Food Research International 48 (2012) 808–819

Contents lists available at SciVerse ScienceDirect

Food Research International

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

Pseudo-linearity of the shrinkage coefficient and a sensitivity study of collapse and shrinkage functions

Seddik Khalloufi [a,*], Cristhian Almeida-Rivera [a], Jo Janssen [a], Peter Bongers [a,b,1]

[a] Unilever R&D Discover Vlaardingen, Department of Structured Materials and Process Science, 3130 AT Vlaardingen, The Netherlands
[b] Chemical Engineering and Chemistry Department, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 26 November 2009
Accepted 25 June 2012

Keywords:
Volume shrinkage coefficient
Bulk density
Porosity
Modeling
Mathematical simulations
Collapse
Drying
Food
Experimental validation
Sensitivity study

ABSTRACT

Several empirical/theoretical models are available in the open literature to predict the volume shrinkage coefficient (S_v). However, the few reported theoretical models do not consider the variation of the porosity as a function of water content during drying. In this contribution, a theoretical model was used to describe S_v as a function of water content. This model takes into account the variation of both the bulk density and the porosity during the entire drying process. Furthermore, the initial amount of air contained in the product at the beginning of the process is also included in the model. The final expression of the present model is a pseudo-linear relationship where the intercept and the slope are moisture-dependent. The model was extensively validated with various experimental data obtained by several groups for different products dried by various technologies. The results showed excellent agreement between the model and the experimental data. Comparison between this model and other published models revealed that the present model gives comparable predictions or even the lowest error when compared to some empirical models. In order to understand the mechanisms occurring during drying , collapse and shrinkage functions were used for eggplant vacuum-dried at two different pressures. Partial shrinkage and partial collapse were observed under these two pressures. However, low pressure led to less deterioration in terms of shrinkage and collapse phenomena. A sensitivity study of collapse and shrinkage functions involved in this model is also presented. In addition to leading to accurate predictions, this model allows getting phenomenological insights into the mechanisms responsible for shrinkage occurring during drying processes.

1. Introduction

During drying processes food matrixes usually undergo some modifications that have a direct impact on the quality attributes and thermal/mass properties of the final products. For example, size reduction of the dried samples can negatively impact the quality perception of dried products. Some published experimental data showed that the final volume of air-dried foods could be reduced to less than 20% of the initial volume (Ratti, 1994; Souraki & Mowla, 2008; Zielinska & Markowski, 2007). Therefore, predicting the shrinkage of food products during dehydration becomes a prerequisite for process design and optimization of the drying conditions.

In the open literature, several mathematical expressions have been proposed to predict the S_v as a function of moisture content during drying. An overview of such models is shown in Table 1. These models can be grouped in 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 the model parameters to the 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 are known to give globally a good fitting of the experimental data, they offer limited insight into the fundamental principles involved in drying (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 broadened 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.

Four theoretical models are available in the open literature to describe the S_v as a function of water content, namely: the models of Lozano, Rotstein, and Urbicain (1983), Perez and Calvelo (1984), Mayor and Sereno (2004), and Madiouli et al. (2007). These models involve eight, two, three or three fitting parameters, respectively. In

* Corresponding author. Tel.: +31 10 460 8501; fax: +31 10 460 5025.
E-mail address: seddik.Khalloufi@unilever.com (S. Khalloufi).
[1] Deceased.

0963-9969/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodres.2012.06.024

Nomenclature

A, $B(X)$, and $C(X)$	parameters involved in Eqs. (3)–(6)
a, b, c, d, and e	fitting parameters involved in the models (Table 1)
$D(X)$ and $E(X)$	parameters involved in Eqs. (9)–(11)
Dia	diameter (Table 2)
g	set of optimization constraints in Eq. (12)
h	set of algebraic equations in Eq. (12)
J	objective function in Eq. (12)
m	mass (kg)
p	fitting parameters in Eq. (7)
r_1, r_2, r_3	polynomial coefficients (Eq. (8))
S_v	Volume shrinkage coefficient (dimensionless) (Eq. (9))
$tanh$	hyperbolic tangent function (Eq. (7))
V	volume (m^3)
X	water content (kg of water/kg of dried product)
X_c	critical water content (Eq. (7))
Y	set of possible solutions for the optimization variables in Eq. (12)
y	the optimization variables in Eq. (12)

