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**INTERNATIONAL MICROWAVE
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DEVELOPMENT OF NOVEL MICROWAVE COOKING MODEL FOR NOT-READY-TO EAT FOODS

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ABSTRACT

Recently safety of microwave cooked food has come under scrutiny because of recent outbreak and recalls associated with some of these not-ready-to-eat (NRTE) frozen foods. Heating uniformity of these foods is paramount in rendering the foods safe for consumption. Degree of uneven microwave heating is influenced by both microwave oven and characteristics of food load which decides the electric field distribution within the food load. Given the complexity of parameters, a computer model is always desirable to optimize heating uniformity by proper selection of food shape, proportions, plating, packaging selection and more. Earlier many researchers have made one or more assumptions in computer model development to simplify the problem and to minimize the computational time. The main objective is to develop a holistic microwave cooking model to capture all real scenarios. Using this model, we studied the effect of microwave oven parameters as well as food load parameters.

Coupled heat transfer and EM equations were solved using QWED software interfaced with Fluent software. The model was validated using 1% gellan gel temperature profile obtained by using Infrared imaging camera (SC640 FLIR) and Fiber optic sensor in both stationary and rotating turntable MW heating situation. The gellan gel as model food was useful in validating temperature profile accurately as it is possible to cut thin slices for temperature mapping of each slice. The predicted temperature profile for each layer was found to be in good agreement qualitatively and quantitatively with experimental profile. Preliminary results have hinted that irrespective of changing any parameters, non-uniform heating will remain an issue to deal with. This study increased our understanding of MW heating/cooking of heterogeneous food products and helped to optimize food parameters.

KEY WORDS: Microwave heating, non-uniform heating, modeling, heat transfer

INTRODUCTION

Microwave processing of bio-products offers a number of well-known advantages, namely faster and more efficient heating. As a consequence, microwave ovens are very popular for domestic applications, and the industrial usage in the food industry. However, recent outbreaks and recalls associated with packaged frozen foods has forced the food industry to have a fresh look in to the microwavable product development. Several problems often arise due to the uneven pattern of microwave heating: unsatisfactory (non-homogeneous) quality of the final product, insufficient microbiological destruction in cold areas, and safety hazards due to over-heating. Uneven heating in frozen NRTE foods is a particular problem, since ice absorbs microwave energy to a lesser extent than liquid water, leading to defrosted sections of food warming faster while frozen sections remain cold (Chamchong and Datta 1999; Chamchong and Datta 1999). Because microwave ovens are commonly used for reheating and cooking just before consumption, microwave heating must assure food safety. The food safety problem in NRTE foods is primarily an engineering problem than a microbiological issue. It is critical to have an understanding of

how microwaves interact with food components in a domestic microwave oven to solve this problem.

The works of Kriegsmann, Brodwin & Watters (1990), Coleman (1990), Hill & Smyth (1990) and Tian (1991, pp. 283–300) are recognized as the seminal efforts in the field of mathematically modeling. Chan & Reader (2000) have been instrumental in developing understanding of electric field distribution in multimode domestic oven cavity. Researchers have made one or more assumptions to simplify the problem and to minimize the computational time. For example, instead of modeling Maxwell's equation, several researchers simplified the problem by using Lambert's law, which calculates dissipated power by simple expression assuming that the power decays in the food exponentially (Lu et al., 1998; Zheng and Faghri, 1994; Khraisheh et al., 1997; Ni et al., 1999; Campanone and Zaritzky, 2005; Zhou et al., 1995; Chamchong and Datta, 199a, b; Mallikarjunan et al., 1996; Chen et al., 1993; Gunasekaran, 2002). Lambert's law does not represent the electromagnetic field completely (Datta, 2001). Few models have been reported that couple electromagnetic and thermal modeling (Zhang and Datta, 2000, 2003; Wappling-Raaholt et al., 2002; Geedipalli et al., 2007; Dincov et al., 2004). (Zhang and Datta 2003) investigated the power absorption in single- and multiple-item foods. Geedipalli et al (2007) modeled the heating of a potato sample in a microwave oven with a rotating turntable. This model is the most comprehensive model reported in the literature. In this model, they have assumed the constant dielectric properties of potato and studied the effect of rotation when the object is at the center of the turntable. It will be a good starting point for further development of a comprehensive computer model for simulating MW cooking for various practical scenarios. The main objective of the present work is to develop a holistic simulation model to simulate realistic case scenarios and validate the model with a model food system. We are trying to simulate the actual microwave oven in which small details are important to simulate effect of these parameters. So far, people have assumed that a microwave oven is a simple cavity in which one port is located at certain place. A close look into the intricacy of the modern oven design hints that the design of the microwave oven has evolved based on engineering intuition rather than any simulation study. In this study we want to verify that those design changes really help in improving heating uniformity or not.

