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Electromagnetic and Heat Transfer Modeling of Microwave Heating in Domestic Ovens

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ELECTROMAGNETIC AND HEAT TRANSFER MODELING OF MICROWAVE HEATING IN DOMESTIC OVENS

by

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Microwave (MW) heating is fast and convenient, but is highly non-uniform. When a food product contains raw or partially cooked food components, non-uniform heating can result in inadequate cooking, leading to a microbiologically unsafe product. A mathematical model of microwave heating helps to understand non-uniform temperature distribution in domestic microwave ovens and a useful tool for food product developers and microwave oven manufacturers. The objective of this study was to develop a mathematical model to predict spatial and temporal variations in temperature of a model food during microwave heating. A mathematical model was developed by solving coupled Maxwell's electromagnetic and Fourier's heat transfer equations using finite-difference time-domain (FDTD) method in QuickWave v7.5 software. The model was used to describe the heating of a gellan gel cylinder for 30 s in a 700 W domestic microwave oven. The model domain included the magnetron, typical waveguide, cavity and turntable. Optimization of modeling parameters such as computational meshing size, heating time step, frequency, and electric field strength was performed to increase accuracy of the prediction of the temperature profile. The model was validated by conducting microwave heating experiments to observe time-temperature and spatial-temperature profiles using fiber optic thermocouples and thermal imaging camera,

respectively. A good qualitative agreement between simulation and experimental temperature profiles was observed. Results of quantitative analysis of point measurement of time-temperature profile showed that average root-mean squared error of the 12 locations was 2.02°C.

Keywords: Modeling, heat transfer, non-uniform heating, temperature variation.

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CHAPTER I

INTRODUCTION

The use of microwave for heating applications dates back to World War II (Tang et al., 2002). Microwaveable food products gained popularity in the early 1990s. Electromagnetic (EM) energy of microwaves has been used extensively in food processing applications as an alternative to conventional heating methods to increase heating rate and reduce process time (Ohlsson, 1983). Microwave heating is a convenient method of cooking foods, particularly in developed countries. In U.S., microwave oven and microwavable foods production contributes a significant role in generating revenue for both the microwave oven and food industries. Rapid and volumetric heating are the advantages of microwave heating. However, non-uniform heating is a disadvantage of MW heating. The complex interaction of microwaves with food properties produces non-uniform heating. A particular microwave oven can behave differently for the same food depending on its physical state such as frozen or un-frozen state. This non-uniform heating in a microwave oven not only affects food safety but also influences food quality (Ma et al., 1995).

Most of the work on designing of microwave heating systems and processes has been done based on only experience and perceptions of engineers (Risman and Celuch, 2000). Experimental assessments alone cannot easily identify the reasons behind non-uniform heating in a microwave oven. A modeling technique can provide a complete platform to study the effects of microwave oven design and food properties on non-uniform heating. Computer simulation that couples basic electromagnetic and heat

transfer equations would help in designing microwave ovens and optimize process parameters to minimize non-uniformity issues (Chen et al., 2008). The modeling started with many approximations/simplifications without considering realistic situations of microwave heating (Schubert and Reiger, 2005). Initially, numerical solutions of microwave heating were developed by solving analytical equations for Lambert's law (Dolande and Datta, 1993; Yang and Gunasekaran, 2004). Lambert's law considers incident power from magnetron that decays exponentially for certain depths in food material along one dimension. In reality, power is absorbed or decayed in three dimensions and not just one-dimension. Node/anti-node formation, standing wave effect, and typical sinusoidal wave of microwave energy cannot be considered using Lambert's law (Barringer et al., 1995: Yang and Gunasekaran, 2004). While Knoerzer et al. (2008) calculated temperature fields in microwave heating, the thermal diffusion inside the food was neglected. Coupled electromagnetic and thermal equations that describe microwave heating are partial differential equations (PDE) in three-dimensional coordinates. PDE equations of three-dimensional coordinates with boundary conditions and complex shapes of food cannot be solved analytically and require iterative numerical methods. Numerical methods such as finite-difference time-domain (FDTD), finite element method (FEM), and transmission line methods (TLM) are available to solve coupled electromagnetic and heat transfer equations. Out of these numerical methods, finite-difference time-domain (FDTD) is most commonly used for solving electromagnetic equations because it requires less computation time and memory (Chen et al., 2008). This thesis explores the use of a well-known FDTD based QuickWave v7.5 software to solve coupled electromagnetic and heat transfer equations for microwave heating.

Objectives

The overall goal of this research was to develop a comprehensive coupled electromagnetic and heat transfer model to predict temperature history of microwave heated foods. The specific objectives of this research were to:

i. develop, optimize and validate a heat transfer model for microwave heating of model food (gellan gel) subjected to 30 s heating and without rotation of turntable, and

ii. quantify non-uniform heating within a microwave cavity for a range of power microwave ovens for the effect of radial distance along the turntable and sectors of the turntable.

Thesis Format

There are three chapters written in this thesis with the format of publishing in scientific journals. Chapter II provides a comprehensive review of literature in the areas of microwave heating principles and modeling techniques. The next two chapters (Chapter III and Chapter IV) address the specific objectives in detail. Chapter III describes the development of coupled electromagnetic and heat transfer model and explains the procedure of selecting model input parameters. This chapter also explains the importance for optimizing model parameters for better accuracy of the developed model.

A cylindrical model food (80 × 50 mm), gellan gel, was subjected to microwave heating for 30 s. This study did not include turntable rotation while heating.

The numerical model was validated qualitatively and quantitatively with experimental data obtained using a thermal imaging camera and fiber optic sensors. Spatial temperature profiles of heated gellan gel were collected at three distinctive layers. Fiber optic sensors were used to monitor temperatures at 12 locations inside the gellan gel. The results of model prediction were in agreement with the experimental findings. The average root mean square error value of time-temperature profiles was 2.02°C.

