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Effect of decoupling electromagnetics from heat transfer analysis on prediction accuracy and computation time in modeling microwave heating of frozen and fresh mashed potato

Jiajia Chen [a], Krishnamoorthy Pitchai [a,b], David Jones [a], Jeyamkondan Subbiah [a,b,*]

[a] Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
[b] Department of Food Science and Technology, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

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ABSTRACT

Microwave heating models incorporating physics of electromagnetics and heat transfer are computationally intensive, which limits their use in the industry. The electromagnetic power density changes within the food during microwave heating were characterized. The effect of decoupling electromagnetics from heat transfer analysis on accuracy and computation time was evaluated for microwave heating of mashed potato at various initial states (frozen and fresh). Coupled models used updated heat source term based on temperature-dependent dielectric properties for every rotation; while decoupled models used a constant heat source term based on dielectric properties at room temperature. The simulation and validation results showed that the simplification of using the decoupled approach did not affect the predicted temperatures considerably, while reducing the computation time by 93%. When compared to the experiment, the averaged RMSE values of six transient point temperatures of room-temperature and frozen decoupled-models were 5.2 and 6.6 °C, respectively, which were close to those of the coupled models. The decoupled model can be used for screening food-package designs in a short computation time. While this study demonstrated the feasibility of using the decoupled approach for a homogeneous food at various initial temperatures, further study needs to be conducted to evaluate this for heterogeneous foods.

1. Introduction

Nonuniform heating is the biggest issue in microwaveable food products in terms of food quality and safety. The heating rate of the food product at one location is determined by the electromagnetic (EM) power density and the heat conduction between hot and cold spots due to the temperature gradient. Heating uniformity is an important parameter to evaluate the food product design in terms of food quality, which is greatly influenced by the uniformity of EM power distribution. It is not easy to evaluate the microwave power distribution experimentally. A "trial-and-error" method is often used in microwaveable food development to evaluate the heating performance of a microwaveable food product. The method is useful, but is time consuming and expensive. Recently, microwave heating models are becoming promising tools to predict the microwave heating performance of a food product in a wide range of ovens, which can be used to assist microwave food product development (Geedipalli et al., 2007; Liu et al., 2013; Pitchai et al., 2012, 2014; Rakesh et al., 2009).

To predict the heating temperature profiles as accurate as possible, many microwave heating models incorporating electromagnetics and heat transfer have been developed to predict microwave heating performance of different food products (Campañone and Zaritzky, 2005; Geedipalli et al., 2007; Pitchai et al., 2012, 2014; Tilford et al., 2007). Several comprehensive microwave heating models, including physics of phase change of evaporation, heat and mass transport, have been developed to predict the heating performance more accurately (Rakesh and Datta, 2012; Rakesh et al., 2012). However, there are many parameters and material properties needed in these computationally-intensive models. Further, the model prediction accuracy is highly depending on the accuracy of the input parameters and material properties values.

Due to high variability in domestic microwave ovens and experimental errors in measuring input parameters for the models, it is difficult to predict the exact temperatures for food safety considerations using current microwave heating models. However, these

* Corresponding author. Address: Departments of Food Science & Technology and Biological Systems Engineering, 212, L.W. Chase Hall, East Campus, University of Nebraska-Lincoln, NE 68583-0726, USA. Tel.: +1 402 472 4944; fax: +1 402 472 6338.

E-mail address: jsubbiah2@unl.edu (J. Subbiah).

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models are highly useful in the food product development for providing design directions and ranking the heating performance of various alternative food-package designs. Instead of validating numerous designs, food product developers can use the models to narrow down and identify the top designs. Thus, these models can accelerate the food product development cycle. However, the utility of these models is limited in the food industry, since the models require many input parameters, powerful computers, and long computation time.

In a practical microwaveable food product development process, it is not necessary to determine the exact spatial temperatures of a food product. A relative prediction of hot and cold spot patterns is useful for food product developers to identify problems in food design. Thus, a simplified microwave heating model based on current microwave heating models that can quickly predict the heating patterns of a food product will enable the model to be useful in food product development.

