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Computer simulation model development and validation of radio frequency heating for bulk chestnuts based on single particle approach

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ABSTRACT

A computer simulation model was developed using finite element-based commercial software, COMSOL, to simulate temperature distributions of single particle chestnuts packed in a rectangular plastic container and treated in a 6 kW, 27.12 MHz radio frequency (RF) system. The developed model was validated by temperature distributions of three horizontal layers and temperature profiles at three representative positions in the container without mixing. Both simulated and experimental results showed similar heating patterns in RF treated chestnuts under same conditions, in which corners and edges were overheated and highest temperatures were located in sample contact points of top and middle layers at four corners in the container. A heating uniformity index (HUI) was used to evaluate effects of processing conditions on RF heating uniformity. The simulated and experimental results showed that the HUI was reduced when three layers chestnuts were separated with two plastic sheets. The better heating uniformity in chestnuts was obtained when they were treated with a single layer, or under mixing conditions. The developed model can help to explore the RF heating patterns on a single particle chestnut and RF heating uniformity in chestnuts of the container, and provide valuable methods to improve the RF heating uniformity for future industrial applications.

1. Introduction

Chestnut (*Castanea mollissima*) is a widely consuming nut around the world due to its special flavor and taste. Since postharvest chestnuts contain high moisture content, rich carbohydrate, and low fat (Chenlo et al., 2009; Vasconcelos et al., 2010), infestations with pests and diseases are major issues on chestnuts during long term storage (Antonio et al., 2011). It is estimated that annual losses of chestnuts due to pests are about 35–50% of total production during storage in China, resulting in high economic losses (Gao et al., 2011). Chemical fumigation with methyl bromide has been widely used to disinfest agricultural products, including chestnuts. However, this chemical fumigation is harmful to not only human's health but also environment due to depleting ozone layer. Therefore, various alternatives for disinfestations, such as ozone, modified atmospheres, low pressure and low temperature, irradiation, etc. have been studied (Carocho et al., 2012; Jiao et al., 2013; Pan et al., 2012). Although there are a large number of suggested potential chemical and non-chemical alternatives for disinfestations, each has limitations in terms of efficiency, cost, penetration, or residues that prevent it from becoming a direct replacement for pesticides (Hansen et al., 1992). Recently, radio frequency (RF) energy is proposed as an effective and environmental-friendly heating method to control insects in nuts and grains, including chestnuts, with acceptable product quality (Gao et al., 2010; Hou et al., 2015a; Jiao et al., 2012; Wang et al., 2007b).

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Nomenclature

A	Surface area (m^2)
C_p	Heat capacity ($J\,kg^{-1}\,°C^{-1}$)
E	Electric field intensity ($V\,m^{-1}$)
f	Frequency (Hz)
h	Heat transfer coefficient at the same surface ($W\,m^{-2}\,°C^{-1}$)
HUI	Heating uniformity index (dimensionless)
k	Thermal conductivity ($W\,m^{-1}\,°C^{-1}$)
Q	Power density generated by electric field ($W\,m^{-3}$)
t	Time (s)
T	Sample temperature (°C)
T_{av}	Average temperature (°C)
$T_{initial}$	Initial average temperature of chestnuts (°C)
ΔT	Temperature difference (°C)
Δt	Total time taken during each mixing process (s)
$\partial T/\partial t$	Increase rate of temperature ($°C\,s^{-1}$)
V	Electric potential (V)
V_{vol}	Volume (m^3)
ε	Permittivity ($F\,m^{-1}$)
ε_0	Free space permittivity ($F\,m^{-1}$)
ε'	dielectric constant (dimensionless)
ε''	Dielectric loss factor (dimensionless)
∇	Gradient operator
ρ	Density ($kg\,m^{-3}$)

Heating non-uniformity is one of the major obstacles for RF technology to be commercially applicable, especially in samples with high moisture contents and large sizes, such as chestnuts. It is reported that several interacting factors (e.g., electrode gap, electrode shape, packing geometries, position of treated sample, and surrounding media) influence heating uniformity during RF treatments (Huang et al., 2015c; Jiao et al., 2015; Tiwari et al., 2011a,b). However, experimental methods to adjust these parameters are time consuming, costly, and often provide limited information. On the contrary, computer simulation can be served as an effective tool for rapid, cheap, and flexible analysis, and provide an insight into the dielectric heating mechanism in agricultural products (Hossan et al., 2010; Romano and Marra, 2008; Tiwari et al., 2011a). To help understand the complex RF dielectric heating process and analyze RF heating uniformity, simulation has previously been used in various products, such as dry soybeans (Huang et al., 2015c), eggs (Dev et al., 2012), fruit (Birla et al., 2008),meat batters (Romano and Marra, 2008), peanut butter (Jiao et al., 2014), raisins (Alfaifi et al., 2014), wheat (Chen et al., 2015), and wheat flour (Tiwari et al., 2011b).