Chapter IV describes the assessment of non-uniform heating within a microwave cavity in a range of domestic microwave ovens. It is important to achieve heating uniformity to improve the safety of microwave-heated products. A custom designed container was used to assess non-uniform heating of a range of microwave ovens using a hedgehog of 30 thermocouples. Heating rate and variation of temperature along the radial distance and sector of the container were studied. Statistical models were developed to understand the interaction effect of radial distance of rings and sectors to identify the best place for food on a turntable. Effects of power and cavity volume and sectors on average temperature raise and heating uniformity variation was also studied for a range of microwave ovens.

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CHAPTER II

REVIEW OF LITERATURE

Introduction

The microwave (MW) oven is one of the predominant inventions of the 20th century. Almost 90% of homes in the US have at least one microwave oven (USDA-FSIS, 2006a). Nearly 25 million domestic microwave ovens are produced globally every year (Ohlsson and Bengtsson, 2001). Microwave ovens play an important role in cooking not-ready-to-eat (NRTE) foods. NRTE foods are often confused with ready-to-eat foods by consumers. The Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA-FSIS) stated that not-ready-to-eat foods may contain some raw or partially cooked meat ingredients and can contain foodborne pathogens (USDA–FSIS, 2006b). NRTE foods require thorough heating before consumption to assure food safety. In contrast, ready-to-eat foods are safe to eat without applying further heating. These foods may be warmed for palatability, but heating is not required for food safety.

Since the 1940s, microwaves have been used to heat food materials. Microwaves have been used in different fields such as food, chemical, medical, and telecommunication industries. The food industry is still the largest consumer of microwave energy, where it has been applied for thawing, cooking, tempering, drying, freeze-drying, pasteurization, sterilization, baking, heating and re-heating (Ayappa et al., 1991). The U.S. Federal Communications Commission (FCC) has allocated two frequencies for microwave food processing in North America, 2450 MHz and 915 MHz. Of these two frequencies, the 2450 MHz is used mainly for domestic microwave ovens

and the 915 MHz is used in industrial microwave heating. It is interesting to note that frequencies of 433.92, 896, and 2375 MHz are used for microwave heating application outside of North America (Datta and Davidson, 2000).

Electromagnetic (EM) energy is used in food processing applications to increase heating rate and reduce process time as alternatives to conventional heating methods (Ohlsson and Risman, 1978). The major uses of microwave ovens in the U.S. at the beginning of 1990s were reheating and defrosting foods, cooking vegetables, preparing snacks, preparing meals, and quickly preparing traditionally long-cooking foods (Happel, 1992). While microwave ovens are common place in homes, industrial application of microwave heating is not as common. This situation still prevails in the microwave food industry. The reasons for differences in applications are the lack of understanding of basic information on dielectric properties of foods and their interactions with microwave heating characteristics, high cost of instruments and electricity (Tang et al., 2002). Experimental studies have essentially focused on using microwave energy for various food processes such as heating (Dahl et al., 1981), drying (Drouzas et al., 1999; Wang and Xi, 2005), freeze drying (Wang and Chen, 2005), thawing (Taher and Farid, 2001) and inactivating microbial spores (Welt et al., 1994). A major setback in developing novel thermal processing technologies based on microwave energy is non-uniform electromagnetic field distribution (Ohlsson, 1991; Ryynanen and Ohlsson, 1996). In a microwave cavity, localized hot and cold spots develop inside the food because of non-uniform distribution of microwave energy.

Although microwave heating has non-uniformity issues, it also provides numerous advantages over conventional heating methods. In microwave heating, heat is

generated throughout the food material as volumetric heating, which leads to rapid cooking and reduces processing time. On the other hand, conventional heating takes place as surface heating and further absorption of heat is by thermal conduction and diffusion processes. In terms of food quality after heating, typically the microwave assisted food product does not become brown and crisp because air in the oven is at room temperature. Whereas, in conventional heating methods thermal degradation to food products due to heated air circulation is typical (USDA, 2006a). Another important advantage of microwave heating is that the desired temperature of the product can be achieved in a shorter processing time. In general, most consumers of NRTE foods think that microwave heated food would be microbiologically safe. After heating, it is not true to believe that all the bacteria are inactivated in microwave heated food products. Microwave heating can result in uneven (non-uniform) heating and leave cold spots where harmful bacteria can still survive. Microwave heating leaves “hot” and “cold” spots at different locations of the food product, when there is not sufficient time for the product to equilibrate to a uniform temperature. The profile of hot and cold spots can be somewhat equilibrated by allowing “standing time” after microwave heating. This standing time helps to raise the temperature of cold spots in the product even after microwave heating stopped.

According to Centers for Disease Control and Prevention (CDC) report on Mobility and Mortality Weekly Report (MMWR) (2008) that four human *Salmonella* serotype I 4,5,12:i:-* have been identified in not-ready-to-eat pot pies. This report summarizes the results of subsequent investigations of the outbreak, which outlined that 401 cases of salmonella occurred in 41 states during 2007, with 32% of ill persons hospitalized. Further investigation by the center confirmed that 77% of people, who ate

pot pies after microwave heating suffered illness. In 2010, microwave heated cheesy chicken and rice-frozen meals of ConAgra Foods have been recalled by CDC due to *Salmonella* contamination. The cheesy chicken and rice frozen meals recall has been linked to at least 29 *Salmonella* Chester illnesses in 14 states. Details of more recent outbreaks associated with microwave-heated foods have been summarized in Table 2.1. These incidents highlight the importance of thoroughly cooking NRTE products before consumption and require the NRTE producers to clearly mention cooking instructions on packaging label.

This review of literature section discusses the fundamentals of microwave heating and continuous to explore the microwave electromagnetic heat transfer model and its development over the years.

