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Exploring drying kinetics and morphology of commercial dairy powders

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ABSTRACT

Understanding the effect of the initial composition of a liquid feed on the spray drying process and morphology of powders is important in order to reduce the time and costs for process design, and ensure the desired properties of the final product. In this work, seven commercial dairy products with different fat content were selected. The effect of initial composition on drying time during single drop experiments was studied. The morphology of powder particles and the influence of morphology changes on the drying rate were investigated in order to assess the effect of fat content on the effective diffusivity of water in dairy products. Results show that fat content influences drying time and morphology of powder particles. The higher the fat content the longer the drying time and particles appear to be less shrivelled. Changes in morphology and the drying rate seem to be related. Two falling drying periods were observed for most of the products. During the first period the drops shrink spherically, while during the second period shrivelling occurs. The effective diffusivity of water shows that high fat contents lead to a lower diffusivity of water in the products.

1. Introduction

Dairy powders have become very common as consumer products and food ingredients in a variety of products. Besides the dry dairy products such as skim milk and whole milk, a large variety of specialised products have been developed for baby food products, fat filled milk powders, protein concentrate powders, and dried caseins, for example.

The most common process to produce dairy powders is spray drying, which consists of simultaneous heat and mass transfer of the atomised liquid feed in a very short time. Usually, spray dryers are designed and operated based on the characteristics of the liquid feed to ensure desired functional properties of the final powders (Mujumdar, 2007). Depending on the characteristics of the feed, the type of atomiser and processing conditions (drying rate) during spray drying powder particles with different size and morphology are created. Many studies have shown the influence of compositions of the liquid feed, degree of feed aeration, and drying temperature on the morphology of inorganic and organic powders, and, as a consequence, on the properties of the final product (Kim et al., 2009a,b,c; Nandiyanto and Okuyama, 2011; Nijdam and Langrish, 2006; Rogers et al., 2012; Walton, 1999). In the case of food powders, skim milk and whole milk are commonly studied. Skim milk and whole milk are usually classified as skin-forming material, and depending on the operating conditions and composition of the feed they can show different surface composition and several morphological features such as particle inflation, particle collapse/shrivelling, particle vacuolation, and hollow particles (Walton, 1999; Walton and Mumford, 1999). Surface composition plays an important role during wettability, dispersibility, flowability, and stickiness of powders (Jayasundera et al., 2009). Studies have shown that surface composition of powder particles is different from the internal particle composition due to segregation among the components during drying. In the case of skim milk and whole milk powders produced by spray drying, a layer of fat covers the powder particle surface, which may be responsible for skin formation (Kim et al., 2009b).

However, the morphological changes of dairy products along the spray drying process and how they are influenced by the drying rate and feed composition have not been elucidated. Sano and Keey (1982) compared the experimental drying rate of a single drop of skim milk with the simulated drying rate obtained for a solid and non-inflating drop, and they have shown that inflation during drying causes a boost in the drying rate. Wallack et al. (1990) and Hecht and King (2000a,b) performed similar studies for different products such as maltodextrin, coffee and sucrose, and the results

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Nomenclature

c_{ext}	external vapour concentration (kg m^{-3})
c_{sat}	vapour concentration on the surface (kg m^{-3})
c_v	volume fraction (m^3 m^{-3})
Cp	specific heat (J kg^{-1} K^{-1})
d	pure density (kg m^{-3})
D	diffusion coefficient (m^2 s^{-1})
D_0	optimised parameter (m^2 s^{-1})
F	flux of water leaving the surface (kg m^{-2} s^{-1})
h_{ext}	external heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_{ext}	external mass transfer coefficient (m s^{-1})
M	molecular weight of water (g mol^{-1})
Nu	Nusselt dimensionless number (–)
P_{sat}	vapour pressure (Pa)
r	radius coordinate (m)
R	radius of the drop (m)
R^2	coefficient of determination (–)
R	ideal gas constant (J K^{-1} mol^{-1})
Sh	Sherwood dimensionless number (–)
t	time (s)
T	temperature (K)
u	water mass fraction on a solid weight basis (kg kg^{-1})
V_{VSOL}	water free volume in the solid solution (m^3)
w	water mass fraction on a total weight basis (kg kg^{-1})
z	solid fixed coordinate (kg)
ΔH_{ev}	latent heat of water evaporation (J kg^{-1})

