical Engineering, Monash University, Clayton, Victoria 3800, Australia
[c] Department of Chemical and Biochemical Engineering, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen City, Fujian 361005, PR China

ARTICLE INFO

Article history:
Received 24 July 2012
Received in revised form 10 November 2012
Accepted 15 November 2012
Available online 23 November 2012

Keywords:
High solids
Drying kinetics
Single droplet drying
Shrinkage kinetics
Shrinkage coefficient
Spray drying

ABSTRACT

Industrial spray drying of milk powder production utilises high solids feed at around 50 wt.% or higher; however there are only a few fundamental studies investigating the droplet drying behaviour. The present work studied the shrinkage behaviour of 50 wt.% skim milk droplet during drying. Temperature effects on both shrinkage kinetics and total diameter reduction were found to be different from low solids milk drying. A high drying temperature at 110 °C led to negligible droplet shrinkage at *X* range between 1 and 0.3 kg/kg. An increase in temperature resulted in larger particles after drying. The high initial solids could sustain the droplet shape and hinder solute diffusion; as such droplet shrinkage behaviour deviates from the description of ideal shrinkage kinetics. A general correlation of shrinkage coefficient *b* was established for skim milk with initial solids content of 10–50 wt.%, useful for estimating droplet shrinkage kinetics within this range.

1. Introduction

Dry powders are one of the most common forms of product in food and pharmaceutical industries. They are less susceptible to microbial spoilage and more convenient to handle and transport than products in liquid form (Fu and Chen, 2011). During a powder manufacturing process such as spray drying, process conditions may exhibit appreciable effects on size and shape of dried particles (Vehring et al., 2007), which further impact the quality and functionality of final products (Kim et al., 2009; Islam and Langrish, 2010). For example, a reduced particle size could increase the rate of dissolution (Sahoo et al., 2008), while particle morphology could affect stickiness, re-dispersibility, friability, and stability (Walton, 2000; Paramita et al., 2010). A spray drying process firstly atomizes feed solution to billions of fine droplets and then dehydrates these droplets in co-current hot air flow (Paramita et al., 2010; Zhu et al., 2011). In this droplet-to-particle transition process, droplets shrink as moisture is removed, while the change in droplet size affects mass and heat transfer coefficients that determine evaporation efficiency (Ranz and Marshall, 1952a; Ranz and Marshall, 1952b; Chen, 2004). Therefore, the understanding of shrinkage behaviour of droplets during drying is of great importance for quality control as well as kinetics study of spray drying.

Droplet size change can be studied by video-recording the drying behaviour of an isolated droplet in a controlled air flow, known as single droplet drying (SDD) experiments (El-Sayed et al., 1990; Walton and Mumford, 1999). SDD experiments could mimic spray dryer environment to some extents, but with more controlled drying conditions for quantitative studies. The technique is capable of generating drying kinetics data including droplet size, temperature and mass changes for drying process modelling (Lin and Chen, 2002; Schiffter and Lee, 2007; Che and Chen, 2010), as well as monitoring morphological development during droplet-to-particle transition process (Adhikari et al., 2003, 2004; Fu et al., 2012a). In previous SDD studies for milk powders, samples investigated contained 10–30 wt.% initial solids content (Lin and Chen, 2002, 2004; Che and Chen, 2010; Fu et al., 2011b). Only a few studies have used higher initial solids of up to 40 wt.% (Adhikari et al., 2003, 2004), although they were conducted on carbohydrate solutions that are relatively easier to handle than complex systems such as milk.

Industrial spray drying operations for milk powder manufacture often adopt high initial solids ($\geqslant$50 wt.%) to improve process efficiency (Lin and Chen, 2009; Fu et al., 2012b). At such high solids level, droplet drying behaviour could be different to that of low solids milk drying because there is little free water on the surface. Rogers et al. (2012) utilised a monodisperse spray dryer to track droplet temperature histories of high solids milk feed up to

* Corresponding authors. Addresses: Department of Chemical and Biochemical Engineering, College of Chemistry and Chemical Engineering, Xiamen University, 422 Siming South Road, Xiamen, Fujian 361005, PR China. Tel.: +86 592 2189911; fax: +86 592 2188855 (X.D. Chen), College of Chemistry, Chemical Engineering and Materials Science, Soochow University, 199 Ren-Ai Road, Suzhou Industrial Park, Suzhou, Jiangsu 215123, PR China. Tel./fax: +86 512 65883267 (N. Fu).

E-mail addresses: nan.fu@suda.edu.cn (N. Fu), meng.woo@monash.edu (M.W. Woo), cordelia.selomulya@monash.edu (C. Selomulya), xdc@xmu.edu.cn (X.D. Chen).