Electromagnetic Waves

Microwave (MW) energy is a form of radiation. The term radiation means that energy is transported by the force fields of electromagnetic waves; they can radiate through a perfect vacuum and do not need any medium to transfer energy from one object to another. All electromagnetic waves have two components, 1) Electric field (E) and 2) Magnetic field (B). When a charge (electric or magnetic) in a medium changes its position in space, the corresponding field that it produces also changes in space. These changes in electric and magnetic fields produce an oscillatory wave, which is called an electromagnetic wave. Electromagnetic waves are characterized by their frequency, velocity, and electric field strength.

Two fundamental characteristics of any periodic wave phenomenon are the frequency and the wavelength. For electromagnetic waves, these properties are related by

$$c = f\lambda \qquad (2.1)$$

where c is the speed of light in the medium (m/s), f is the frequency of the wave (Hz), and λ is the wavelength (m). In 1873, Maxwell discovered that electromagnetic waves are composed of electric and magnetic field components that are aligned perpendicular to one another (Figure 2.1). The components (E and B) vary in time and space as they propagate through the medium. The orientation of components assures a right-hand thumb rule, where the index finger indicates the direction of propagation, the extended thumb indicates the alignment of the E field, and the middle finger indicates the alignment of the B field component. As with other electromagnetic wave such as radio waves, microwaves are also prone to reflection, refraction, and polarization.

Fundamentals of Microwave Heating

Microwave (MW) heating takes place in a dielectric material due to the polarization of water molecules with electromagnetic radiation at frequencies between 300 MHz and 300 GHz (wavelength(λ) : 1cm to 1 m). At this frequency interval, microwave energy cannot be transferred by basic wired circuits rather it will be transferred by a vacuum medium, waveguide (Metaxas and Meredith, 1983). Figure 2.2 shows the electromagnetic spectrum with corresponding wavelength and frequency of each radiation format. MW energy penetrates into a food product and produces a volumetrically distributed heat source, due to molecular friction caused by dipole rotation

of a polar solvent (water in the food) in response to the changing electric filed at a rate of approximately 2.45 billion times per second. The dipolar rotation is caused during microwave heating due to change in polarity of EM fields inside the cavity over time (Figure 2.3). The following section will discuss in more detail on the fundamentals of microwave heating in food materials.

Dielectric Properties

Food materials are considered as poor electric conductors. Electromagnetic energy subjected to a food material can be dissipated as heat energy. Dielectric properties play a critical role in deciding the interaction between the electric field and the foods (Buffler, 1993). The relative complex permittivity consists of two parts, real and imaginary, which are dielectric constant (ε') and dielectric loss factor (ε''), respectively. The relative complex permittivity, ε^* is given by

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{2.2}$$

where ε' is the dielectric constant and ε'' is the dielectric loss factor. ε' describes the material's ability to store electric energy (for vacuum $\varepsilon' = 1$), while ε'' indicates the material's ability to dissipate electric energy into heat. In microwave and high frequency heating (radio frequency), the dielectric loss factor is considered to be the primary factor in determining the food material's ability to dissipate electric energy into heat. Typically, the dielectric constant in biological materials is considered to be constant with minimal variation with respect to change in temperature and frequency. In low loss materials, the value of the dielectric loss factor is considered to be minimal ($\varepsilon''<0.01$), describe low loss materials as those that have the ability to absorb more energy but less ability to

dissipate as heat (Metaxas and Meredith, 1983). In contrast, lossy materials dissipate any absorbed electric energy into heat energy more rapidly than low- loss materials.

Dielectric materials are characterized by a quantity known as the dielectric loss tangent (tan δ) (low loss material - ≤ 0.005; medium loss material - 0.005 to 0.01; Baker-Jarvis, 2002), which is the ratio of dielectric loss factor to that of dielectric constant.

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (2.3)$$

The electrical conductivity (σ) of the dielectric medium (S/m) is measured by

$$\sigma = 2\pi f \varepsilon_0 \varepsilon'' \qquad (2.4)$$

where f is the frequency (Hz), ε_0 is the free space permittivity (8.854×10^{-12} F/m), and ε" is the dielectric loss factor. The magnetic permeability for most biological materials is the same as that of free space ($\mu_o = 4\pi \times 10{-}7$ N/A^{-2}). Therefore, biological materials do not interact with the magnetic field component of electromagnetic waves. Magnetic materials such as ferrite, often used in susceptors and browning dishes, however, interact with the magnetic field, which results in substantial heating (Buffler, 1993). Conversion of the electric component of microwaves into power dissipation in a lossy material (Goldblith and Wang, 1967) can be calculated by

$$P_v = 2\pi f \varepsilon_0 \varepsilon'' E^2 \qquad (2.5)$$

where P_v is the conversion of power per unit volume (W/m^3), f is the frequency (GHz), ε" is the relative dielectric loss factor, ε_0 is the permittivity of free space (8.854×10^{-12} F/m), and E is the electric field strength (V/m) in food. In theory, electric conduction and various polarization mechanisms (including dipole, electronic, atomic and Maxwell-Wagner) all contribute to the dielectric loss factor (Metaxas and Meredith, 1983; Kuang

and Nelson, 1998). But, the microwave frequency in food applications contributes to conduction and dipole rotation as the dominant loss mechanisms.