Greek alphabet

α	proportionality factor (–)
ρ	density (kg m^{-3})

Subscripts

0	initial value
eff	effective
exp	experimental
ext	external
max	maximum value
s	solid
sim	simulated
w	water

show that there is an effect of morphological changes on the drying rate: when a rupture of droplets occurs a surge in the drying rate is observed due to the consequent exposure of the interior liquid to the external air.

The goal of this paper is to: (i) determine the drying kinetics of dairy products with different composition; (ii) investigate the morphology of the powders formed; and (iii) understand the influence of morphology changes on drying rate, in order to assess their effects on the effective diffusivity of water in dairy products during spray drying.

2. Material and methods

2.1. Material

To investigate the effect of initial composition drying experiments were performed on four different types of fresh milks and three different creams. In Table 1, the compositions of the fresh products are shown. All products were purchased in local stores except for the diluted coffee cream, which was obtained by combining 20 g of coffee creamer with 40 g of whole milk to reach a desired fat content of about 0.4 kg_{fat}/kg_{solid}. These products were selected to cover a large range of fat content, from 0.012 to 0.880 kg_{fat}/kg_{solid}.

2.2. Drying kinetics measurements

A drying kinetics device based on the suspended drop method was used to record the weight, temperature and size change of a single drop during convective drying. The description of the device is available in a previous publication (Malafronte et al., 2015). For each experiment a single drop of initial weight of about 2 mg was created using a micropipette and drying was performed at three different air temperatures (50, 70 and 90 °C), at air humidity of 0.007 $kg_{water}/kg_{dry\ air}$, and air velocity of 1 m/s.

2.3. Evaluation of effective diffusion coefficient of water

Effective diffusivities of water in dairy products were calculated using a parameter estimation method suggested by Malafronte et al. (2015). The method compares the experimental data obtained using the drying kinetics device with the results of a distributed heat and mass transport model to estimate the values of two parameters — D_0 and $\alpha \times V_{VSOL}^{-1}$ — used in the effective diffusion correlation:

Table 1
Compositions on a solid weight basis of the dairy products.

Products	Fat kg_{fat}/kg_{solid}	Protein $kg_{protein}/kg_{solid}$	Carbohydrate $kg_{carbohydrate}/kg_{solid}$	Water kgwater/kg_{solid}
Skim milk	0.012	0.576	0.412	9.000
Light milk	0.056	0.551	0.393	9.000
Medium milk	0.151	0.353	0.495	8.091
Whole milk	0.268	0.429	0.304	7.333
Diluted coffee creamer	0.381	0.302	0.267	6.143
Coffee creamer	0.571	0.177	0.251	4.556
Heavy cream	0.880	0.046	0.066	1.174

$$D_{eff}(u,T) = g(u)f(T) \quad (1)$$

$$f(T) = exp\left(-2060\left(\frac{1}{T} - \frac{1}{323}\right)\right) \quad (2)$$

$$g(u) = D_0 exp\left(\frac{\alpha}{V_{VSOL}}\left(1 - \frac{1}{1 - c_{s,v}(u)}\right)\right) \quad (3)$$

$$c_{s,v}(u) = (1 - w_1)\frac{\rho(u)}{d_s} \quad (4)$$

As shown in Eq. (1) the effective diffusion coefficient is considered a function of water content and temperature. The temperature dependency, $f(T)$, is assumed to be the same as obtained for skim milk by Malafronte et al. (2015). The concentration dependency of diffusivity follows the free-volume theory (Masaro and Zhu, 1999) since it showed the best agreement of experimental with simulated data at each temperature in cases of drying of skim milk (Malafronte et al., 2015).

2.3.1. Model

The detailed description of the drying model is available in a previous publication (Malafronte et al., 2015). The distributed drying model consists of a heat and mass balance on a spherical geometry solved in solid fixed coordinates by using