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Influence of shrinkage on convective drying of fresh vegetables: A theoretical model

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ABSTRACT

The aim of the present work was the formulation of a theoretical model predicting the behavior of a convective drier over a wide range of process conditions. The proposed approach was based on the coupling of a transport phenomena model, describing the simultaneous transfer of momentum, heat and mass both in the drying chamber and in the food, and of a structural mechanics model aimed at estimating food sample deformations, as due to moisture loss. The effects of food shrinkage on drying performance were ascertained by analyzing the spatial distributions of temperature, moisture content, strain and stress, as a function of operating conditions. The agreement between model predictions and a set of experimental data collected during drying of cylindrical potatoes was good as far as the time evolutions of food average moisture content and of its main dimensions, i.e. length and diameter, were concerned.

1. Introduction

Convective drying is characterized by the simultaneous transfer of momentum, heat and water, whose removal determines significant modifications to food structure. On modeling food convective drying it is essential to develop reliable simulation tools capable of predicting the actual influence of operating conditions either on dried foods characteristics or on process performance. Within this frame, multiphysics modeling plays a key role, since it combines multiple physical phenomena in a single computational environment, which may allow predicting the mutual interactions between transport phenomena, governing food drying process, and the modifications occurring in food structure.

The presence of both liquid water and vapor in the solid matrix, the dependence of food transport properties on the local values of temperature and moisture content, the complex fluid–structure interactions determined by air-flow around the sample, the variation, with time, of food shape and of its dimensions do actually make drying modeling rather problematic (Chen, 2007). Datta's research group proposed several comprehensive and general multiphase models predicting the heat and mass transfer rates in different industrial processes involving foods (Datta, 2007; Halder et al., 2011; Zhang and Datta, 2004; Ni et al., 1999; Halder et al., 2007; Zhang et al., 2005; Dhall and Datta, 2011). In these papers, the transport phenomena occurring at food/air interfaces were described in terms of heat and mass transfer coefficients estimated from semi-empirical correlations and referred to samples having a constant characteristic dimension. When food shape is not regular or it even changes with time, i.e. when shrinkage is significant, the exploitation of literature correlations might significantly limit the model accuracy (Bernstein and Noreña, 2013), thus providing unreliable predictions of the actual system behavior. Curcio et al. (2008) formulated a theoretical model describing food convective drying without resorting to any empirical transport coefficient. The model, however, was based on several assumptions; among these, the exploitation of an effective diffusion coefficient, which did not make any distinction between the transport of liquid water and that of vapor, and the negligibility of water evaporation inside the food were definitely the most critical. In a subsequent paper, Curcio (2010) improved the predictions of the previous model and simulated drying behavior when inner evaporation could not be neglected; a multiphase approach, based on the conservation of both liquid water and vapor, was formulated. In both the above-described studies, however, food shrinkage was neglected assuming that, in the chosen range of operating conditions, food shape and its dimensions did not change appreciably as drying proceeded.

The removal of water from a porous solid material is actually responsible for the development of a field of contracting stresses in the matrix (Kowalski and Mielniczuk, 2006; Mihoubi and Bellagi, 2009; Kowalski and Rajewska, 2002). An ever-different

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Nomenclature

C^+	universal constant for smooth walls (–)
C_2	water concentration in air (mol/m^3)
C_{pa}	air specific heat (J/(kg K))
C_{ps}	food specific heat (J/(kg K))
C_v	vapor concentration in food (mol/m^3)
C_w	liquid water concentration in food (mol/m^3)
D	potato diameter (m)
D_a	diffusion coefficient of water in air (m^2/s)
dC_w	water concentration variation (mol/m^3)
D_v	effective diffusion coefficient of vapor in food (m^2/s)
D_w	capillary diffusion coefficient of water in food (m^2/s)
E_y	Young modulus (Pa)
$G_m = E_y/[2 * (1 + \nu)]$	shear modulus (Pa)
H'	strain-hardening rate (Pa)
$\dot{I}$	volumetric rate of evaporation (mol/(m^3 s))
k	turbulent kinetic energy (m^2/s^2)
k_a	air thermal conductivity (W/(m K))
K_{ds}	constant in Eq. (5) (m^3/mol)
k_{eff}	effective thermal conductivity of food (W/(m K))
L	potato length (m)
$\underline{n}$	unity vector normal to the surface (–)
p	pressure within the drying chamber (Pa)
p_v	vapor pressure of water (Pa)
p_{vs}	saturated vapor pressure of water (Pa)
r	radial coordinate (m)
T	food temperature (K)
t	time (s)
T_2	air temperature (K)
T_{air}	air temperature at the drier inlet (K)
$\underline{u}$	averaged velocity field (m/s)
$\underline{u}'$	fluctuating part of velocity field (m/s)
U_r	air relative humidity at the drier inlet (–)
u_τ	friction velocity (m/s)
V	food volume (m^3)
v_0	air velocity at the drier inlet (m/s)
X_b	moisture content on a dry basis kg water/kg dry solid
$\overline{X}_b$	average moisture content on a dry basis kg water/kg dry solid
z	axial coordinate (m)