Electromagnetic Field Equations

Lambert's law

Lambert's law provides a simplified approach to calculate the microwave power dissipation in a dielectric material. The heat source term (Q) is calculated based on microwave power penetration depth inside the food material. In Lambert's law, electric field distribution inside a food material is not required to calculate the power dissipation term. This is contrary to Maxwell's equations, where electric field distributions are required. The other limitations of Lambert's law approach are: 1) sample size should be semi-infinite, 2) standing wave effect not considered, and 3) microwave energy penetration is one-dimensional. The principle of Lambert's law is that incident energy is normal to the surface and dissipates energy exponentially as it travels through the food product. Lambert's law (Yang and Gunasekaran, 2004) states that

$$P(x) = P_0\, e^{-2\beta x} \qquad (2.6)$$

where x is the depth from the surface (m), $P(x)$ is the power dissipation value at depth x (W), P_0 is the incident power at the surface (W), and β is the attenuation constant (m^{-1}) as a function of frequency (Hz); velocity of radiation (m/s); and loss tangent. There have been several studies in the past that compared Maxwell's equation and Lambert's law equation (Yang and Gunasekaran, 2004; Curet et al., 2006; Liu et al., 2005). Liu et al. (2005) stated that Lambert's law is less applicable to microwave power processing, but its simplified numerical results are comparable with the experimental methods.

Computationally, Lambert's law can be used to predict the temperature distribution within a shorter time because it does not require the tedious calculation of the electric field. Curet et al. (2006) compared the potential of Lambert's law with Maxwell's equations in predicting temperature of tylose using COMSOL Multiphysics modeler. In their study, Lambert's law provided simulation results that agreed well with the experimental results. The predicted temperature distribution using Maxwell's equations did not agree well with experimental results due to sensitivity of dielectric properties in field calculations. Yang and Gunasekaran (2004) compared temperature distribution in 2% agar gel cylinders using both Maxwell's equations and Lambert's law for pulsed microwave heating. The predictions based on both methods are statistically accurate with the experimental results. However, the power calculated term from Maxwell's equations was more accurate than Lambert's law.

Maxwell's equations

Maxwell's equations are a set of four basic equations governing electromagnetism. These four equations were formulated through numerous experiments by many researchers and then combined into a final form of time varying vector fields by James Clerk Maxwell in 1873 (Guan, 2003). These equations are derived in differential or integral form. The differential form is used to govern variations of the electric and magnetic fields in space and time. It is assumed that the field vectors are single-valued, bounded and continuous function of time and space in order to make these equations valid (Balanis, 1989). To completely define an electromagnetic field, boundary conditions need to be incorporated to take into account the discontinuous charges and

currents along the interface between different mediums. Microwave heating of a food material inside the oven is basically governed by a set of four Maxwell's equations.

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.7a}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2.7b}$$

$$\nabla . D = q \tag{2.7c}$$

$$\nabla . B = 0 \tag{2.7d}$$

with

$$J = \sigma\, (\omega) E(t) \tag{2.8a}$$

$$D = \varepsilon\, (\omega) E(t) \tag{2.8b}$$

$$B = \mu_m\, (\omega) H(t) \tag{2.8c}$$

where B is the magnetic induction (T), D is the electric displacement (N/V m), E is the electric field intensity (V/m), H corresponds to the magnetic field intensity (A/m), J is the current flux (A/m^2), ρ is the density (kg/m^3), ω is the angular frequency (radians /s), σ is the electric conductivity (S/m), ε is the permittivity (F/m), and μ is the permeability (H/m). Eqn.2.7a is called Faraday's law, indicating that the circulation of electric field strength surrounded by a closed contour is determined by the rate of change of the magnetic flux density. Eqn.2.7b is referred to as Ampere's law, indicating the circulation of magnetic field strength enclosed by a closed contour is equal to the net current through

the surface. Eqn.2.7c presents Gauss's electric law, which requires net electric flux equal to the charges contained within the region. Eqn.2.67d presents Gauss's magnetic law, which requires net magnetic flux out of a region to be zero.

Factors Influencing Microwave Heating

Physical properties

Microwave processing is a very complicated process that depends on many variables such as dielectric properties, size, shape, and microwave design. The critical factors influencing microwave heating absorption in a material are volume, surface area, composition, and food geometry (Zhang and Datta, 2000). George and Burnett (1991) have mentioned in their work that apart from physical and chemical properties, microwave heating is also impacted by sensory properties such as food consistency. For example, one of the sensory properties, food consistency (meat with bone), is a critical factor for uniform heating throughout the product because dielectric properties of bone and meat are dissimilar and are therefore heated at different rates. The inherent nature of non-uniform heating in microwave-heated products can be improved by proper designing of food components and layouts in food packages. Not-ready-to-eat meals have many food components which are heated at different rates based on their dielectric properties. In not-ready-to-eat meals, the arrangement of food components in a compartmented tray should be designed relative to the food geometry and size in order to achieve better heating uniformity (Ryynänen and Ohlsson. 1996). Bows and Richardson (1990) have mentioned that throughout the not-ready-to-eat meal, uniform temperature distribution can be achieved by proper selection of food layout. For multi-component

ready-to-eat meals, the difference in dielectric properties and thermo-physical properties of the components will influence the heating results as well electromagnetic distribution due to different boundary conditions between food components (Mudgett, 1988). Different shapes of the food product influences the power absorption in microwave heating. For example, curved shape food products tend to absorb more energy in center than surface (Ohlsson and Risman, 1978). A large surface area food heats rapidly because of the greater area available for interaction with the microwave energy which results in run-away heating in edges and corners of the food. When the sample size increases, there is a high possibility for edge-heating to happen (Ayappa et al., 1992). Remmen et al. (1996) developed a heat transfer model for different shapes of the same model food, agar gel, to predict temperature distribution. Their model included the shape of slabs, spheres and cylinders of agar gel that helped in designing heat treatments for different shapes of food products. They studied the effects of changes in model parameters such as electric field strength (E), dielectric properties and thermal properties on changes in food size. Their model was not designed to give an exact prediction of temperature distributions during microwave heating because it was based on Lambert's law. However, it can be a helpful model to design heat treatments. Chen et al. (1993) studied the effect of load on microwave power absorption for distilled water of size ranges from 20 to 200 g and a potato sample with different diameters. The study showed that water and potato sample absorbing microwave power differently based on their sizes. Giese (1992) reported the effect of shape of the load on microwave power absorption. He suggested that a sphere can be considered the best shape for total power absorption or uniformity, followed by a cylinder. Chamchong and Datta (1999b) studied the effect of

shape and aspect-ratio on thawing time and non-uniform heating. They reported that volume and aspect ratio had significant effects on heating rate, thawing time, and non-uniform heating. It was recommended from their work that flattening the load (small thickness) for a given volume, total energy absorbed in the load becomes higher. Therefore, small thickness loads will achieve faster heating rates because it is easier for microwave energy to penetrate into the product. It is recommended that product thickness should be less than 2.5 times the microwave penetration depth at the applied frequency.