0260-8774/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2012.11.005

Nomenclature

b	shrinkage coefficient
D	droplet diameter (m)
T	temperature (°C)
v	volume (ml)
w	droplet initial solids content (wt.%, kg/kg)
X	average moisture content on dry basis (kg/kg)
ρ	density (g/ml)

Subscripts

0	initial value
b	bulk air
d	drying
dp	droplet
f	final value
m	mass
s	solids
w	water

40 wt.% during drying. Changes in droplet parameters including temperature, mass and diameter were predicted with known environmental parameters. Nonetheless, the investigation of droplet shrinkage was limited to end-point analysis of final particle diameter that were obtained with different initial solids levels and at different inlet temperatures. Intermediate droplet changes were not studied due to equipment limitation (Rogers et al., 2012). For a better understanding on the intermediate droplet-to-particle transition process inside the spray dryer, Alamilla-Beltrán et al. (2005) attempted to collect sprayed samples within the drying tower, at progressively further distances from the atomizer. Specially designed sampler was added to the interior of drying tower, while sampling sites were set along the wall with 0.1 m interval. However, semi-dried droplets collected in this manner were usually crushed into a thin smear. Hence it remained difficult to conduct quantitative analysis on droplet size changes during drying with such set-up.

Lin and Chen reported size changes of 20 and 30 wt.% skim milk under varied drying air temperatures and air flow velocities, measured using glass-filament SDD experiments (Lin and Chen, 2002, 2004). At each initial solids level, droplet shrinkage kinetics under the different conditions was found to be similar when plotted against the moisture loss, implying that the loss of water is the main mechanism governing the droplet shrinkage. Later they developed an approximate correlation between diameter reduction and moisture removal for 40 wt.% milk drying and attempted to extrapolate the correlation to high solids level of 50 wt.% (Lin and Chen, 2009). However, no experimental works were conducted to validate the applicability of such extrapolation approach. Fu et al. (2012b) used an improved glass-filament SDD system to measure the drying kinetics of 50 wt.% skim milk at drying temperatures of 70 and 90 °C. Drying kinetics data were correlated with the Reaction Engineering Approach (REA) model to describe the drying histories. It was found that diameter reduction kinetics at these two temperatures did not collapse into a general trend as observed for lower initial solids of 20 and 30 wt.% (Lin and Chen, 2002, 2004); however, this trend was not further explored (Fu et al., 2012b).

The present study aims to study the shrinkage behaviour of 50 wt.% skim milk as affected by the drying temperature. The shrinkage kinetics data at 110 °C were compared to those reported for 70 and 90 °C (Fu et al., 2012b). The results confirmed that different drying temperatures could lead to a variation in shrinkage kinetics for 50 wt.% skim milk drying, contrary to observations made for lower initial solids, where the shrinkage kinetics at varied drying temperatures was found to be similar (Lin and Chen, 2002, 2004). In addition, higher drying temperatures produced larger final particles (i.e., less diameter reduction, $(D_0 - D_f)/D_0$) than lower temperatures, as opposed to the prediction by ideal shrinkage kinetics of smaller particles at higher temperatures. A general correlation for shrinkage coefficient b was established in the initial solids range of 10–50 wt.%, useful for estimating shrinkage kinetics of skim milk droplet within this range.

2. Material and methods

2.1. Material

Commercial skim milk powder was obtained locally and comprised 37.97 wt.% of protein, 1.34 wt.% of fat, 58.96 wt.% of sugar, and 1.73 wt.% of minerals. Reconstitution was carried out by mixing 50.0 g of the milk powder with 50.0 g of Milli-Q water in a 50 °C water bath with continuous stirring for 3–5 min until the powder was fully dissolved. At such high solids level, the reconstituted skim milk (RSM) solution naturally contained a significant amount of air bubbles. Thus the solution was successively subjected to 5-min homogenisation (Wisemix™ Homogenizer HG-15D, Daihan Scientific Co. Ltd., Korea) and 5-min ultrasonication (Ultrasonic cleaner DC-400H, M.R.C Ltd., Israel) to remove air bubbles.

During SDD experiments, the milk was stirred regularly to avoid material segregation. The temperature of RSM solution used for drying experiments was maintained at the range of 25–30 °C to ensure that the viscosity was similar for each drying run, as RSM solution with lower temperatures would have higher viscosity affecting the rate of droplet shrinkage.

2.2. Single droplet drying system

The detailed set-up and experimental procedure of the glass-filament SDD experiments have been described elsewhere (Lin and Chen, 2002; Che and Chen, 2010; Fu et al., 2011b). Basically, the rig consisted of a drying chamber and three droplet suspension modules. The drying chamber was connected to upwards-flowing air flow with controlled humidity, temperature and velocity. The three droplet suspension modules enabled measurements of changes in droplet mass, temperature and diameter to be carried out in separate runs with identical drying conditions.

The single milk droplet was generated using a 0.2–2 µl micropipette (Pipetman P2, Gilson S.A.S., France). The generated single droplet was transferred to the drying chamber using a transferring glass filament. Inside the drying chamber, the droplet was hung on the tip of a suspending glass filament in one of the droplet suspension modules. During droplet transfer, hot air flow blowing into the drying chamber was diverted away to minimize undesired evaporation before the start of observation. The process of drying was continuously captured by a camcorder (Sony DCR-HC36, Sony Corporation, Japan) equipped with five 4× close-up lenses.

The conditions used in the single droplet experiments are listed below:

- Drying air temperature: 110 °C.
- Drying air velocity: 0.75 m/s.