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Modeling radio frequency heating of food moving on a conveyor belt

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ABSTRACT

A multiphysics model that coupled electric fields and heat transfer was developed to simulate the radio frequency (RF) heating of food moving on a conveyor belt. A discrete moving step approach was used in the simulation. The total power absorption increased considerably during the entry of the sample into the RF system, remained stable when the sample was fully covered by the top and bottom electrodes, and decreased when the sample moved out of the system. Edge and corner heating was observed from the power absorption distribution and electric field distribution. The model was validated by heating a rectangular container of wheat kernels moving on a conveyor belt in a RF system (27.12 MHz, 6 kW). The predicted spatial temperatures in top, middle, and bottom layers showed less than 3.5 °C lower prediction than the experimental result. The measured anode current showed a good linear correlation with the predicted total power absorption. The optimum number of discrete moving steps was determined to be nine for accurate temperature prediction with total conveyor belt movement distance of 1.13 m which is equivalent to optimize step size of 0.1256 m/step (0.3 m for entry and exit, respectively, and 0.53 m for fully covered by electrodes) at speed of 14.23 m h^{-1}. The movement of food product could help improve the heating uniformity of RF heating process.

1. Introduction

Electromagnetic heating is a non-traditional thermal processing method for its rapid and volumetric heating characteristics. Electromagnetic heating has been widely used for processing food, which involves interactions of electromagnetic waves with food products, such as radio frequency (RF) heating and microwave heating. Radio frequency waves are electromagnetic waves typically with a frequency range of kHz (Chen et al., 2016a) or MHz (Huang et al., 2015b) to 300 MHz (Datta and Anantheswaran, 2001). Because of higher penetration depth compared to microwaves due to relatively lower frequency and longer wavelength, RF heating is suitable for treating large bulk food products. RF heating process has shown potential in pasteurization of milk (Awuah et al., 2005), meats (Schlisselberg et al., 2013), and spices (Jeong and Kang, 2014; Kim et al., 2012); disinfestations in various agricultural commodities, such as chestnuts (Hou et al., 2014, 2015), walnuts (Mitcham et al., 2004; Wang et al., 2001), almonds (Wang et al., 2013), dried fruits (Alfaifi et al., 2014), fresh fruits (Birla et al., 2004, 2008; Wang et al., 2006), soybeans (Huang et al., 2015a), and wheat (Jiao et al., 2015); and thawing and cooking meat (Laycock et al., 2003;

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Table 1 – Electrical, thermal, and physical properties of materials.

	Air[a]	Aluminum[a]	Wheat	Polypropylene[a]
Dielectric constant	1	1	4.3[b]	2.0
Dielectric loss factor	0	0	0.11[b]	0.0023
Electrical conductivity ($S\,m^{-1}$)	0	3.77×10^7	–	–
Density ($kg\,m^{-3}$)	–	–	860	900
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	–	–	0.15	0.2
Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)	–	–	2670[b]	1800

[a] COMSOL Multiphysics (2015).
[b] Shrestha and Baik (2013).

Wang et al., 2012). The food products processed with RF heating also show higher (Fiore et al., 2013) or similar (Tang et al., 2005) nutritional values, and better functional properties (Boreddy et al., 2014, 2016) when compared to those products cooked conventionally. However, nonuniform heating is a big challenge for RF heating reported in these studies.

Computer simulation models have been developed as tools to understand and improve the heating uniformity of RF heating. Many factors that influence the heating uniformity in RF systems have been extensively studied, such as sample size, shape, position between the top and bottom RF electrodes, and dielectric properties of samples (Romano and Marra, 2008; Tiwari et al., 2011a; Uyar et al., 2014, 2015). Computer simulation model also has been developed to understand the effect of immersion of fruits in water to improve its heating uniformity (Birla et al., 2008). Jiao et al. (2014) developed a new strategy of placing polyetherimide (PEI) around peanut butter samples to improve the heating uniformity using modeling. However, these models only simulated the batch heating process where the products were placed at a stationary location between the top and bottom electrodes in the RF system.

Birla et al. (2004) developed a system to rotate and move the fruit in water when subject to RF heating, showed significant temperature uniformity improvement, even though it was still a batch process. In a real food industry application, it is more applicable to utilize the RF system for continuous processing of food products moving between the electrodes on a conveyor belt through the system. During the movement, the interactions between the food product and the RF system will change with time and the relative location of food in the system. A model that could simulate this continuous movement will help us understand the changing interaction and develop better processes to improve the RF heating performance. Chen et al. (2016a) developed a computer simulation model for RF heating of wheat considering the sample movement on a conveyor belt using an "equivalent power absorption" method. In this method, the power absorption of the food product at different locations in the RF system was determined by multiplying the power absorption at stationary condition (center of the RF system) with an arbitrary power ratio factor function. However, this method did not consider the change of the power distribution within the food product, which occurs when the food product is moving through the RF system. Therefore, a model that considers this power distribution change during the movement of products needs to be developed.

The movement (rotation) of food product in domestic microwave oven has been simulated in several studies (Chen et al., 2014, 2015, 2016b; Pitchai et al., 2015a,b) using discrete rotational steps. Instead of continuous rotation, food products were assumed to be rotated discretely on turntables. A similar approach of discrete moving steps could be utilized to simulate the translational movement of a food product in a RF system, which was also mentioned and discussed by Chen et al. (2016a). The more steps used, the closer is the simulation of movement to the actual "continuous" movement; however, more computational power or capacity may be needed. Therefore, it is necessary to determine the optimum number of moving steps to achieve accurate model prediction with acceptable computation time.

Therefore, the objectives of this study are to:

1) develop a 3-D numerical model that simulates RF heating with movement of food product on a conveyor belt using discrete moving step approach;
2) characterize the heating process to enhance the understanding of RF heating process with food product movement;
3) validate the model for RF heating of wheat kernel product moving on a conveyor belt; and
4) determine an optimum number of discrete moving steps that could provide accurate model predictions.

2. Materials and methods

In this study, a multiphysics based model was developed according to a reported and validated model that simulated RF heating of a stationary food product (wheat) placed at the center of the RF system (Chen et al., 2016a). The geometric model, material properties, governing equations, and initial and boundary conditions were obtained from this reported model (Chen et al., 2016a), which are also described briefly in the following sections.

2.1. *Sample preparation and material properties*

The wheat sample was obtained from a local farmer in Yangling, Shaanxi, China, and stored at 25 °C with relative humidity of 65% in a controlled chamber (BSC-150, Shanghai BoXun Industrial & Commerce Co., Ltd., Shanghai, China) prior to RF treatments. The initial moisture content of wheat was 8.7% (w.b.). During RF treatment, the wheat sample was placed in a rectangular container (inner dimension 300 mm × 220 mm × 60 mm). The thickness of the bottom and side walls of the container was 3 mm.

The electrical, thermal, and physical properties of materials (air, wheat sample, polypropylene container, and aluminum electrode base) used in the model are shown in Table 1.

2.2. *Physical model development*

2.2.1. *Geometric model and meshing scheme*

A 6 kW, 27.12 MHz parallel plate RF heating system with a free-running oscillator (COMBI 6-S, Strayfield International Limited, Wokingham, UK) was used in this study. The RF system was consisted of a metallic enclosure, a generator, and a RF applicator, as shown in Fig. 1(a). The applicator had a pair of parallel electrode plates, in which the top electrode can be adjusted to different heights to control the electrode gap between top and bottom electrodes. The bottom electrode was connected with the grounded metallic enclosure. The dimensions of the RF system and the food product are shown in Fig. 1(b).