Agricultural products, such as fruits and nuts, in bulk may contain a certain amount of air among the product particles. On the one hand, air reduces flow of heat throughout the material during RF treatments. On the other hand, dielectric properties and thermal conductivity of air are totally different from those of fruits and nuts. Therefore, mixing equations are used to estimate effective dielectric properties and thermal conductivity of the air–particle mixture made up of air (voids) and particles of the solid (Nelson, 1991). Alfaifi et al. (2014) used mixing equations to calculate dielectric and thermal conductivity of raisins in container, and determined heating uniformity of the raisin in the container as a whole sample during RF heating. They found that heating uniformity in raisins was mostly affected by density of the raisin followed by the top electrode voltage, the dielectric properties, the thermal conductivity, and the heat transfer coefficient. Similar mixing equations have been applied to simulate RF heating on dry soybeans (Huang et al., 2015c), meat batters (Uyar et al., 2016), wheat (Chen et al., 2015), and wheat flour (Tiwari et al., 2011b). However, container's shape and size are totally different from those of samples, resulting in poor RF heating uniformity (Tiwari et al., 2011a). Therefore, it is necessary to determine the temperature distribution of RF treated bulk nuts and a single nut, which has not been reported so far using the finite element simulation.

The objectives of this research were to (1) develop a computer simulation model for bulk chestnuts based on a single particle approach when subjected to a 6 kW, 27.12 MHz RF system using commercial finite element software COMSOL, (2) validate the computer simulation model by comparing with the experimental temperature profiles of chestnuts after 5.4 min RF heating, (3) apply the validated model to predict the behavior of RF heating non-uniformity in bulk chestnuts and the single particle chestnut, and (4) explore effective methods to improve the RF heating uniformity in chestnuts.

2. Materials and methods

2.1. *Sample preparation*

Chinese chestnuts (*C. mollissima*) were purchased from a local wholesale market in Yangling, Shaanxi Province, China. The average initial moisture content and individual weight of tested chestnuts were 51.27 ± 1.19% on wet basis (w.b.) and 11.71 ± 0.91 g, respectively. The chestnuts were stored with mesh bags in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 4 ± 1 °C, taken out from the refrigerator 12 h before the experiment, and kept at ambient room temperature (20 ± 1 °C) for equilibrium.

2.2. *Simulation model development*

2.2.1. *Physical model*

A 6 kW, 27.12 MHz parallel electrodes, pilot scale free-running oscillator RF unit (SO6B, Strayfield International Limited, Wokingham, UK) was used in this research, with an area of 83 × 40 cm^2 for top plate electrode and a larger bottom plate electrode (Fig. 1). In the RF cavity (2.98 m long, 1.09 m wide and 0.74 m high), about 2.5 kg chestnuts were filled into a polypropylene plastic container (24 × 18 × 6 cm^3), and placed on the center of the bottom electrode, for RF treatments. The electrode gap was changed by adjusting position of the top electrode to achieve the required the RF power and heating rate.

It was considered that there are three layers chestnuts in the container with 72 chestnuts in each layer. Individual weight and density of tested chestnuts were 11.71 ± 0.91 g and 1.22 ± 0.03 g/cm^3, respectively. Chestnut was simplified as an ellipsoid shape in the simulation model. The sizes of a, b, and c in semi-principal axes were selected as 1.5 cm, 1.5 cm, and 1.0 cm, respectively, to achieve a small volume difference between the real chestnut and the simplified ellipsoid model.

2.2.2. *Governing equations*

The Maxwell's equations can be used to solve the electric field intensity in the electromagnetic field. Since the RF wavelength (11 m) in the 27.12 MHz RF unit is often much longer than the RF cavity size, the Maxwell's equation can be simplified to the Laplace equation by neglecting the effect of magnetic fields. The Laplace equation is described by a quasi-static assumption (Birla et al., 2008):

$$-\nabla \cdot ((\sigma + j2\pi f \varepsilon_0 \varepsilon')\nabla V) = 0 \quad (1)$$

where σ delegates electrical conductivity of the treated sample or air ($S\,m^{-1}$) and ε' represents also dielectric constant of treated sample or air, depending on which domain the equation is solved. $j = \sqrt{-1}$, f is the frequency (Hz), ε_0 is the permittivity of free space ($8.86 \times 10^{-12}\,F\,m^{-1}$) and V delegates the