Chemical composition

Compositions of food products, particularly water and salt content have significantly impact microwave power absorption due to their influence on dielectric properties. The higher the moisture content, the higher the heating rate and vice versa. This is because polarized water molecules align with the changing electric field resulting in increased friction leading to heating. Similar to water, a higher salt content will increase the ionic concentration in the product leading to increased energy absorption in the microwave oven. The product, which has more water and salt content, absorbs most of the energy near the surface of the product and causes "shielding" effect. This means that less microwave energy reaches the center of the product, resulting in non-uniform heating. Thus, food products with high moisture and salt content needs to be designed to have smaller thickness to achieve more uniform heating. George and Burnett (1991) discussed the effects of chemical composition on microwave heating which includes water, fats, carbohydrates, and proteins. Fat is another critical factor in deciding the heating rate of a food product. Fats have low dielectric loss factor; the product with

higher fat content would require more time to heat to reach the desired level of temperature. Gunasekaran et al. (2002) developed a mathematical model to study the effect of different levels of fat content on dielectric properties in ground beef. They observed a decrease in dielectric properties as fat content in ground beef increases at temperatures above 0 °C. However, below 0 °C dielectric properties remain constant irrespective of the fat content. Kress-Rogers and Kent (1987) studied the effect of carbohydrates on microwave heating and found that foods with more carbohydrates will bind to the available amount of water when heated in microwave ovens. Thus, the amount of water molecules available for interaction with the electromagnetic field will be reduced, resulting in slower heating rate. Food proteins tend to bind with water molecules easily like carbohydrates and therefore, the effect of proteins on microwave heating is similar that of carbohydrates

System and process factors

There are several process and microwave oven factors that influence microwave heating. These factors include power level, cycling, standing time, operating frequency, dimensions of the cavity, rotation of the turntable, presence of the mode stirrers, and position of a food in turntable. Power absorbed in food is directly related to the heating rate. Absorbed power is a function of material property and will vary for a frozen state where dielectric properties are totally different from the non-frozen state (Chamchong and Datta, 1999a). An oven's output power from the magnetron is generally different from the rated power by the manufacturer. To understand the problem of non-uniform heating and arcing effect, knowledge of the microwave field strength and the power distribution inside the applicator is essential (Jia and Jolly, 1992). Barringer et al. (1994)

experimentally studied the power absorption of corn oil and water as affected by their volumes in a domestic oven and in a specially modified oven system. They reported that total power absorption in corn oil and water is significantly affected by food volumes and dielectric properties. Zhang and Datta (2003) studied the effect of microwave power absorption in single and multiple foods (ham and frozen vegetable) foods. They reported that the total power absorption generally increases with volume for different shapes as wells as dielectric properties, but in the range of small volume loads power absorption does not have a linear trend. They also reported that relative power absorption in simultaneous heating of two different foods follows the same relationship of foods when heated individually. One of the best ways to improve heating uniformity and heating rate in microwave heating is to adopt power cycling instead of continuous power supply to the cavity (Chamchong and Datta, 1999a). In power cycling, the microwave power is applied to the cavity for a certain amount of time and then turned off to facilitate heat transfer equilibrium and then followed by turning on the power again. By intermittently turning the power off and on, the heat generated due to applied power would be able to diffuse through the material and eventually improve heating uniformity. Chamchong and Datta, (1999a) studied the effect to optimize the power cycling period in solid food as compared to the continuous but reduced power level. Authors concluded that temperature raise and non-uniform heating do not change appreciably for continuous against cycled power when the continuous power was set equal to the time average power. They also found that thawing time decreases when the power level of the microwave oven increases. But, the salty- shield in food develops quickly when it was heated in high power levels, thus time needed for thawing the salt-shielded food takes

longer. When the power level was more than 30 % of maximum power, the salty-shielding effect develops quickly and increases the thawing time.

Improving Heating Uniformity

Microwave heating leaves “hot” and “cold” spots due to complex interaction of electromagnetic equations with a lossy material. Improving microwave heating uniformity has been a real challenge to both microwave oven manufacturers and food processors. Vadivambal et al. (2010) reviewed various studies on microwave heating and identified a research need to improve heating uniformity in microwave ovens. Improving heating uniformity of a microwave food product can be achieved by modifying food composition and geometry (Ryynanen and Ohlsson, 1996). In the past two decades, many serious efforts have been made by researchers to understand the phenomenon of non-uniform heating experimentally and through computer simulation (Wäppling-Raaholt et al., 2006; Knoerzer et al., 2007). In the past, many researchers looked at different factors that affect the heating uniformity in microwave ovens such as food shape (Chamchong and Datta, 1999b; Zhang and Datta, 2005), size (Vilayannur et al., 1998), location of food on a turntable (Wappling-Raaholt and Ohlsson, 2000), dielectric properties of food (Chamchong and Datta, 1999b), and microwave power and cycling (Chamchong and Datta, 1999a). Another promising approach that has been looked at to improve heating uniformity is to combine microwave heating with infrared and/or hot air (Datta and Ni, 2002; Datta et al., 2005). The effects of using variable frequencies for microwave heating (Bows, 1999; Kashyap and Wyslouzil, 1977) and the use of mode stirrers (George and Bergman, 2006) on heating patterns have also been studied to improve heating uniformity. Bows (1999) demonstrated that using the variable frequency

