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Modeling the heating uniformity contributed by a rotating turntable in microwave ovens

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Abstract

The role of a carousel in improving heating uniformity of food in a microwave oven is studied. A physics-based computational model is developed coupling the Maxwell's equations for electromagnetics and energy equation for heating inside a microwave oven with food load. The model is solved numerically using a finite element based computational software. Transient simulation of the heating process is done by considering the rotation of the turntable by repeating the computations for discrete angular positions of the turntable. The model is experimentally validated by measurements of point temperatures using fiber optic probes. Power absorbed in the food as a function of the angle of rotation of the turntable covering the entire cycle is available for the first time. Using various measures of heating uniformity, it is shown that the carousel helps in increasing the temperature uniformity of the food by about 40%.

Keywords: Microwave oven; Carousel; Maxwell's equation; Heat equation; Finite element method; Heating uniformity

1. Introduction and objectives

Microwave ovens are known for their benefits such as speed and convenience during heating of foods. However, microwave heating leads to non uniform temperatures inside the food due to different factors depending on microwave waveguide location, food composition, geometry and placement of food inside the oven. The carousel, or turntable, is one of the earliest and the most intuitive methods of increasing temperature uniformity inside a microwave oven. Microwave ovens heat food volumetrically by electromagnetic radiation. The process of microwave heating of foods has been extensively studied, both experimentally (Nott & Hall, 2005; Swain, Russell, Clarke, & Swain, 2004) and theoretically using analytical (Shou-Zheng & Han-Kui, 1988; Watanabe & Ohkawa, 1978) and numerical methods (Knoerzer, Regier, & Schubert, 2006; Ma et al., 1995). Numerous methods have been suggested to improve heating uniformity in microwave ovens that include using microwaves in combination with some other heating source, changing food composition and using active packages like shields and susceptors. In addition, some ovens include mode stirrers to change the electromagnetic field continuously to obtain uniform heating. However, no specific criteria have evolved for increasing temperature uniformity of food being heated in a microwave oven. This is partly due the complex non-linear physics governing microwave heating, but more significantly because different kinds of food (with different properties, shapes and volumes) need different specifications.

The carousel is one such rare addition to a microwave oven which works universally to increase temperature uniformity. As the food rotates, different locations on the food go through different field strengths. Though developed from intuitive reasoning and not from a basic scientific understanding of the process, the carousel still remains the most popular method to increase food heating uniformity. In spite of its popularity, there has been no previous study that deals with modeling food heating in a

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Nomenclature

$\mathbf{E}$	electric field intensity, V/m	T_a	oven temperature, °C
$\mathbf{H}$	magnetic field intensity, A/m	ϵ_0	permittivity of free space, 8.854×10^{-12} F/m
T	temperature, °C	μ	permeability of free space, $4\pi \times 10^{-7}$ H/m
t	time, s	ϵ	complex relative permittivity, dimensionless
c_p	specific heat, J/kg K	ϵ'	dielectric constant, dimensionless
k	thermal conductivity, W/m K	ϵ''	dielectric loss, dimensionless
P	power density, W/m^3	ω	angular frequency, rad/s
h_c	convective heat transfer coefficient, W/m^2 K	ρ	density, kg/m^3

microwave oven with a carousel. The objective of this study is to model the heating of a food inside a microwave oven while it rotates on a carousel. Using the model, the exact role of the carousel in improving heating uniformity will be determined.

2. Previous work on microwave heating of foods

As discussed, there have been a number of studies involving microwave heating of foods in the past. Experimental studies have essentially focussed on using microwave energy for various food processes like heating (Dahl, Matthews, & Lund, 1981), drying (Drouzas, Tsami, & Saravacos, 1999; Wang & Xi, 2005), freeze drying (Wang & Shi, 1999), thawing (Taher & Farid, 2001) and looking at final food quality and changes in chemical (Welt & Tong, 1993) and other properties (Kentish, Davidson, Hassan, & Bloore, 2005) of the products due to microwave application. Additionally, researchers have explored different methods to measure temperatures during microwave heating ranging from the use of thermal cameras (Bengtsson & Lycke, 1969) in the past to magnetic resonance imaging (MR1) (Knoerzer et al., 2006; Nott & Hall, 2005) more recently.

The process of microwave heating has been mathematically modeled using analytical and numerical techniques. The earliest efforts in this area were primarily analytical (Shou-Zheng & Han-Kui, 1988; Watanabe & Ohkawa, 1978). However, with the availability of extensive computing facilities, solution of Maxwell's equations for electromagnetics coupled with heat transfer in the oven cavity can be obtained using different numerical methods such as finite difference time domain (FDTD) method (Dincov, Parrott, & Pericleous, 2004; Ma et al., 1995) and finite element method (FEM) (Zhang & Datta, 2000). Other studies have modeled microwave heating by solving the heat and mass transfer equation and assuming a source term with exponential decay (Lambert's Law) instead of solving the set of Maxwell's equations for the electromagnetic field (Ni, Datta, & Torrance, 1999; Zhou, Puri, Anantheswaran, & Yeh, 1995; Campanone & Zaritzky, 2005).

Researchers in the past have observed non uniformity in temperatures and development of hot and cold spots inside foods heated using microwaves (Ohlsson & Risman, 1978; Watanabe, Suzuki, & Sugimoto, 1971). Past studies have looked at different factors that affect the heating uniformity in microwave ovens such as food shape (Chamchong & Datta, 1999b; Zhang & Datta, 2005), size (Vilayannur, Puri, & Anantheswaran, 1998), location (Wappling-Raaholt & Ohlsson, 2000), dielectric properties of food (Chamchong & Datta, 1999b; Peyre, Datta, & Seyler, 1997), microwave power and cycling (Chamchong & Datta, 1999a). Researchers have also explored various alternatives to increase the temperature uniformity during microwave heating (Wappling-Raaholt & Ohlsson, 2000). Combination heating, which involves heating food with microwaves in combination with infrared and/or hot air, is one of the most significant methods used to achieve uniform temperatures in the food (Datta & Ni, 2002; Datta, Geedipalli, & Almeida, 2005; Wappling-Raaholt et al., 2002). The effects of using variable frequencies for microwave heating (Bows, 1999; Kashyap & Wyslouzil, 1977) and the use of mode stirrers (George & Bergman, 2006; Plaza-Gonzalez, Monzo-Cabrera, Catala-Civera, & Sanchez-Hernandez, 2004) on heating patterns have also been studied.

No work has, however, focused on the study of the rotation of the oven turntable and the improvement of the uniformity of power deposition in the food due to such rotation. The goal of this study is to quantify the extent of uniformity of heating in a food material contributed by the rotation of the carousel (food) inside a microwave oven. An electromagnetic model is first set up for a microwave oven with a food load inside it. The model is solved numerically using the FEM for discrete positions of the turntable covering the entire 360° of rotation. FEM is selected as the FDTD method is difficult to apply for complex geometry and can require long computational time. The energy equation is subsequently solved and the computed transient temperatures at several locations are compared with experimental results. The non-uniformities in temperatures are quantified in a number of ways and comparisons are made between non-uniformities with and without the rotation of the food.