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Modeling microwave heating of frozen mashed potato in a domestic oven incorporating electromagnetic frequency spectrum

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A B S T R A C T

Domestic microwave oven magnetrons produce microwaves in a frequency range of 2.45 ± 0.05 GHz. Most microwave heat transfer simulations simplify that the magnetron produces a monochromatic electromagnetic wave of frequency of 2.45 GHz to reduce the computational complexity. This study assumes that the magnetron produces a frequency spectrum defined by a Gaussian distribution of frequencies with a central frequency of 2.45 GHz and investigates the effect of Gaussian distribution variance of $(0.05\ \mathrm{GHz})^2$, $(0.025\ \mathrm{GHz})^2$, $(0.017\ \mathrm{GHz})^2$ on prediction accuracy when compared to using monochromatic frequency of 2.45 GHz. A three-dimensional finite element model coupling electromagnetic and heat transfer physics was developed to simulate heating of 550 g of frozen mashed potato for 6 min. The model was validated in a 1250 W rated microwave oven with the mashed potato tray placed at the center of the stationary turntable. The electromagnetic power densities were determined separately at five different frequencies equidistant between 2.4 and 2.5 GHz. They were then weighted averaged, based on the selected Gaussian distribution. Simulated temperature profiles of the models using the monochromatic frequency of 2.45 GHz and Gaussian frequency spectrum with different variances were compared with experimental temperature profiles obtained using a thermal imaging camera at the end of cooking and five fiber-optic thermocouples during cooking. The model results showed that predicted spatial surface temperature pattern by the model using frequency spectrum with the largest variance $(0.05\ \mathrm{GHz})^2$ had better agreement with the experimental temperature pattern when compared to that using a monochromatic frequency of 2.45 GHz. In the transient temperature profile measurement, the average RMSE value of five locations was 7.5 and 13.1 °C for simulations using frequency spectrum and monochromatic frequency of 2.45 GHz, respectively. When compared to using the monochromatic frequency of 2.45 GHz, the frequency spectrum with an assumption of having a Gaussian distribution with mean of 2.45 GHz and variance of $(0.05\ \mathrm{GHz})^2$ improved the accuracy of temperature field pattern and transient temperature profile.

1. Introduction

According to the Industrial, Scientific, and Medical (ISM) band allocated by Federal Communications Commission (FCC) for the food applications, microwave ovens are designed to be operated at 2450 MHz with a frequency tolerance limit of 50 MHz (Buffler, 1993). The modern day microwave ovens use “cooker” magnetron which is 70% efficient in its performance and whose performance is inconsistent due to lower price (Osepchuk, 2002). The cooker magnetron is complex in its operation due to various factors such as varying anode current and the cold-start process. Due to these factors, a magnetron does not operate at a fixed single frequency but at a range of frequencies (Risman, 2009).

A magnetron frequency spectrum depends on type of power supply, dielectric properties of food material, magnetron temperature, and magnetron physical construction. Gerling and Fournier (1991) reported that the frequency bandwidth is also affected by the stability of the power supply to the magnetron. As the magnetron frequency bandwidth changes, the number of

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electromagnetic (EM) modes generated inside the cavity is also affected. Also, Gerling and Fournier (1991) reported that magnetron frequency can change as much as 0.25 MHz for every degree change in the magnetron temperature.

Simulation of electromagnetic and heat transfer during microwave heating is becoming a promising tool to understand and visualize the EM field patterns of microwave heated foods. Many microwave heat transfer models have been developed using a monochromatic frequency of 2.45 GHz (Curcio et al., 2008; Dinčov et al., 2004; Liu et al., 2013). Pitchai et al. (2012) and Birla et al. (2010) demonstrated through microwave heat transfer simulations that EM field patterns are affected by the selected frequency. Soltysiak et al. (2010) demonstrated the effect of different monochromatic frequencies on temperature pattern with respect to different rotational position of the food on the turntable through modeling. The predicted temperature showed that temperature within the food varies over 10 °C as the food heated with different frequencies. Thus the magnetron frequency influences the electromagnetic field patterns within the food (Tang and Resurreccion Jr, 2009; Schubert and Riegel, 2005). The EM power density is the heat source and therefore directly influences the final temperature distribution or cooking performance of a food product. Therefore, for accurate prediction of temperature distribution in food, frequency spectrum has to be incorporated in the model.

Previously, researchers have not included the frequency spectrum in the electromagnetic and heat transfer simulation of domestic microwave heating of food. As a new paradigm in the microwave heat transfer simulations, this study evaluates a methodology to incorporate the electromagnetic frequency spectrum in simulation in the form of Gaussian shape distribution. While adding frequency spectrum to computational model invokes more complexity and computational burden, this study investigates the effect of adding frequency spectrum in the simulation on the accuracy of temperature predictions.

The objectives of this study were to:

i) develop a methodology to incorporate electromagnetic frequency spectrum in the coupled electromagnetic and heat transfer model.
ii) investigate the effect of variance of Gaussian shaped frequency distribution on prediction accuracy in comparison to the monochromatic frequency of 2.45 GHz.

2. Materials and methods

2.1. Governing equations and boundary conditions

Solution of the combined wave form of Maxwell's equations gives the estimated electromagnetic field strength at any point in the computational domain which is the entire oven cavity. The governing equations, boundary conditions applied in the simulation are explained in detail in Pitchai et al. (2014).

2.2. Geometric model

Geometric model was developed for a 1250 W rated power (1200 W available power measured using IEC 60705 method) microwave oven (Model no: NN-SD9675; Panasonic Corporation, Shanghai, China). The detailed geometric model of the microwave oven, mashed potato tray, and a turntable is shown in Fig. 1. A near perfect geometric model of the microwave oven and a 550 g mashed potato tray was created in the commercial Finite Element Method (FEM) software, COMSOL Multiphysics 4.3b (COMSOL, Burlington, MA). In this study, we included the magnetron as a coaxial power source feeding microwave energy into the waveguide.

2.3. Model assumptions

The shape of magnetron operating frequency spectrum was approximated to be as Gaussian function. It is challenging to accurately measure the frequency spectrum during microwave heating. Birla et al. (2010) measured the microwave frequency spectrum of a 700 W rated power microwave oven by the analysis of microwave leakage signal using a spectrum analyzer connected to horn antennas placed inside an anechoic chamber. From the frequency spectrum, the resonance frequency was in the range of 2.43–2.49 GHz for that particular microwave oven. Similarly, Chan and Reader (2000) also measured a microwave leakage spectrum generated by a 2.45 GHz magnetron which ranged from 2.40 to 2.46 GHz. It is also not clear whether the leakage spectrum is the representative of the microwave spectrum absorbed by the food or complimentary (i.e. whatever frequencies the food, that had not absorbed, leaked). Frequency spectrum is dynamic and can change with the type of food product heated in microwave oven. The

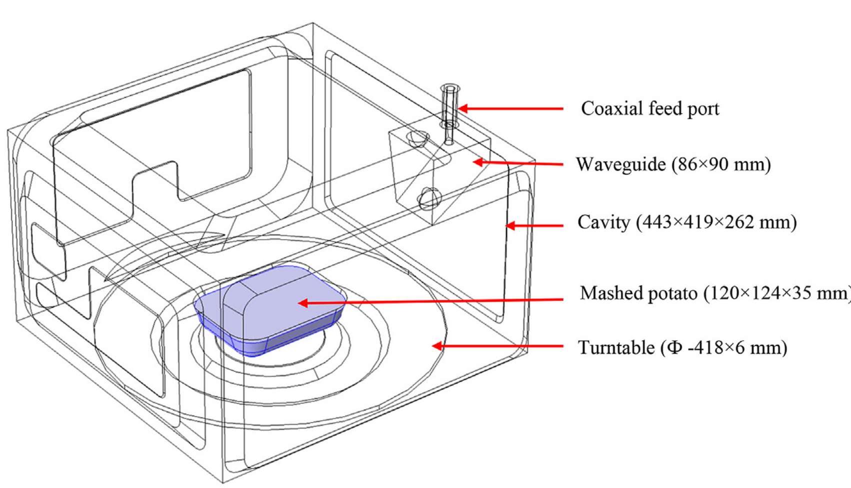

Fig. 1. Geometric model of a 1250 W rated power domestic microwave oven (Model No: NN-SD9675, Panasonic Corporation, Shanghai, China).