microwave ovens (VFMO), the mean target temperatures of 50,75, and 90°C in a spherical shape foodstuff (90 % water and cellulose structure) at the center plane were achieved within 2 min of heating based on combing 8 discrete frequencies between 2.4 and 6.2 GHz than at a single frequency. Kashyap and Wyslouzil (1977) demonstrated a method to improve the heating uniformity in a thermal wet paper by sweeping the frequency of the magnetron over 2450 ± 50 MHz. They found that sweeping the frequency in the range of 2450 ± 50 MHz gives better heating uniformity than using field stirrer inside the cavity. George and Bergman (2006) demonstrated a modeling approach of using mode stirrers to improve the heating uniformity in a thermal fax paper. Geedipalli et al. (2007) demonstrated through computer simulation techniques that the rotation of the turntable could improve heating uniformity by 40%.

A method to quantify non-uniform heating is required to understand and evaluate the effect of various factors on the heating performance of microwave ovens, which includes heating uniformity. Historically, wet thermal fax paper has been used to demonstrate MW heating non-uniformity in domestic ovens (Bradshaw et al., 1997). The problem with this approach is that one has to use it in an empty cavity. In reality, the presence of a food product inside the microwave oven will alter the electromagnetic field drastically. Moreover, it does not provide a quantitative assessment of heating uniformity. Commercially, there are microwave active compositions (Atlanta Chemical Engineering, Atlanta, GA) available that change color depending upon temperature. Colorant used in the composition loses or gains different color depending on temperature under microwave heating. Response time of the colorant to change in temperature is

short and the spots are well outlined. The major limitation of this approach is that it is again not a quantitative assessment.

In 2007, a chemical marker technique has been used in locating hot and cold spots in industrial microwave sterilization process (Bhuwan et al., 2007). To quantify the color change, the authors developed a computer vision system to measure the temperature inside a model food product. James et al. (2002) developed a methodology for assessing the heating performance of domestic microwave ovens using a set of quick response thermocouples. A 350 g of water poured in a PET tray was used to assess the heating performance in six microwave ovens in the range of 600 to 1000 W. The PET tray (173 × 35 mm) designed to cover a small region in a turntable. Swain et al. (2008) developed a test procedure to characterize the performance of domestic microwave ovens for heating of a food simulant. They used food simulant (171× 127 × 35 mm) made of TX151 powder (Weatherford Inc., Aberdeen, Scotland), a hydrophilic polymer and a hedgehog of 39 quick response thermocouples to study the heating performance of domestic microwave ovens. In their study, only seven microwave ovens were considered in the range of power output from 800 to 1000 W. Their study did not include higher power microwave ovens. IEC 60705 standard suggests to use a square container (228 mm × 228 mm × 30 mm) made of material transparent to microwaves for measuring the performance of microwave ovens (IEC, 1999). The square container is divided into 25 compartments in which 1000 g water is poured to measure the microwave heating non-uniformity. The compartment separators have a small hole approximately positioned in center of them to allow the water flow from one compartment to another. In this method, a microwave oven’s percentage of variations in heating uniformity measured by the

difference in highest and lowest temperature raise of 25 compartments over the average temperature raise of 25 compartments. Wang et al. (2008) designed a test rig consisting of an array of 24 plexiglass cups filled with water and an array of 24 thermocouples to assess non-uniform heating in a radio frequency heating system. They also used a foam sheet to evaluate non-uniform heating of the radio frequency system using an infrared camera. Thermal imaging is an industry standard tool for assessing heating uniformity of products at the end of the microwave heating process. The only limitation in using a thermal imaging system is that it only provides surface temperature.

Modeling of Microwave Heating

MW heating process has been mathematically modeled using analytical and numerical techniques. Studies related to the modeling of the microwave heating process started with Ohlsson and Bengtsson (1971). They used the finite-difference time-domain technique to model microwave heating in infinite slabs of salted ham and beef. Temperature profiles from numerical model prediction and experimental measurement compared favorably using spatial profiles. In earlier studies, microwave heat transfer model were performed using analytical methods (Shou-Zheng and Han-Kui, 1988; Watanabe et al., 1978). With the advent of powerful computing technologies, solutions of microwave heating can be obtained by using different numerical methods such as finite-difference time-domain (FDTD) method (Dincov et al., 2004; Ma et al., 1995) and finite element method (FEM) (Zhang and 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 a set of Maxwell's

equations for the electromagnetic field (Ni et al., 1999; Zhou et al., 1995; Campanone and Zaritzky, 2005). Due to variation in geometry and dielectric properties of foods, modeling consists of solving specific and limited problems in microwave heating. However, modeling can be a useful tool to study the effect of modeling parameters influencing microwave heating. Accurate modeling of microwave heating process requires bringing the most effective methods for solving both electromagnetism and thermodynamics (Kopyt and Celuch, 2006). An ideal numerical tool should integrate all the physical processes involved in the microwave heating problem like electromagnetics, thermodynamics and flow dynamics. There is no single modeling tool available to include all the effects as a package. However, there are separate software packages available to take care of each physical phenomenon (Kopyt and Gwarek, 2004).

Up to now, electromagnetic modeling has been performed by trial-and-error procedure (Knoerzer et al., 2006). This situation arises due to a lack of understanding of non-uniform heating and complicated interactions of microwaves with food involving electromagnetism and heat and mass transfer. Knoerzer et al. (2006) mentioned that it is impossible to predict realistic temperatures or even electromagnetic field distributions inside a microwave oven when foods are involved. Thus, modeling requires partial-differential equations of electromagnetic waves and heat transfer to be solved in a coupled approach to minimize the variation in simulation results. The following sections will discuss in more detail the modeling of microwave heating and the challenges in developing an accurate model.