MATERIALS AND METHODS

Water and ions are primary food components that absorb microwaves, leading to volumetric heating. The volumetric heating rate, or the power absorption of the microwave Q , is related as:

$$Q = 2 \pi f \epsilon_0 \epsilon'' E^2$$

where f is microwave frequency (Hz), ϵ_0 is the permittivity of free space, ϵ'' is the dielectric loss factor of the material, and E is the electric field strength (V/m). Electric field intensity at any point in the domain is governed by a set of Maxwell's equations for constant permittivity and permeability and with no sources as shown below (Datta and Anantheswaran 2001):

$$\nabla \times E = -j\omega\mu H; \nabla \times H = j\omega\epsilon_0 \epsilon^* E; \nabla \cdot E = 0; \nabla \cdot H = 0$$

where, H is the magnetic field intensity, μ is the permeability, ϵ^* is the relative complex permittivity of the material, and expressed as $\epsilon' - j \epsilon''$ in which ϵ' is the dielectric constant of the material, ω is the angular frequency ($2\pi f$), and ϵ is the complex permittivity of the material.

Boundary conditions for the electromagnetic modeling of a cavity are set on the walls of the oven cavity which are considered perfect conductors. It is essential to exactly know the power output of microwave for providing correct input electric field amplitude at the wave port. The microwave output is proportional to the square of the modulus of the electric field intensity. The power output of magnetron was determined by using IEC 60705 standard method (IEC 2006). The dissipated heat diffused by conduction inside the material is governed by the Fourier unsteady state equation (Datta and Anantheswaran 2001):

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q$$

where T is the temperature at a position x and time t , ρ is density, c_p is specific heat, k is thermal conductivity. At present we are assuming adiabatic boundary conditions at the load-air interface.

As the Quickwave software (QWED SP, Poland) is finite difference based software, the convergence of the electric field is quite fast, hence this software is well suited for modeling of microwave heating scenarios. In case of solid materials, Basic Heat Transfer module of the software was used for prediction of transient temperature. In case of more complicated problems involving moments transfer, Fluent package was coupled with the Quickwave software.

Figure 1 shows the geometric model of two microwave selected in this study. The geometry of the Panasonic microwave is the most complex and microwaves are fed from the side walls, whereas the Sharp oven is the simplest one and microwaves are fed from the top wall of the cavity.

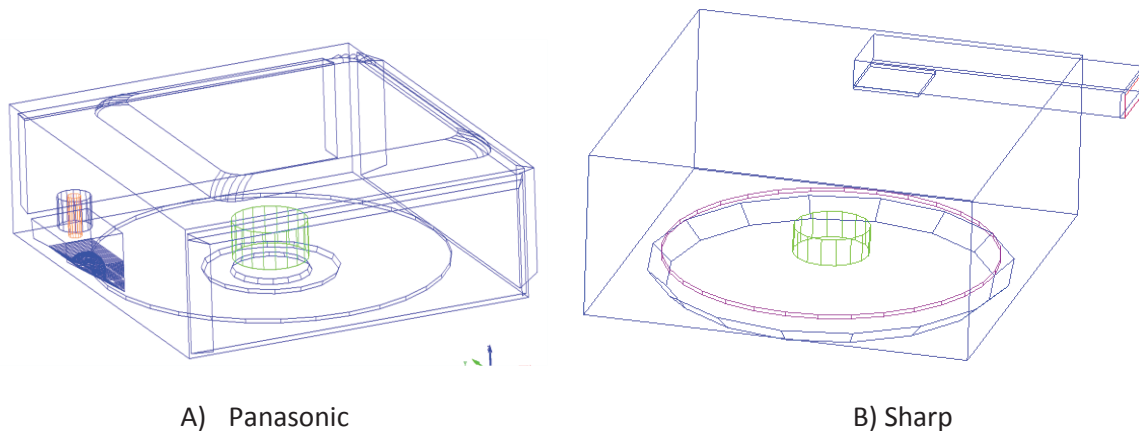


Figure 1 Geometric model Panasonic MW oven 1100 w (420 × 390 × 210 mm) and Sharp Carousel 700 w (410 × 420 × 250 mm) oven with 1% gellan gel cylinder (80 × 50 mm)

