Journal of Food Engineering 97 (2010) 177–187

Contents lists available at ScienceDirect

Journal of Food Engineering

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

A fundamental approach and its experimental validation to simulate density as a function of moisture content during drying processes

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ARTICLE INFO

Article history:
Received 3 August 2009
Received in revised form 24 September 2009
Accepted 3 October 2009
Available online 12 October 2009

Keywords:
Bulk density
Particle density
Theoretical model
Modeling
Mathematical simulation
Shrinkage
Collapse
Drying
Food
Experimental validation

ABSTRACT

Although several empirical models are available in the literature to predict density in solid matrices, only a very limited number of theoretical models have been reported. So far, no model considered the possible variation in the initial air volume existing at the beginning of the drying process. In this contribution, a theoretical model to predict bulk density of dried materials was built by considering two mechanisms that might occur during drying processes. These mechanisms are represented by collapse and shrinkage functions. The predictions obtained by this theoretical model were extensively validated with experimental data published by several independent groups for different food products dried with different technologies. In all these cases, the model gave excellent agreement with the experimental data regardless the topology of the curve bulk density versus moisture content. The model was also compared with other published models. The result of this comparison revealed that the errors resulting from the predictions obtained by the present model are among the smallest. Shrinkage and collapse functions were used to analyze the mechanisms by which bulk density varies during air-drying and freeze-drying. The model showed that both shrinkage and collapse phenomena are dramatically involved during air-drying. However, in the case of freeze-drying, no collapse is observed and only partial shrinkage is taking place. Hence, the present model can be used as a tool to predict the bulk density with excellent accuracy, to understand the dynamic mechanisms involved during drying. Moreover, this model can be incorporated to other models involving the variation of density as a function of moisture.

1. Introduction

Drying is the oldest way to preserve food products. However, so far, the quality of some dried products is still below the acceptance levels of consumers. Therefore, extensive research has been performed aiming at developing new drying technologies or drying conditions with less negative impacts on the final quality of food products. Density is one of the physical properties which is dramatically affected by the moisture content during drying processes (Boukouvalas et al., 2006; Koc et al., 2008; Krokida and Maroulis, 1997; Rahman et al., 2005, 1996). As such, density can be linked directly to some quality indicators; it could provide, for instance, a good idea about shrinkage and porosity, which have direct impact on the visual attributes and re-hydration kinetics of dried products.

In addition to being considered as a quality indicator, density is involved in mass and heat transfer phenomena which are crucial in drying processes. Indeed, most thermophysical and transport properties are affected by density (Guine, 2006; Rahman et al., 1996). Optimization of these phenomena, taking into account the quality of the output product and the cost of the processing, is a requirement for the development and the perpetuity of drying technologies. In this context, simulations using density as a function of moisture content could be used to investigate drying processes and optimize their parameters and operation conditions. However, the credibility and validity of these simulations depend, among others, on the accuracy of the density models. As a first approximation and for the sake of simplicity, the majority of the mathematical models available assume that the physical parameters, such as density, are constant and do not depend on the process conditions (Madamba et al., 1994). This assumption seems not to be realistic as shrinkage of food products is seldom negligible (Mayor and Sereno, 2004; Moreira et al., 2000). In fact, the final volume of some air-dried foods could be reduced to less than 20% of the initial volume (Ratti, 1994; Souraki and Mowla, 2008; Zielinska and Markowski, 2007). Therefore, the control and optimization of food processes require expressions that describe the evolution of physical parameters like density as a function of moisture content.

Several mathematical expressions have been suggested to predict density as a function of moisture content. Tables 1 and 2 summarize some of the most used models to predict bulk and particle densities for dried food products. These models can be grouped in

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doi:10.1016/j.jfoodeng.2009.10.007

Nomenclature

a, b, c, and d	fitting parameters involved in the models (Tables 1 and 2)
A, B, C, and D	parameters involved in Eq. (6)
E, F, and G	parameters involved in Eq. (13)
g	set of optimization constraints in Eq. (20)
h	set of algebraic equations in Eq. (20)
J	objective function in Eq. (20)
m	mass (kg)
p	fitting parameters involved in Eq. (12)
r_1, r_2, r_3	*polynomial* coefficients involved in shrinkage function (Eq (11))
S_V	volume shrinkage (Table 1)
$Tanh$	hyperbolic tangent function (Eq. (12))
V	volume (m^3)
W	water content ($W = X/(1 + X)$) (kg of water/kg of wet product)
X	water content (kg of water/kg of dried product)
X_c	fitting parameters involved in Eq. (12)
y	optimization variables in Eq. (20)
Y	set of possible solutions for the optimization variables in Eq. (20)