Necessity of Modeling

The main reasons for performing modeling in microwave heating are as follows: 1) understanding non-uniform heating of microwave heated food products. 2) addressing the effect of various variables in absorption of power. 3) integrating with microbial destruction model to assess food safety risk. 4) validating cooking instructions for NRTE food products.

Challenges in Microwave Heating Modeling

Microwave heating has been described as challenging to model because, 1) dielectric properties and thermal properties of food change with temperature and frequency, which reduces the accuracy of any model using constant data. 2) so far, complete microwave heating physics has not included in a single package to solve for real scenarios of microwave heating. 3) it is difficult to construct the model, which takes into account actual microwave oven reflection and refraction to the food material. 4) geometry of microwave oven structure cannot be created in a realistic manner in most of the available commercial numerical softwares. 5) electromagnetic solvers have not been designed to couple with external optimizer tools to adjust the scenarios of microwave heating based on outcome of the solution.

Electromagnetic Field Models

The three-dimensional electromagnetic fields are varying in space and time. Several numerical techniques are available to solve Maxwell's equations to get the power dissipation term. Solving for electromagnetic equations requires optimization of electromagnetic parameters such as resonance frequency and electric field strength

(Mechenova and Yakovlev, 2004). The solution of electromagnetic models requires intensive computation with the discretization of whole model domain into small cells. A discretized cell, “mesh”, can be represented in Cartesian, spherical, or cylindrical coordinates. The typical case of the discretized cell of Cartesian coordinates for popular FDTD and FEM methods is shown in Figure 2.5. The main difference in implementing these two methods for solving electromagnetic and thermal fields is location of the points where corresponding fields are solved. The FDTD based solver consists of rectangular structured mesh with the option of conformal boundary condition. The field for example thermal is calculated at center of each mesh (T_A, T_B, T_C, T_D). To get the field value at nodal points of the mesh in FDTD method, external interpolation functions has to be defined to find the nodal field values. But, the FEM method solves the field in the nodes of the each mesh. Electromagnetic field equations of differential forms are applied to each mesh for calculating electric field strength based on properties assigned for that cell and adjacent cells. The solution of electromagnetic equations requires a large number of iterations for each time step for meeting the criteria of convergence. In solving for field distributions in a small enclosed space like a microwave cavity, the metal walls of the model provide a boundary for the solution regime. The interactions at the conducting walls are typically accounted for boundary conditions where electric field will not exist. Because metallic walls of the cavity are coated with a material that reflects almost all the incident microwave energy as a result there will not be any temperature rise in the walls of the cavity. The calculated electric field strength, E (V/m) is used as an input to determine the dissipated power density (W/m^3) using Eqn.2.5. Chapman et al. (1993) developed 3-D FDTD based electromagnetic model to calculate the resonant frequency

and a Q factor (a dimensionless parameter, which is ratio of energy stored in the resonator to the energy supplied by the generator per cycle) in a cavity, and the specific absorption ratio (SAR) distribution in the sample. Xiaowei et al. (2010) recently developed a procedure for optimizing and calculating electromagnetic field distributions based on microwave oven cavity design and excitation of power.

Heat Transfer Models

Applied microwave energy is converted into power based on the electric field distribution at a particular location. The absorbed power term is considered a source term in heat transfer equations to calculate transient temperature profile. The equation governing diffusion of heat into a conductor (i.e. food) is as follows:

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + P_v\,(x,y,z,t) \qquad (2.9)$$

where ρ is the density (kg/m^3), C_p is the specific heat at constant pressure (kJ/kg °C), k is the thermal conductivity (W/m°C), $\frac{\partial T}{\partial t}$ is the change in temperature over time, and P_v is the power absorbed in the load over volume (W). For the system under consideration, the boundary condition is relatively simple and is prescribed by the heat balance through radiation into the environment.

$$-k\widehat{n}.\ \nabla T = (T^4 - T_\infty^4)\sigma_s\varepsilon_s \qquad (2.10)$$

where ε_s is the surface emissivity, σ_s is the Stefan-Boltzmann constant (5.670×10^{-8} J s^{-1} m^{-2} K^{-4}, and T_∞ is the ambient temperature (°C). Typically, the convective effect is ignored because the thermally induced free convection inside the microwave cavity is negligible (Akarapu et al., 2004).

To calculate the temperature profile in a material, the heat transfer equations require initial temperature (T_i) of the product, boundary conditions of the domain, and material properties. Several kinds of boundary conditions are used with Eqn.2.9 to model various physical scenarios. The Dirichlet condition requires that temperature at the boundary should be explicitly mentioned. The Neumann boundary condition assumes that the heat flow through a boundary is declared, while the Robin condition, known as the convective boundary condition, is a combination of these two. The transient heat transfer equations can be solved using either explicit or implicit formulations of numerical methods. To know more about the formulations, readers are suggested to refer to a discussion on computational techniques of finite difference method (Özişik, 1994). The accuracy of the heat transfer analysis relies on selecting an optimized time step for heating. The choice of heating time step (Δt) at each thermal iteration influences convergence and rate of convergence of solution (Celuch et al., 2006). The heating time step and mesh size are inter related with each other in deciding the error bounds of the numerical computation. The level of dispersion depends on the direction of propagation, time step, and mesh size. To get better simulation results, the numerical techniques should meet the criteria of courant stability. The courant stability factor is calculated by the following equation for the case of homogeneous, lossless, and equidistant meshes (Taflove and Hagness, 2000):

$$\mathrm{r} = \mathrm{v}\left(\frac{\Delta \mathrm{t}}{\mathrm{a}}\right) \qquad (2.11)$$

where v is the phase velocity of the medium (m/s), Δt is the heating time step (s), r is the courant stability criteria factor, and a is represents equal size of mesh in all three

directions in Cartesian coordinates ($a = \Delta x = \Delta y = \Delta z$). The courant criteria dictates that factor r be $\geq 3^{0.5}$ for stable operation of the numerical algorithm.

