Journal of Food Engineering 175 (2016) 15–23

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Coalescence and agglomeration of individual particles of skim milk during convective drying

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ARTICLE INFO

Article history:
Received 4 September 2015
Received in revised form
18 November 2015
Accepted 23 November 2015
Available online 12 December 2015

Keywords:
Spray drying
Stickiness
Dairy
Shell formation
Modelling
Single drop

ABSTRACT

This work presents a methodology, which combines experiments and modelling, for investigating the coalescence and agglomeration ability of a product and to support the modelling of product properties during spray drying. Two particles were dried simultaneously and contact tests were performed along the drying time. A validated mathematical model describing the drying kinetics of milk particles was used to predict surface conditions during contact tests. Three major mechanisms were observed, coalescence, stickiness, and non-stickiness, which were related to adhesion and cohesion forces. The simulation model allowed evaluation of the surface Ohnesorge dimensionless number and surface glass transition temperature, which showed to be good parameters for predicting contact mechanisms. The model was also used to predict shell formation in drying particles. Wet and dry shell formation was simulated over the drying time, to improve understanding of observed contact behaviour.

1. Introduction

Spray drying is a unique drying technique, involving both particle formation and drying, in which powders are produced by introducing atomized liquid feed into a hot air stream. Spray drying can be considered a suspended particle processing system, as drying is performed while particles are suspended in air (Masters, 1991). It is a common process used for producing a large variety of pharmaceutical and food powders, including dairy powders. The functional properties of spray-dried powders, such as flowability and foaming, are difficult to control due to lack of knowledge of how product properties form and are changed during the spray-drying process.

Modelling is an important tool when designing and scaling up industrial spray-drying equipment, in order to reduce development time and costs. However, model validation is needed in order to achieve accurate predictions; this is a challenging task due to the dynamic (i.e., non-stationary) nature of the spray-drying process and difficulties in sampling and monitoring particle changes during the drying process (Norton and Sun, 2006). In addition to changes in each particle, wall–particle and particle–particle collisions occur, which strongly affect the performance of the drying process and influence the morphology of the final powder and consequently functional properties. Collision between particles may lead to coalescence, agglomeration, or rebound, depending on the physical properties of individual particles at the time of collision. Coalescence occurs between liquid particles; agglomeration and rebound depend on the stickiness of the particle material, though their occurrence during spray drying is not completely understood. Some authors have modelled these mechanisms based on calculations of the physical conditions of particles (Verdurmen et al., 2004). In modelling coalescence phenomena during spray drying, the physical conditions are calculated based on theoretical assumption only, and experimental set-up for validating these assumptions has not been implemented. In modelling agglomeration phenomena, the physical conditions used are based on experimental results. Various measurement methods have been developed to characterize the agglomeration of food powders in terms of their stickiness *after* drying (Boonyai et al., 2004); however, there is a need for a methodology allowing the investigation of coalescence and agglomeration *during* spray drying.

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http://dx.doi.org/10.1016/j.jfoodeng.2015.11.021

Nomenclature

c_{ext}	external vapour concentration (kg m^{-3})
c_{sat}	vapour concentration on the surface (kg m^{-3})
C_p	specific heat (J kg^{-1} K^{-1})
d	pure density (kg m^{-3})
D	diffusion coefficient (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 (−)
Oh	Ohnesorge dimensionless number
P_{sat}	vapour pressure (Pa)
r	radius coordinate (m)
R	radius of the particle (m)
$\underline{R}$	ideal gas constant (J K^{-1} mol^{-1})
Sh	Sherwood dimensionless number (−)
t	time (s)
T	temperature (K)
TS	percentage of total solids (%)
u	water mass fraction on a solid weight basis (kg kg^{-1})
u^*	maximum water mass fraction on a solid weight basis (kg kg^{-1})
x	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

ρ	density (kg m^{-3})
μ	viscosity (Pa s)
μ^*	minimum viscosity for wet shell formation (Pa s)
σ	surface tension (N m^{-1})

Subscripts

0	initial value
I	Case I
II	Case II
eff	effective
ext	external
g	glass transition
max	maximum value
s	solid
surf	particle surface
w	water

Adhikari et al. (2003) developed a probe tack test to determine the stickiness of individual particles on a surface during convective drying, and Haider et al. (2014) used a micromanipulation particle tester to study the deformation of two homogenous particles. These are the only two methods reported in the literature that facilitate a better understanding of the stickiness and inter-particle forces of individual particles. However, the probe tack tester focuses on the stickiness of a drying particle on a surface, while the micromanipulation particle tester concentrates on inter-particle forces but not during drying.

In our view, a pure experimental approach to studying particle coalescence and stickiness during drying is difficult due to difficulties in measuring water content and temperature profiles inside and on the surface of particles. On the other hand, a pure modelling approach cannot be used due to lack of validation of the theories applied. The goal of this work is therefore to develop a novel methodology that combines experiments and modelling to help understand the physical conditions of the coalescence and stickiness of two skim milk particles brought into contact. This knowledge will be combined to simulate the shell formation in a single particle during drying and to improve our understanding of coalescence, stickiness, and non-stickiness behaviour within the spray dryer.

2. Drying-kinetics model

The drying-kinetics model consists of heat and mass distributed parameter balances on a spherical geometry. The model was solved in solid fixed coordinates using Multiphysics® 4.3b (COMSOL, Stockholm, Sweden). The drying model and its validation are described in detail in a previous publication (Malafronte et al., 2015a).

The mass and the heat balances in solid fixed coordinates, together with the initial conditions (I.C.) and boundary conditions (B.C.), are the following:

Mass balance

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left(\rho_s^2 r^4 D_{eff}\frac{\partial u}{\partial z}\right) \tag{1}$$

$$\text{I.C. } t = 0;\ u = u_0 \tag{2}$$

$$\text{B.C. } t > 0\ z = 0;\ \frac{\partial u}{\partial z} = 0 \tag{3}$$

$$z = z_{max}\quad -D_{eff}\rho_s\frac{\partial u}{\partial z} = \frac{F}{\rho_s {R_{ext}}^2} \tag{4}$$

Heat balance

$$\rho C_p\frac{\partial T}{\partial t} = k\rho_s\frac{\partial}{\partial z}\cdot\left(r^4\rho_s\frac{\partial T}{\partial z}\right) \tag{5}$$

$$\text{I.C. } t = 0;\ T = T_0 \tag{6}$$

$$\text{B.C. } t > 0\ z = 0;\ \frac{\partial T}{\partial z} = 0 \tag{7}$$

$$z = z_{max}\quad -k\rho_s\frac{\partial T}{\partial z} = \frac{h_{ext}(T - T_{ext}) + \Delta H_{ev}(T)F}{{R_{ext}}^2} \tag{8}$$

where u is the mass fraction on a solid basis, r is the real coordinate, and ρ_s is the solid concentration, which equals 1248 kg$_{solid}$ m^{-3} (Singh and Heldman, 2001). D_{eff} is the effective diffusivity of water in skim milk as a function of water content and temperature: