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Determination of thickness of microwaveable multicompartment meals using dielectric, thermal, and physical properties

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ABSTRACT

Multiphysics based numerical model are promising tools to enhance understanding of microwave heating of foods. These models are specific for particular microwave oven and food configuration, which limits generalization. In addition, the models are computationally expensive limiting their utility in the food industry. In this study, we have developed a simple 1-dimensional (1-D) analytical model based on planar wave assumption to predict the average heating rate of a food product and to determine the thickness of multicompartment meals based on the dielectric, thermal, and physical properties. The model was benchmarked by comparing with earlier developed 1-D model. A numeric "vpasolve" solver in MATLAB was used to adjust the thickness of two compartments such that they would heat at the same rate and have better heating uniformity. To validate this approach of determination of thickness using the 1-D model, a 3-D multiphysics based numerical model and experimental microwave cooking were used to evaluate the average heating rate in the original equal and adjusted food designs. The validation using 3-D numerical model was also performed for three multicompartment meals, three top surface areas, three food shapes, and three microwave ovens. The meals with adjusted thicknesses showed that the average heating rates of two compartments were closer indicating improved heating uniformity. The average heating uniformity indices based on average final temperature difference and coefficient of variation of 21 scenarios are 57.6% ± 9.4% and 29.3% ± 5.3%, respectively. Therefore, the simple 1-D model can be used for preliminary design of microwaveable food products.

1. Introduction

Nonuniform heating is the biggest challenge of the food products cooked in domestic microwave ovens. This nonuniform heating not only influences the food quality, but also may cause food safety issues, especially for the food products containing raw or partially cooked ingredients. The heating nonuniformity is attributed to the complex interactions between microwaves and food components, but can be improved by properly designing the food product. Without completely understanding the interactions between microwaves and dielectric food material, the food industry currently uses "trial-and-error" method in microwaveable food product development. This is time consuming and expensive.

To change this "trial-and-error" concept, many analytical and numerical models have been developed to enhance understanding of microwave heating of foods, and serve as tools in food product development. The earlier microwave heating models were developed to predict microwave power distribution using analytical methods (Watanabe and Ohkawa, 1978; Zhou and Chen, 1988). With extensive computing ability, numerical methods were employed to simulate microwave heating process. Ayappa et al. (1991a, 1991b) and Basak and Ayappa (1997) solved coupled electromagnetic and heat transfer equations to predict microwave

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heating performance of 1-dimensional (1-D) food products. Some studies have modeled microwave heating by applying a simplified source term on the food surface where the microwaves exponentially decay into the food product (Lambert's Law) (Campañone and Zaritzky, 2005; Ni et al., 1999; Zhou et al., 1995). More microwave heating models have been developed by solving Maxwell's equations of electromagnetic and coupling with heat transfer within food product to understand the microwave heating performance of foods cooked in a 3-D microwave oven cavity (Chen et al., 2015b; Geedipalli et al., 2007; Liu et al., 2014a, 2014b; Oliveira and Franca, 2000; Pitchai et al., 2014, 2012; Rakesh et al., 2010, 2009; Romano et al., 2005). Several more comprehensive models incorporating electromagnetic, heat and mass transfer, and phase change of evaporation have been developed to describe more complex microwave heating phenomenon (Chen et al., 2014, 2016; Rakesh et al., 2012).

These numerical microwave heating models have been developed focusing on accurate temperature prediction by incorporating more and more complicated physics and model geometries. However, the state-of-the-art of these microwave models that describe the heating of foods rotating on the turntable are not accurate enough to predict exact temperatures within the food. Continuing to add more physics will add more computational complexity and may limit its utility in the food industry. In addition, the performance of heating food in microwave ovens dramatically changes with oven cavities. Therefore, these models are specific for a microwave oven and food layout and newer models have to be simulated for every new microwave oven and food layout. The food product developers see the limited utility of these models in their food design, due to (a) the large number of properties and parameters needed in the model, (b) expertise required to properly setup the model, (c) and the expensive commercial software and computational intensity required to run the model (Chen et al., 2015b). These comprehensive models are more useful in evaluating and improving the food product designs in the later design stage of a development process. In the preliminary design stage, the food developers may need a simple mathematical tool to design microwaveable food in a generalized manner for any microwave ovens (e.g., design thickness of homogeneous food components in a multicompartment meal).

