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Drying modeling in products undergoing simultaneous size reduction and shape change: Appraisal of deformation effect on water diffusivity

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ABSTRACT

The mathematical modeling of simultaneous size reduction (shrinkage) and shape change (deformation) during food drying was investigated. A whole new approach was developed for (i) solving the unsteady state mass transfer equation in a deformable mesh and (ii) modeling the simultaneous shrinkage–deformation (SD) of product in drying simulation. The SD model for continuous mesh updating is based on the estimation of the minimum discrepancy configuration. Developed theory was applied to estimate water diffusivities during the analysis of potato drying data (9.525 mm × 9.525 mm × 80 mm, 50–80 °C, 2 m/s) by considering the product shrinkage with and without deformation. The drying model including the simultaneous SD rendered the best description of experimental drying curves ($R^2 > 0.98$). Under current experimental conditions, water diffusivities corrected for simultaneous SD were in the range of 1.93×10^{-10}–3.44×10^{-10} m^2/s. On the other hand, water diffusivities calculated by neglecting product deformation were overestimated in about 57–66% in comparison with those considering the phenomena. The dependency of water diffusivity on drying temperature was unaffected by the inclusion of product deformation in drying modeling.

1. Introduction

Hot-air drying is one of the most widespread techniques for reducing the water content in foods while extending their shelf-life. This operation involves several simultaneous heat and mass transfer phenomena; yet, Fickian water diffusion within the product is usually considered the governing mechanism for modeling and simulation purposes (da Silva et al., 2014; Pacheco-Aguirre et al., 2014). Both an accurate description of drying process and a reliable estimation of diffusion coefficients require considering the reduction of product dimensions as demonstrated in several studies (Dissa et al., 2008, 2014; García-Pérez et al., 2012; Ruiz-López et al., 2012; Golestani et al., 2013; Luo et al., 2013).

For drying modeling purposes, shrinkage refers to the size reduction experienced by product due to the *regular* shortening of its dimensions along mass transfer directions in the chosen curvilinear system (Torres-Irigoyen et al., 2014; Ortiz-García-Carrasco et al., 2015). In these cases, shrinkage information in mass transfer models is provided as a single lumped metric, such as thickness, area or volume (Mayor and Sereno, 2004; Ponkham et al., 2012; Brasiello et al., 2013). Thus, product shape in drying simulations evolves as a smaller version of its initial state in which all dimensions are scaled either by the same (isotropic shrinkage) or by a different (anisotropic shrinkage) factor. However, foods can also experience other geometric changes during drying such as bending, twisting, and irregular size reduction, producing an evident shape change or deformation (Campos-Mendiola et al., 2007; Yadollahinia and Jahangiri, 2009; Yadollahinia et al., 2009; Chen and Martynenko, 2013; Sampson et al., 2014), but very limited information regarding modeling and simulation of drying in products undergoing these phenomena is currently available.

Drying modeling of deformable products is a challenging task as it imposes certain restrictions or special requirements as opposed to regular shrinking products, most notably, (i) drying simulation obliges mass transfer in more than one direction, increasing computational cost, (ii) complex numerical methods able to handle regular or irregular geometries changing during simulation are required, and (iii) special methodologies should be used to experimentally appraise and describe product deformation. According to

