FOOD AND BIOPRODUCTS PROCESSING 96 (2015) 314–325

Contents lists available at ScienceDirect

Food and Bioproducts Processing

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

Microwave drying of spheres: Coupled electromagnetics-multiphase transport modeling with experimentation. Part I: Model development and experimental methodology

Huacheng Zhu[a,b], Tushar Gulati[b], Ashim K. Datta[b,*], Kama Huang[a]

[a] Institute of Applied Eletromagnetics, Sichuan University, Chengdu 610064, China
[b] Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Article history:
Received 27 January 2015
Received in revised form 25 July 2015
Accepted 3 August 2015
Available online 22 August 2015

Keywords:
Microwave drying
Heat and mass transfer
Electromagnetics
Finite element method

ABSTRACT

To understand the effects of shape, size and property changes in a spherical sample during microwave drying, a fundamentals-based coupled electromagnetics and multiphase porous media model is developed and associated experimental details are described. Microwave drying of different sized spheres is carried out in a domestic microwave oven operating at 10% power level. Maxwell's equations for electromagnetics are solved inside a three dimensional (3D) microwave oven to obtain the electric field distribution inside the oven cavity and the spheres. The drying samples are treated as a porous media consisting of three phases: solid (skeleton), liquid (water) and gas (water vapor and air). Modes of transport for the fluid phases include capillary flow, binary diffusion between vapor and air, gas pressure driven flow and phase change between liquid water and vapor which is spatially distributed. An elaborate experimental system comprising of infrared camera, optical fiber probe and digital balance is built to validate the model in terms of temperature distribution, point temperatures, gas pressure generation and moisture loss from the samples at different times during the drying process. Results, validation, sensitivity analysis and "what-if" scenarios are presented in the companion paper. The work together would provide tremendous benefits when designing and developing microwave drying processes and products through a novel synergy between physics-based modeling and detailed experimentation.

1. Introduction

Drying (dehydration) of food products is one of the many ways of food preservation that prevents microbial growth, increases shelf-life, and significantly reduces product weight resulting in cheaper storage, packaging and transportation costs. Drying is a complex interaction of heat, mass and momentum transport requiring enormous time and energy. Nowadays, different kinds of drying equipment are available that consist of a combination of different drying techniques. This is advantageous since it uses the best of different methods to achieve more efficient drying (Clary et al., 2005; Bai-Ngew et al., 2011; Cui et al., 2008; Lu et al., 2014; Vega-Mercado et al., 2001).

Microwaves have been used widely for dehydration of food, wood and other high moisture materials (Ozkan et al., 2007; Askari et al., 2008; Song et al., 2009; Vongpradubchai and Rattanadecho, 2009a,b; Hansson and Antti, 2003). Microwave heating results from volumetric heating and rapid internal evaporation of liquid water that promotes faster drying. The process does not require long warm-up times and therefore

---

* Corresponding author at: 208 Riley Robb Hall, Ithaca, NY 14853, USA. Tel.: +1 607 255 2482.
E-mail address: akd1@cornell.edu (A.K. Datta).

http://dx.doi.org/10.1016/j.fbp.2015.08.003

Nomenclature

Symbol

c	concentration (kg/m^{-3})
C_p	specific heat capacity (J/kg K)
C_g	molar density (kmol/m^3)
$D_{eff,g}$	vapor diffusivity in air (m^2/s)
$D_{w,cap}$	capillary diffusivity (m^2/s)
$\mathbf{E}$	electric field intensity (V/m)
h_t	heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (m/s)
$\mathbf{H}$	magnetic field intensity (A/m)
i	imaginary unit ($\sqrt{-1}$)
$\dot{I}$	rate of evaporation (kg/m^3 s)
k_i^{in}	intrinsic permeability (m^2)
k_i^r	relative permeability of component i
K_{evap}	evaporation rate constant (1/s)
m	overall mass fraction
m	moisture content (dry basis) (kg water/kg dry solid)
M_a, M_v	molecular weight of air and vapor
$\vec{n}$	unit normal
P, p	total pressure and partial pressure, respectively (Pa)
p_c	capillary pressure of water (Pa)
Q	microwave source term (W/m^3)
r	radius (m)
r	universal gas constant (J/kmol K)
S_i	saturation of a fluid phase, i
t	time (s)
t	temperature (°C)
$\bar{v}$	velocity (m/s)
x_a, x_v	mole fraction of air and vapor in gas phase
V	volume (m^3)
x, y, z	directions (m)