One percent gellan gum (Kelcogel, Kelco Division of Merck and Co., San Diego, CA) was dissolved in deionized water and the solution was heated to 90°C in 15 min. CaCl₂ salt 0.17% was added into the hot gellan gum solution to adjust the loss factor and form stable gel. The hot gel solution was poured into the mould and allowed to cool at room temperature for 30 min to ensure gel setting. The dielectric, thermal and physical properties of the gellan gel is summarized in the Table 1 (Birla, Wang et al. 2008). Infrared imaging camera (640x480 Pixels, FLIR

systems Model # SC640 accuracy $\pm 2^{\circ}\text{C}$) was used to map surface temperature immediately after heating for specified time. Eight fiber optic sensors (FOT, FISO Technologies Inc, Quebec) were used for monitoring temperature at various locations in the sample.

Table 1 Properties of 1 % gellan gel spiked with 0.17% CaCl_2

Properties	Gellan gel
Thermal conductivity, w/m/K	0.56
Density, kg/m^3	1010
Specific heat, kJ/kg/K	3600
Dielectric constant	$-0.254 T + 82.78$
Loss factor	$-5\text{E-}05T^3 + 0.0074T^2 - 0.3793T + 14.82$

RESULTS AND DISCUSSION

The computer simulation model has been validated using 1% gellan gel cylinder (80 mm \times 50 mm). The preliminary simulation results qualitatively agreed well with the temperature profile obtained using IR camera (Figure 2). We are currently studying the effect of various parameters on the heating uniformity. Following are some results.

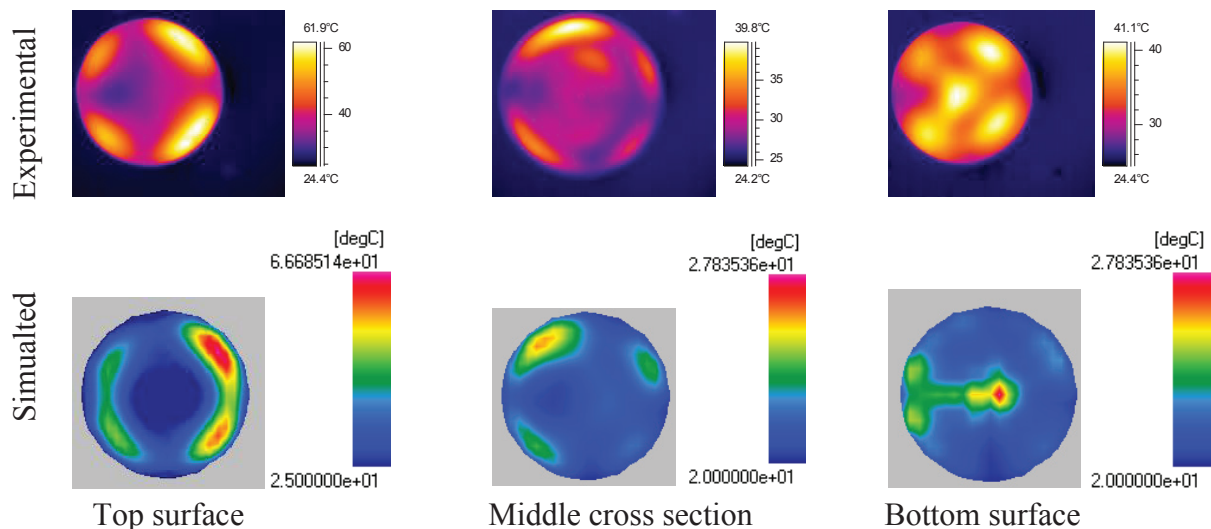


Figure 2 Comparison of experimental and simulated and heating profile of the 1% gellan gel cylinder (80 mm \times 50 mm) after 1 min of MW heating in 700 w Sharp oven .

Effect of rotation of foo:

Figure 3 shows the simulated temperature profile reasonably similar to the experiential temperature profile of gellan gel subjected to microwave heating for 30 s on turntable. We have also studied the effect of offset location of the food items. Rotation helps in alleviating the problem on non uniformity but does not completely resolve the problem.