Currently, penetration depth (a function of dielectric properties) is an important term that is used in the preliminary design of microwaveable food products. Penetration depth is the distance at which the power decreases to 1/e of its incident value. The penetration depth was derived by considering microwaves incidenting only on one (top) surface. However, in real microwave heating, the microwaves incident on all sides, including top and bottom. Therefore it can be recommended that the product thickness should be less than 2–3 times of the penetration depth for minimizing surface heating. However, the heating rate of a food product depends on not only the dielectric properties, but also thermal properties (e.g., specific heat capacity) and physical properties (e.g., density). A model to describe the heating rate of a food product based on its dielectric, thermal, and physical properties will be helpful to assist the food developers in the earlier design stage.

The objectives of this study are to:

(1) develop a simple 1-D model to determine the thicknesses of different homogeneous food components in multicompartment meals to achieve similar heating rate;
(2) validate the utility of the 1-D model to determine thicknesses of different homogeneous food components by evaluating the heating performance of a multicompartment meal in a 3-D multiphysics numerical model and microwave heating experiments; and
(3) validate the robustness of the 1-D model by evaluating the heating performance of different multicompartment meals in different top surface area and shape across different microwave ovens using a 3-D multiphysics numerical model.

2. Materials and methods

The overall concept of the thickness determination is shown in Fig. 1. The overall objective of is to achieve same heating rate for two compartments in a multicompartment meals by determining the thicknesses by using a simple 1-D model. The detailed model development, thickness determination, and model validation are described as follows.

2.1. Simple 1-D analytical model development and thickness determination

The simple 1-D model was developed to predict the average heating rate of a food product based on dielectric, thermal, and physical properties. As shown in Fig. 2, planar wave propagating in the positive z direction (i.e. downward) with an x directed electric field of intensity $E_{f,1,a}$ in air is normally incidenting from air on the top surface of a food material, where part of the microwave energy is reflected back at the air-food interface (microwave propagates from air to food domain) into the food. The incident electric intensity was set as 4750 V/m, which corresponds to a 1.2 kW domestic oven (Hossan and Dutta, 2012). The transmitted microwave energy propagates into the food product of thickness "d". Two scenarios of microwave propagation were evaluated using the 1-D model, as shown in Fig. 2: a. without reflection (there is no microwave reflected at the food-air interface and the food domain was considered to have infinite thickness); b. with reflection (the food product is placed on a glass turntable in an oven and microwave propagates to the metal boundary and reflects back; reflections are considered at each interface).

The electric field strength (E(z)) at location z within the food product for the two scenarios can be derived based on the dielectric properties and thickness of each layer. For scenario 1 (without reflection), the transmitted microwave exponentially decays along the propagation direction within the food. For scenario 2 (with reflection), the electric field strength was derived using a wave-transmission matrix formulation (Collin, 1960). The derivations for two scenarios of microwave propagation are described in detail in the Appendix.

After the electric field strength within the food product is calculated, the power absorbed per unit volume by the dielectric food product at location z can be described as:

$$P(z) = \frac{1}{2}\omega\varepsilon_0\varepsilon''|E(z)|^2 \quad (1)$$

The total power absorbed by the food product per unit cross section can be integrated over the food product thickness to get the total power absorbed per unit cross section:

$$Q = \int_{z=0}^{d} P(z)d_z = \frac{1}{2}\omega\varepsilon_0\varepsilon''\int_{z=0}^{d}|E(z)|^2 d_z \quad (2)$$

The average heating rate of the food product can then be calculated as:

$$\frac{\Delta T}{\Delta t} = \frac{Q}{\rho C_p d} \quad (3)$$