The heating pattern of a food product is mainly determined by the EM power distribution. Thus, characterizing the EM power density during the heating process helps to understand the interactions between microwaves and dielectric food products. In addition, the EM power density analysis is the most time-consuming step in microwave heating modeling (Liu et al., 2014). Thus, reducing the computation time on EM power density analysis enables the utility of the microwave heating models. Liu et al. (2013) reported that, spatial EM power density did not change considerably during the heating process if the penetration depth of the food product did not change considerably. In such cases, the EM field analysis can be decoupled from the heat transfer analysis to minimize the computation time considerably, without overly compromising the accuracy. For other food products with rapid change of dielectric properties (great change of penetration depth) during heating, such as frozen food, the EM power density changes during heating need to be understood.

Therefore, the main objective of the study is to develop a simplified microwave heating model that reduces the model complexity and computation time, while not overly compromising the prediction accuracy of the microwave heating performance. The specific objectives are:

(1) to characterize the EM power density changes within the food product during heating of mashed potato at various initial temperatures (frozen, −10 °C; refrigerated, 4 °C; and room temperature, 20 °C) using the coupled model;
(2) to evaluate the effects of decoupling electromagnetics from heat transfer analysis on nodal EM power density, nodal temperature, and computation time, when compared to the coupled model results; and
(3) to validate the simplified (decoupled) model and the coupled model using experimental measurements of temperature.

2. Methodology

2.1. Model development

2.1.1. Model geometry

The model was developed in a finite element based software COMSOL Multiphysics 4.3a (COMSOL Inc., Boston, MA). A geometric model was developed for a domestic microwave oven (Model no: NN-SD9675; Panasonic Corporation, Shanghai, China) rated at 1250 W and a tray of 550 g mashed potato. Details of oven cavity, magnetron, waveguide, turntable, crevices and metal bumps are important features in microwave oven design and were included in the model, as shown in Fig. 1. The distance between the bottom of the waveguide and the bottom of oven cavity was 83 mm.

2.1.2. Governing equations and boundary conditions

The governing equations of Maxwell's equations, heat transfer equation, convective heat transfer boundary condition, and perfect electric conductor boundary condition were described in Pitchai et al. (2014).

2.1.3. Model parameters

For domestic microwave ovens, the instantaneous frequency emitted by a magnetron in a microwave oven has a spectrum that depends on the cathode–anode voltage and the high frequency output impedance of the magnetron, which is set by the load (Ghammaz et al., 2003). The operating frequency will influence the heating patterns of the microwave oven (Pitchai et al., 2012). In this model, it was assumed that magnetron is operating at a single frequency of 2.45 GHz.

The material properties for computational domains of air and turntable were obtained from Pitchai et al. (2014). The temperature-dependent dielectric properties (dielectric constant and loss factor) and thermal properties (thermal conductivity and specific heat capacity) measured in a previous work (Chen et al., 2013) were applied in the model. The temperature-dependent dielectric properties and penetration depth of mashed potato at microwave frequency (2.45 GHz) were shown in Fig. 2. The penetration depth dropped greatly from the maximum value of 32.5 mm at −10 °C to a low value of 7.6 mm at −5 °C and then slightly decreased to 3.8 mm at 100 °C.

2.1.4. Simulation strategy

The whole domain was discretized into tetrahedral and prism shape elements. The mesh sizes were determined according to the normalized power absorption method (Chen et al., 2014; Geedipalli et al., 2007). The total number of elements was 546,960, out of which 190,985 elements were in the food domain, and they provided mesh-independent prediction results.

The rotation of the food product was considered in the microwave heating model. Without considering continuous rotation of the turntable, rotations of 30° for each step were found accurate enough (Liu et al., 2013) and were used in this study to simulate the rotational microwave heating process. During one rotational cycle of the turntable (10 s), the temperature-dependent dielectric properties of the food product did not change greatly, which thus did not significantly influence the electric field distribution (Liu et al., 2013). Therefore the electric field distribution was calculated within the food product at 12 discrete locations on the turntable using constant dielectric properties for one rotation. The EM power density at all 12 locations within a rotation were then averaged to determine the heat source for that complete rotational cycle.

Two approaches of applying heat source term (coupled and decoupled) were used to simulate the microwave heating process, as shown in Fig. 3.

(1) Coupled model (Fig. 3a):

In the common coupled model approach, the electric field distribution was calculated at every location based on temperature-dependent dielectric properties at the end of previous rotational cycle. The updated EM power density was provided as heat source for temperature prediction of that rotational cycle. Based on the predicted new temperatures, dielectric properties were updated to calculate the EM power density for the next rotational cycle. This cyclic coupled process was continued until the desired heating time reached. This is the most accurate method for computing microwave heating process; however it is computationally intensive.

(2) Decoupled model (Fig. 3b):