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Nomenclature

a_{I0}, a_{I1}, a_{I2}	interpolating coefficients in the I-th mesh cell ($I = 1, \ldots, T$)
$\mathbf{a}_I$	vector of interpolating coefficients in the I-th mesh cell ($I = 1, \ldots, T$)
A	area
$\mathcal{A}$	denotes the air-product interface
Bi_m	mass Biot number (dimensionless)
$\mathbf{c}_I$	I-th mesh cell ($I = 1, \ldots, T$)
c_s	volumetric concentration of dry solids (kg dry solids/m^3 product)
$\mathbf{C}$	connection matrix
d_{ij}	Euclidian distance between vertices i, j
D	effective diffusivity of water in food (m^2/s)
$\mathbf{D}_i$	vector of unknown derivatives in the i-th vertex ($i = 1, \ldots, N$)
$\mathbf{e}$	basis vector
$\mathbf{E}$	vector of expected displacements
f_I	interpolating function in the I-th mesh cell ($I = 1, \ldots, T$)
$\mathbf{f}_I$	vector of interpolating function values in the I-th mesh cell ($I = 1, \ldots, T$)
g	connectivity function
H	absolute humidity of drying air (kg water/kg dry air)
h_m	external mass transfer coefficient (m/s)
I_1, I_2	integrals in volume weighted moisture content
k, n	parameters determining the shrinking rate of product
K	water partition ratio between gas and solid phases
$\mathbf{J}_I$	matrix containing coordinates of the I-th mesh cell ($I = 1, \ldots, T$)
ℓ	represents any dimensionless coordinate
$\boldsymbol{\ell}$	set of shortening distances along ℓ coordinate (dimensionless)
$\mathbf{L}, \mathbf{R}$	vector of barycentric and rectangular coordinates for volume integrals, respectively
L_1, L_2	first and second barycentric coordinates
M	refers to product mesh
$\mathbf{n}$	unit vector normal to product surface
N	number of vertices in product mesh
N_{1i}, N_{2i}	number of elements in one-ring and two-ring neighborhood of vertex i
$\mathbf{R}_3, \mathbf{T}$	transformation matrices between rectangular and barycentric coordinates
$\mathbf{S}$	matrix of weighted distances between vertices
s_{ij}	parameter controlling the final distance shortening between vertices
i, j	along ξ or ζ directions
t	drying time (s)
T	number of triangles in product mesh
u	moisture content of product (dry basis) (kg water/kg dry solids)
$\mathbf{U}$	matrix of weighted moisture differences
v	humid volume of drying air (m^3 humid air/kg dry air)
$\mathbf{v}_i$	i-th mesh vertex ($i = 1, \ldots, N$)
$\mathcal{V}$	denotes the product volume
w	weighing function
x, y	rectangular coordinates (m)
X, Y	reference length for diffusion along x and y-axes, respectively (m)
$\mathbf{Z}$	vector of expected displacements

Greek letters

δ_1, δ_2	parameters for lumped shrinkage model
ε_i	expected displacement of i-th vertex along ξ coordinate (dimensionless)
κ	Y-to-X ratio (dimensionless)
Ω_1, Ω_2	one and two-ring neighborhood
τ	Fourier number for mass transfer
ξ, ζ	dimensionless coordinates along x and y-axes, respectively
$\psi, \hat{\psi}, \Psi$	free moisture fraction: local, second order approximation and averaged, respectively (dimensionless)

Subscripts

0	at the beginning of drying process
b	at the air-product boundary
e	at equilibrium
i, j, k	indices for global numbering of mesh vertices ($i, j, k = 1, \ldots, N$)
I	index for global numbering of mesh cells ($I = 1, \ldots, T$)

Curcio and Aversa (2014) "*it is crucial to develop a model capable of predicting the actual variation of food shape and dimensions*".

Earlier attempts to predict product deformation during drying go back to the application of the plasticity theory (Itaya et al., 1995; Kowalski, 1996, 2000), previously formulated to predict crack development in empty and fluid-saturated porous solids (Green, 1972; Zienkiewicz and Cormeau, 1974; de Boer and Kowalski, 1983). The same theory or its modifications have been applied in recent studies to describe the size reduction and geometrical shape changes during drying and puffing of some foodstuffs (Niamnuy et al., 2008; Aregawi et al., 2013a, 2013b; Rakesh and Datta, 2013; Curcio and Aversa, 2014). However, whenever product deformation is considered during drying, simulated shape evolution did not resemble the experimental behavior. A pioneer study on food drying simulation targeting to reproduce the real product shape was that of Yang et al. (2001) where the changes in lateral contour of potato cylinders were registered and used to generate an equation describing an ideal deformation profile where a given point in product surface moves toward its center without angular displacements. Mesh displacement was achieved through the same mechanical deformation models based on plasticity theory. It should be noticed that all references including solid deformation (Yang et al., 2001; Aregawi et al., 2013a, 2013b; Curcio and Aversa, 2014) focused on drying simulation only, without estimating water diffusivity; besides, the product was considered to suffer a mild symmetrical deformation.

The objective of this study was to evaluate the effect of product deformation on water diffusivity while introducing new approaches to solve an unsteady state mass transfer equation in a deformable mesh targeting to describe the real product shape achieved during drying.

2. Theoretical development

2.1. Model formulation

The non-steady state mass transfer equation for moisture diffusion within a homogeneous and isotropic material (represented by $\mathcal{V}$) is very often used to describe the drying of food products (Brasiello et al., 2013; Curcio and Aversa, 2014; da Silva et al., 2014; Torres-Irigoyen et al., 2014). In a general coordinate system this equation is expressed as

$$(c_s u)_t = \nabla \cdot [D \nabla (c_s u)] \text{ in } \mathcal{V} \tag{1}$$