Greek parameters

δ	collapse function (dimensionless)
ρ	density (kg/m^3)
β	density ratio (ρ_s/ρ_w)
ε	porosity (volume the air over the total volume m^3/m^3)
Φ	shrinkage function (dimensionless)
χ	constituent concentration (kg/kg of dried product)

Subscript/superscript

0	initial (at time = 0);
a	air
A	relative to surface (Table 2)
b	bulk
cw	cell wall material
exp	relative to experimental data
L	relative to length (Table 2)
l	relative to lower bound in Eq. (12)
n	number of experimental observation
p	relative to particle
pre	relative to predicted data
s	solid
sg	sugar
sn	sugar solution
st	starch
SV	relative to surface per volume (Table 2)
u	relative to upper bound in Eq. (12)

addition to having a high number of fitting parameters, Lozano et al.'s (1983), model involves complex data that depend on the composition of the matrix such as the cell wall material. Consequently, despite the physical meaning of the parameters involved in Lozano et al.'s (1983) model it did not get the popularity expected. One of the parameters involved in the models of Perez and Calvelo (1984), Mayor and Sereno (2004), and Madiouli et al. (2007) is the porosity of the matrix. However, none of these models considers the variation of the porosity as a function of water content during drying. Moreover, in the case of Perez and Calvelo's (1984) model, the initial porosity is not taken into account.

In the present contribution, the four theoretical models were converted into one linear relationship, with the following advantages: (i) they are supported by a theoretical background with fitting parameters that have a physical meaning; (ii) they are formulated using simple linear algebraic expressions for rapid calculations; and (iii) except for Lozano et al.'s (1983) model, they involve some parameters that are experimentally easy to measure (e.g. initial porosity and density ratio). However, the main limitations of these theoretical models are that: (i) they are not able to describe all the possible profiles of the S_v curves as a function of moisture content, and (ii) for the models that involve more than two fitting parameters (e.g. except Perez and Calvelo's (1984) model) the physical meaning of these fitting parameters should be interpreted with prudence.

The calculation of the S_v involves the bulk volume, which includes the air incorporated within the food matrix. According to our previous studies (Khalloufi, Almeida-Rivera, & Bongers, 2009, 2010) the amount of this air volume depends on both the initial air volume existing at the beginning of the drying process and the amount of water removed. So far, no model that predicts the S_v has taken into account: (i) the possible change over time of the initial volume of air during drying processes, and/or (ii) the evolution of the porosity as a function of water content.

Our underlying assumption is that the introduction of the variation of initial air volume and porosity during the drying process would lead to an improved accuracy of theoretical model predictions. Moreover, we expected that a single model would be able to describe most behaviors of the S_v as a function of moisture content. The aim of this contribution is six-fold: (i) to summarize the empirical and the theoretical models usually used to predict S_v as a function of moisture content in food products, (ii) to use a fundamental approach to build a mathematical model involving only parameters that have a physical meaning (e.g. collapse and shrinkage functions), which can predict the S_v without being limited by the product, the process conditions and/or the drying technology, (iii) to validate the model by using experimental data published by several independent groups for different dried food products and for diverse drying technologies and processing conditions, (iv) to compare the present model to the most accurate and used empirical models, (v) to explain the behavior of the S_v curves by using shrinkage and collapse functions, (vi) to perform a sensitivity study of S_v by monitoring the random changes of collapse and shrinkage functions.

2. Definitions

The shrinkage phenomena (size reductions) are the direct consequence of the combination of water elimination and a weak structure forming the solid network of the dried matrixes. When the volume reduction is equivalent to the volume of water removed, the size reduction is referred to as ideal shrinkage (Madiouli et al., 2007; Rahman, 2003;). Lewicki (1998) reported the existence of a balance between shrinkage forces (ability of the material to deform) and the resistance to deformation, which very much depends on the kind of material and pre-drying treatments. Furthermore, Madamba, Driscoll, and Buckle (1994) reported that for dried garlic the shrinkage behaves differently depending on the direction of fibers. This fact suggests that for some foods products the shrinkage is not isotropic. Non-isotropic shrinkage leads to unbalanced stress and failure of the material which result in surface cracking (Mayor & Sereno, 2004). In the drying field, different expressions are used to represent the shrinkage phenomenon. The mathematical relationships between these expressions are given in Table 2. Indeed, shrinkage can be represented by relative or reduced dimensional change of volume, thickness, length, diameter or the ratio of surface per volume (Mayor & Sereno, 2004). In this study, the focus is on the S_v which is used as a reference to express the size reduction during drying.