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Investigation of radio frequency heating uniformity of wheat kernels by using the developed computer simulation model

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ABSTRACT

To explore the potential of using radio frequency (RF) energy to control insects or microorganisms in low-moisture granular food crops, wheat kernels were selected as a sample product, and a computer simulation model was developed to study the influence of sample size (wheat kernels filled in plastic container in cuboid shape) and vertical position on RF heating uniformity and to determine the cold and hot spots in the samples. The simulated temperature profile of RF heating was compared with the experimental results to validate the computer model. Temperature uniformity index (TUI) was selected as a criterion to evaluate RF heating uniformity. Results suggested that temperature uniformity of sample depended on sample size and location, where for small sample size, sample placed on either bottom electrode or closed to top electrode would achieve better RF heating uniformity; while for sample in large size, placed in the middle or slightly lower than middle position between the two parallel electrodes achieved better temperature uniformity. Also, a larger sample size had better RF heating uniformity, especially when sample size equaled to the size of the top electrode, indicating that RF energy is more suitable for treating bulk materials. Corner heating was also observed where hot spots located at the corner of samples in cuboid shape, and cold spots depended on sample vertical position. In this study, cold spots were at the center of the top and bottom layers when the sample was placed at the middle position between the two parallel electrodes, at the center of top layer when sample was placed on the bottom electrode, and at the center of bottom layer when sample was placed close to top electrode. Information generated from this study would be essential for developing RF treatment protocol to control insects or microorganisms in low-moisture granular agricultural products.

1. Introduction

Wheat is one of the most important food crops for human beings, and more than one third of the world population consume wheat as a principal food. Preservation of wheat kernels for long-term storage has always been a challenge due to insect attack, which has resulted in significant economic loss. Another problem associated with wheat kernels storage is the putrefactive spoilage caused by fungi, especially in some areas with high relative humidity. Some of the fungi can produce mycotoxin which would not only cause serious quality loss, but also food safety concern. Many methods have been studied to control the insects and reduce the number of fungi colony inside the food crops, including conventional heat treatment, chemical fumigation, and irradiation. Conventional food treatment can kill some insects and reduce the number of fungi colony by properly controlling temperature and time, but energy efficiency is low and it could affect the quality of the food crops (Feng, Hansen, Biasi, Tang, & Mitcham, 2004). Chemical fumigation has advantages of low cost, easy operation and huge production, but negative impact to environment and human health, and many of the chemical fumigants have been banned in some countries (Wang & Tang, 2001). Irradiation is an effective method, such as X-ray and γ-ray, but its application is limited by radiation source and consumers acceptance (Schweiggert, Reinhold, & Schieber, 2007).

Radio frequency (RF) dielectric heating, typically with a frequency range from 3 kHz to 300 MHz, is an advanced thermal treatment method. It generates heat inside the food products by friction of molecules dominated by ionic conduction and dipole rotation, thus heating dielectric materials very rapidly and volumetrically. RF technology has been successfully applied in controlling insects in walnuts (Wang, Monzon, Johnson, Mitcham, & Tang, 2007a, 2007b) and legumes including lentils and peas (Jiao, Tang, Johnson, & Wang, 2012) without obvious quality degradation of the product. More recently, RF has been proposed as an alternative pasteurization method for low-moisture foods, such as almonds (Gao, Tang, Villa-Rojas, Wang, & Wang, 2011), peanut butter

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cracker sandwiches (Ha, Kim, Ryu, & Kang, 2013), and powdered red and black pepper spices (Jeong & Kang, 2014; Kim, Sagong, Choi, Ryu, & Kang, 2012). Therefore, RF holds great potential to control insects and microorganisms in agricultural products. In addition, few studies have shown that microwave treatment can enhance the germination rate of agricultural seeds (Wu & Feng, 2011), it is anticipated that RF heating may have similar effect based on the similar heating mechanisms (ionic conduction and dipole rotation), but this needs to be validated in the further study.

For the application of RF dielectric heating, heating uniformity has always been the first concern. Sample size, shape, and non-homogeneous dielectric properties could result in non-uniform electric field distribution, in turn causing non-uniform temperature distribution (Alfaifi et al., 2014; Tiwari, Wang, Tang, & Birla, 2011a, 2011b). In RF dielectric heating, thermal effect is the main killing factor on insects or microorganisms (Geveke, Kozempel, Scullen, & Brunkhorst, 2002). Generally, the lethal temperature for insects in agricultural products was less than 60 °C (Wang & Tang, 2001), while to reduce the number of fungi and mold colony, higher temperatures are needed. Higher temperature would absolutely cause larger temperature difference inside the sample which would result in seriously quality deterioration. Therefore, it is essential to determine the position of cold and hot spots and to achieve relative uniform heating for RF treatments, especially for RF pasteurization treatments (Jiao, Tang, & Wang, 2014).