Greek symbols

δ	collapse function (dimensionless)
ρ	density (kg/m^3)
β	density ratio (ρ_s/ρ_w)
ε	porosity (m^3/m^3)
λ	volume-shrinkage coefficient (dimensionless)
Φ	shrinkage–expansion function/shrinkage function (dimensionless)

Subscripts/superscripts

0	initial (at time = 0)
a	air
b	bulk
exp	relative to experimental data in Eqs. (21) and (22)
l	relative to lower bound in Eq. (20)
n	number of experimental observation in Eqs. (21) and (22)
p	relative to particle in Eq. (17)
pre	relative to predicted data in Eqs. (21) and (22)
s	solid
u	relative to upper bound in Eq. (20)
w	water

two categories: (i) theoretical models that are built based on the understanding on the fundamental phenomena and mechanisms involved during drying; (ii) empirical models that are built by fitting model parameters to experimental data. The fitting parameters of the theoretical models have a physical meaning, while those involved in empirical models do not provide any. Although the empirical models have been known to give globally a good fitting of the experimental data, they offer limited insight into the fundamental principles involved, hindering the understanding of the mechanisms that are responsible for water removal. The main drawbacks of these empirical approaches are: (i) the fitting parameters do not have any physical meaning, which limits the interpretation of data and hinders the understanding of the governing mechanisms involved in water removal; and (ii) these models are not generic as they depend on the product, the drying technology and the processing conditions (temperature, pressure, humidity, air speed, etc.) (Madiouli et al., 2007; Rahman, 2001, 2003). The dependency of the empirical models on the specific systems used for their determination makes them non-applicable to other matrices or experimental conditions.

Therefore, there is a necessity to build mathematical models which have a fundamental basis and lead to a broaden understanding of the changes in physical parameters which occur during drying. A theoretical approach in combination with realistic assumptions is one of the strategies available to reach this goal. The model of Zogzas et al. (1994) is a successful example of this theoretical approach, which has been used and validated for some dried food products. This model involves two fitting parameters; one is the bulk density of dry solid and the second is a volume-shrinkage coefficient. It also assumes that, during drying, the shrinkage phenomenon is a linear function of moisture content. The model of Zogzas et al. (1994) presents some relevant advantages: (i) it is supported by a theoretical background with fitting parameters that have a physical meaning; (ii) the model is formulated using simple algebraic expressions for rapid calculations; and (iii) it involves some parameters that are experimentally easy to measure (e.g. bulk density of dry solid). However, despite these advantages, the main limitation of this theoretical model is that it is not able to describe all the possible profiles of the bulk density curves as a function of moisture content.

The calculation of the bulk density involves the air incorporated within the food matrix. According to our previous study, the amount of this air volume depends on both the initial air volume existing at the beginning of the drying process and the water removed (Khalloufi et al., 2009). So far, no model of bulk density has taken into account the possible change over time of the initial volume of air during drying processes. Our hypothesis is that by introducing this variation of initial air volume during the drying process, the accuracy of theoretical model predictions would be significantly improved. Moreover, we expect that a single model would be able to describe most of the bulk density as a function of moisture content.

The aim of this contribution is fivefold: (i) to summarize the mathematical expressions usually used to predict bulk and particle densities as function of moisture content in food products, (ii) to use a theoretical approach to build a mathematical model that can predict the bulk density regardless of the product, the process conditions and the drying technology, and involving only parameters that have a physical meaning (e.g. collapse and shrinkage functions), (iii) to validate the model by using experimental data published by independent groups for different dried food products and for different drying technologies, (iv) to compare the present model to other empirical and theoretical models, and (v) to explain the behavior of the bulk density curves by using shrinkage and collapse functions.

2. Definitions

By definition, density is the ratio between mass and volume. For the sake of simplicity, the food matrixes can be divided in three compounds namely water, solid and air. Depending on which com-