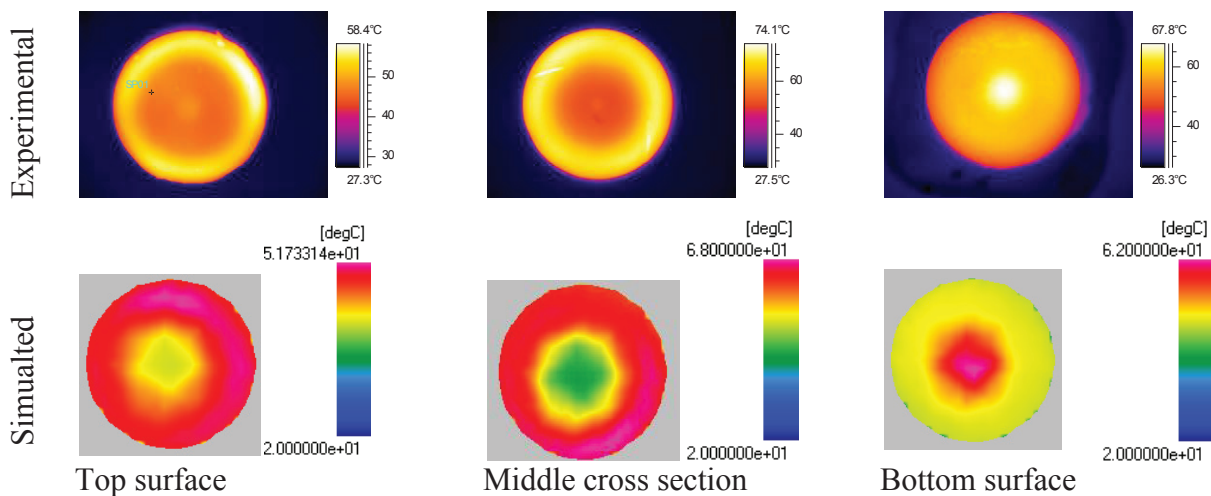


Figure 3 Simulated and experimental profile of 1 % gellan gel cylinder placed in the center of the turn table rotating at 6 rpm (MW heating for 30 s in 1100 w Panasonic oven)

Position of the waveguide port

Figure 4 show the simulated effect of the position of the microwave feed port on the temperature distribution in gellan gel. The simulation results hints that the position of the feed port greatly influence the temperature distribution. We are also studying the effect of multi-feed cavity on improvement in heating uniformity.

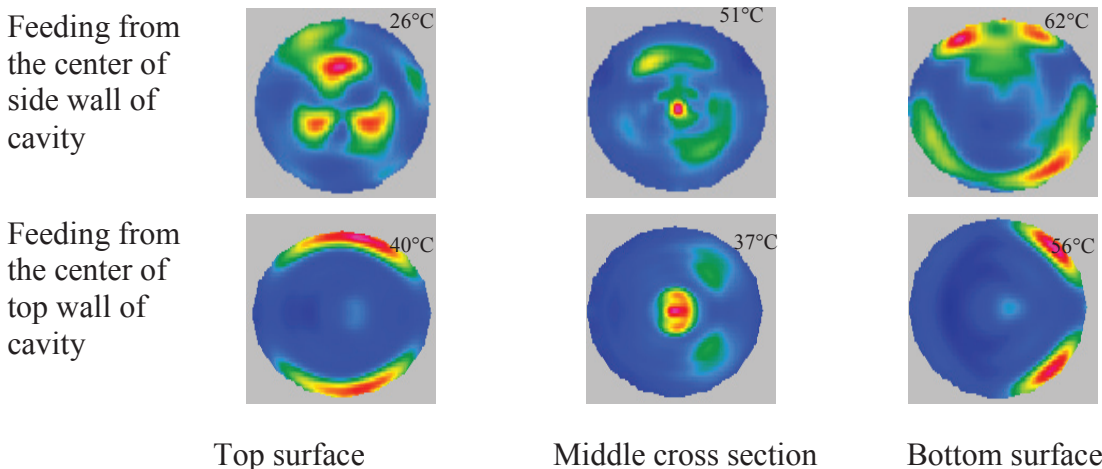


Figure 4 Comparison of simulated heating profile of the 1% gellan gel after 1 min of MW heating in 700 w Sharp model. (Temperature scale is 20 °C minimum corresponding to dark blue and red color shows maximum temperature on the each picture)

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