Computer simulation is a very effective tool to help understand the complex RF dielectric heating process, to analyze RF dielectric heating uniformity, and to determine the cold and hot spots. Yang, Zhao, and Wells (2003) developed a computer simulation model to investigate RF dielectric heating of radish and alfalfa seeds based on a three dimensional finite-element computer program package (TLM-FOOD-HEATING Program). Instead of using conventional electrostatics method, Chan, Tang, and Younce (2004) introduced a new and effective approach to simulate RF dielectric heating process by using the wave equation in three dimensions. Marra, Lyng, Romano, and Mckenna (2007) developed a computer simulation model for RF heating of meat batters in cylindrical shape by first using finite-element commercialized software-FEMLAB. To study the effect of different treatment factors on temperature distribution within a spherical object under RF dielectric heating system, Birla, Wang, and Tang (2008) built a computer simulation model by using the FEMLAB software, and used 1% gellan gel as model fruit to validate the developed model. Tiwari et al. (2011a) developed a computer simulation model based on finite element method (COMSOL Multiphysics v3.4) to predict the temperature changes and RF power distribution during RF heating for wheat flour. Alfaifi et al. (2014) also developed a computer simulation model based on COMSOL software for RF dielectric heating of dry fruit (raisins) and validated the model by experimental results, and further utilized the model to analyze the influence of different factors on RF dielectric heating uniformity. More recently, Huang, Zhu, Yan, and Wang (2015) built a model to analyze RF heating temperature distribution and uniformity in dry soybeans; and Llave, Liu, Fukuoka, and Sakai (2015) and Uyar, Erdogdu, and Marra (2014, 2015) conducted computer simulation studies on RF defrosting of frozen meats by using the COMSOL software by considering water phase changes. However, there was no available computer simulation model in the literatures, especially for fungi inhibition in grain seeds for RF dielectric heating of wheat kernels to extend storage life or enhance the seeds vigor and germination rate.

The objectives of the current study were (1) to determine the physical and thermal properties of wheat kernels associated with RF heating, (2) to build computer simulation model for RF heating of wheat kernels, (3) to investigate the influence of sample size and vertical position on RF heating uniformity and determine the cold and hot spots in the samples, and (4) to provide the guidance for developing treatment protocol by using RF energy to control insects and microorganisms in wheat kernels.

2. Materials and methods

2.1. RF heating system

A 12 kW, 27.12 MHz parallel electrodes, pilot scale free-running RF unit ($310 \times 100 \times 165$ cm^3) with a built-in hot air system and an imbedded conveyor belt (GJD-6A-27-JY, Huashi Jiyuan Co. Ltd., Hebei, China) was used in this study. More information about the RF system can be found from Jiao et al. (2012) and Wang, Tiwari, Jiao, Johnson, and Tang (2010). Wheat kernels were purchased from a local seed station (Anhui Province, China), and were placed inside polypropylene (PP) plastic cuboid container (16.0 L × 10.5 W × 6.8 H cm^3) with small holes on the side and bottom for RF treatment. Fiber optic sensors (ThermAgile-RD Optsensor, Xi'an Heqiguangdian Co. Ltd., Shanxi, China) with 6 ports were used to monitor the real-time temperature changes during RF heating process, and the obtained temperature profiles were further used to validate computer simulation model.

2.2. Development of computer simulation model

Commercialized software COMSOL Multiphysics (v4.2, Burlington, MA, USA) based on finite element method (FEM) was used to simulate the RF heating process for wheat kernels. It was installed on a computer workstation (Intel(R) Core(TM) i5-3470 CPU, 16 GB memory, 64-bit Windows 7 Professional operating system). The whole steps for the development of computer simulation model are illustrated in Fig. 1. In the current simulation study, wheat kernel properties, including thermal, physical and dielectric properties, were assumed homogeneous and isotropic, and the density of wheat kernels was assumed temperature independence. The influence of the plastic container on RF heating process was minimal based on our previous study, so the container influence was not considered in the present study. Wheat kernels are dry products with moisture content less than 12.0% w.b., and when subjected to RF heating for a short time period (7.0 min), the influence on moisture content was unnoticeable (<5%) based on our preliminary study. Hence, the mass transfer of water was ignored in the current simulation study.

2.2.1. Governing equations

The built-in module (Joule heating module) was used to model the RF heating process, which combined both electromagnetic heating and heat transfer phenomena. Assumption of quasi-static RF electric field inside food samples was valid and had been successfully used to build RF simulation model in a few studies (Alfaifi et al., 2014; Llave et al., 2015; Tiwari et al., 2011a; Uyar et al., 2014, 2015). The electric field within the sample load followed Gauss law derived from a quasi-static approximation of Maxwell's equations ($\nabla(\varepsilon \cdot \bar{E}) = 0$). RF heating process can be described by the solution of Fourier heat transfer equation coupled with the quasi-static electromagnetic field equations (Uyar et al., 2014, 2015):

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{abs} \tag{1}$$

where ρ was density (kg m^{-3}), C_p was specific heat (J kg^{-1} K^{-1}), k was thermal conductivity (W m^{-1} K^{-1}), ε_0 was the permittivity of free space (8.85×10^{-12} F m^{-1}), t was time (s), T was the temperature (K), and Q_{abs} was the RF power absorbed per unit of volume (W m^{-3}) by the load, generated by the electric field distribute inside the samples, and could be expressed as:

$$Q_{abs} = 2\pi f \varepsilon_0 \varepsilon'' |\bar{E}|^2 \tag{2}$$

where f was the frequency (Hz), ε'' was the relative dielectric loss factor of the samples, and $|\bar{E}|$ was the modulus of the electric field (V m^{-1}).