Greek symbols

α	constant comparing in k–ω model (–)
β	constant comparing in k–ω model (–)
β_κ	constant comparing in k–ω model (–)
δ_w	distance from the wall (m)
$d\varepsilon$	local total strain (–)
$d\varepsilon_0$	shrinkage strain (–)
$d\varepsilon_{r0}$	shrinkage strain in radial direction (–)
$d\varepsilon_s$	mechanical strain (–)
$d\varepsilon_{z0}$	shrinkage strain in axial direction (–)
η_a	air viscosity (Pa s)
$\eta_t = \rho_a k/\omega$	air turbulent viscosity (Pa s)
κ	von Karman's constant (–)
λ	water latent heat of vaporization (J/mol)
ν	Poisson ratio (–)
ξ	yield stress parameter
ρ_a	air density (kg/m^3)
ρ_s	food density (kg/m^3)
σ	stress (Pa)
σ'	deviatoric stress (Pa)
$\bar{\sigma}$	equivalent stress (Pa)
σ_d	yield stress (Pa)
σ_k	constant comparing in k–ω model (–)
σ_ω	constant comparing in k–ω model (–)
ω	dissipation per unit of turbulent kinetic energy

Subscripts

0	initial condition ($t = 0$)
atm	atmospheric conditions
r	in radial direction
rz	referred to shear
z	in axial direction
θ	angular direction

Superscripts

I	referred to first principal stress

mechanical equilibrium of the material is attained and a change both of its shape and dimensions is observed (Mayor and Sereno, 2004; Aregawi et al., 2012). Drying methods as well as the exploited operating conditions differently affect both the quality and the main characteristics of dried foods, including volume and shape changes (Panyawong and Devahastin, 2007). In the case of vegetables undergoing drying under different conditions, Ratti (1994) proposed that shrinkage characteristics were strictly dependent on food moisture content; in addition, the observed variations in the surface-to-volume ratio were a function of sample geometry and of the type of foodstuff. Yadollahinia and Jahangiri (2009) analyzed the influence of various drying temperatures and air velocities on the shrinkage of potato slices undergoing convective drying. Ramos et al. (2004) proposed the exploitation of a microstructural approach to quantify the physical changes occurring during air-drying of grapes quarters, so to ascertain the actual cellular shrinkage. Hassini et al. (2007) reported that shrinkage effect could not be neglected when moisture diffusivity in highly shrinking materials, like vegetables and fruits, had to be determined. The extent of shrinkage strongly depends on matrix mobility; in particular, it was proved that shrinkage is more significant during the constant and the falling rate periods, i.e. when matrix mobility is higher (Karathanos, 1993; Rahman, 2001; Shishehgarha et al., 2002; Troncoso and Pedreschi, 2007). Katekawa and Silva (2007), observed that the reduction of food volume actually corresponded to the volumetric amount of liquid water removed from the sample (ideal shrinkage).

A comprehensive mathematical model describing shrinkage phenomenon of materials undergoing drying processes was firstly proposed by Kowalski (1996). The model was based on the methods of continuum mechanics and on the principles of thermodynamics of irreversible processes. Hernandez et al. (2000) provided a mathematical description of food drying kinetics taking into account the effect of shrinkage. The authors validated the model consistency by performing various experiments under different drying conditions for fruits available in two shapes. Several empirical models were also formulated to fit the experimental results collected during drying of different foods and expressing the variation of samples volume vs. its moisture content (Aversa et al., 2012). Mayor and Sereno (2004) summarized the results obtained by different authors and concluded that shrinkage affects the predictions both of moisture and temperature profiles. Shrinkage, therefore, has necessarily to be taken into account when a mathematical model aimed at describing drying process is to be formulated (Márquez