Greek Symbols

ρ	density (kg/m^3)
λ	latent heat of vaporization (J/kg)
ω_a, ω_v	mass fraction of air and vapor
ϕ	porosity
μ	dynamic viscosity (Pa s)
ε_0	permittivity of free space (8.854×10^{-12} F/m)
μ_0	permeability of free space ($4\pi \times 10^{-7}$ H/m)
ε	complex relative permittivity
ε'	dielectric constant
ε'	dielectric loss
ν	volume fraction

Subscripts

a, f, g, s, v, w	air, fluid, gas, solid, vapor, water
eff	effective
eq	equilibrium
i	ith component
0	time $t = 0$

results in a significant reduction of drying time of 10–75% and increased drying rates of 4–8 times when compared with convective drying (Feng et al., 2001; Prabhanjan et al., 1995; Rzepecka et al., 1976; Maskan, 2001). However, microwave drying of foods (fruits and vegetables) have been found to result in large textural changes in the product such as puffing, crack formation and even burning due to the inhomogeneous heating associated with microwaves (Ratti et al., 1989; Clark, 1996; Nijhuis et al., 1998; Wang et al., 2003). Moreover, microwave drying characteristics are dissimilar for different sizes and shapes of the same product; for example, a thicker sample has been found to have a higher drying rate (Lu et al., 1998).

For microwave heating or drying of sphere-shaped foods, focusing of microwave energy occurs almost always (Ohlsson and Risman, 1978; Lu et al., 1998; Zhang and Datta, 2005; Araszkiewicz et al., 2007). Focusing refers to the concentration of microwaves at a point when they interact with spherical and cylindrical objects. For a material that dissipates microwave energy, due to focusing temperatures become extremely high near those locations. Use of Lambert's law has been the norm to qualitatively explain microwave penetration inside materials and experimental moisture profiles except for one exception (Zhang and Datta, 2005). Experiments mapping temperature distribution within various shaped materials during microwave heating were measured and significantly higher temperatures were found to develop in the center of sphere-shaped materials leading to non-uniform heating (Araszkiewicz et al., 2007). However, there are advantages of using sphere-shaped materials for microwaves as there is no edge and corner heating that is routinely observed for shapes having sharp edges, for example, cubes. Edge heating results in extremely high temperatures resulting in over-drying and even scorching of the material near those locations affecting final quality of the dried product. This phenomenon is absent for spheres making them suitable candidates for microwave drying. In order to address heating non-uniformity, two techniques are commonly employed: controlling microwave output power and power cycling (Cheng et al., 2006). Microwave power control (e.g., by using phase controllers) in domestic microwave ovens is still not standard since installing such settings adds to cost. Duty cycling the microwave power ON and OFF is the other alternative providing a common and low cost method of adjusting the power level on domestic ovens. Cycled microwave power can reduce the non-uniform heating by allowing thermal energy to slowly diffuse within the material and therefore lead to more uniform drying (Shivahare et al.,1993; Gunasekaran, 1999; Jolly and Turner, 1989). In this study, cycle-controlled microwave power (10% power level) is applied for the microwave drying process.

Design, development and optimization of a large scale microwave drying process and equipment for efficient drying requires detailed understanding of the drying process. It is here that mathematical modeling complemented with experimentation can contribute to and provide a level of understanding in ways that are impossible to achieve through experiments alone. Therefore, the main aim of this work is to develop a fundamentals-based model to understand drying of sphere-shaped samples of different sizes to comment on their suitability as a material for microwave drying.

1.1. *Previous mathematical models for microwave heating/drying*

Microwave drying involves a complex coupling of electromagnetics and heat and mass transport. To be able to better understand the process, a fundamentals-based model that can provide quantitative information about the most important process parameters (microwave energy deposition, temperature, pressure, internal evaporation rate, and moisture)