Basak (1997) reported that the effective heat capacity (enthalpy) is the best suited method to analyze the thawing of heterogeneous material over the range of temperature. Swami (1982) used the finite difference method to describe microwave heating of cylindrical and rectangular shaped high moisture foods. The model predicted temperature distribution was in good agreement with experimental measurements for gel samples of high moisture content and different salt concentrations. Wei et al. (1985) conducted heat and mass transfer analysis during microwave heating in porous medium, water-filled sandstone. The model predicted temperatures and moisture profiles that compared favorably with experimental values. Chen et al. (1993) derived and incorporated a heat generation term into an axisymmetric finite element model to analyze temperature distribution within a cylinder-shaped potato particulate.

Coupled Electromagnetic and Thermal Models

Electromagnetic and thermal phenomena often encountered in microwave heating should be solved in a coupled approach because the power dissipation calculated from electromagnetism influences other physical phenomenon, such as heat transfer and evaporation in heated foods (Bengtsson and Ohlson, 1974), and phase changes during microwave thawing (Basak and Ayappa, 1997). These physical situations cause rapid changes in material properties, which in turn makes the problem highly non-linear. Thus, non-linear problem of microwave heating needs to be approached as coupled electromagnetic and heat transfer equations in a cyclic manner. In a coupled approach,

multiphysics of microwave heating is separated into two consecutive parts and solved using appropriate modeling methods. At each time step, updated information of electric field distribution is used as an input to calculate temperature rise in the material using heat transfer equations. The temperature rise in the product will alter the thermo-physical and dielectric properties. These altered properties will be fed to the electromagnetic part to calculate the new electromagnetic field. This process will be continued until the total heating time is reached. The process of coupling electromagnetic and heat transfer effects in microwave heating is shown in Figure 2.6. Accurate modeling of microwave heating process requires bringing together the most effective numerical methods for solving both electromagnetics and thermodynamics. The most two common methods widely applied are: Finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM). The FDTD based algorithms are typically applied in electromagnetic solving because it requires only reasonable time and computer resource, whereas the FEM is widely applied for solving thermal problems due to less computation time required compared to electromagnetic problems. Zhang and Datta (2000) developed a methodology for coupling electromagnetics and heat transfer in the analysis of microwave heating using two finite element based softwares and mentioned that coupling of electromagnetism and heat transfer should be needed when the dielectric properties of the product change significantly with temperature. Wappling-Raaholt et al. (2002) successfully implemented coupled numerical solver with a custom developed MATLAB based program. In this study, authors used the Fourier heat conduction equation with a convective boundary condition on food-air interface. Akarapu et al. (2004) have developed algorithms to couple the electromagnetic and thermal equations mutually and

one-way. Mutual coupling has been approached when the thermo-physical properties are temperature dependent. One-way coupling has been applied when the properties are temperature independent. Real frozen cheese sauce heated in a microwave oven was modeled successfully using a coupled approach (Tilford et al. 2007). In this study, the authors accounted for the phase change effect with the placement of sauce in the center and at an offset in the rotating turntable.

Numerical Methods

There have been many numerical methods developed and implemented in electromagnetic software packages to develop predictive model for microwave heating process. The most predominant numerical methods used for electromagnetic field equations are as follows: Finite-Difference-Time-Domain (FDTD), Finite Element Method (FEM), Finite Volume Method (FVM), Transmission Line Method (TLM), and Method of Moments (MOM), Boundary Element Method (BEM), Asymptotic-Expansion Methods (AEM), and Partial Element Equivalent Method (PEEC). In most situations, space and time discrete numerical methods are used to solve for electromagnetic Maxwell's equations. Niziolek (2009) reviewed the available numerical methods for electromagnetic simulation with each of its strengths and weakness. He mentioned that in real world problems, it is difficult to find a method for all physical problems thus hybrid methods (combination of two methods) would be useful. The Finite Difference Time Domain (FDTD) and Finite Element Method (FEM) are the numerical methods adopted mostly in electromagnetic solving problems. Traditionally, Transmission Line Method (TLM) and Method of Moments (MOM) methods are used in microwave power

engineering applications, but are less powerful and flexible for other applications (Yakovlev, 2001b).

Available Software

Computational techniques and numerical methods have been developed to solve electromagnetic equations over time. Though there have been computer simulation techniques developed for solving microwave power engineering problems, non-communications engineers lack an understanding of the physics of microwave heating. Yakovlev (2001b; 2001c; 2006) has extensively summarized the available softwares capable of modeling microwave heating problems and noted that conformal FDTD based QuickWave and Microwave studio (MWS) softwares effective for modeling microwave heating. Curet et al. (2006) studied the microwave thawing of a piece of tylose using COMSOL Multiphysics software where the heating due to microwave is introduced in the heat equation solved by both Maxwell’s law and Lambert’s law separately. More recently, exchanging information between two different numerical methods in two different softwares has also been made possible. For example, one numerical software solves electromagnetic equations and another one solves heat transfer equations. This exchange of information between softwares enables the inclusion of all the physical phenomena in microwave heating. Knoerzer et al. (2007) developed a user-friendly MATLAB based interface to couple two prominent software packages namely QuickWave and COMSOL Multiphysics. Some customized softwares are also developed using object oriented programming languages to couple the electromagnetic–heat transfer equations. It is also possible that commercial software can be coupled to custom-built

software. Pandit and Prasad (2003) studied the possibility of linking finite element based software with their own C code.

Yakovlev (2006) compared different electromagnetic softwares, which included Multiphysics by ANSYS, Quickwave 3-D by QWED, EMC20000-VF by Matra Systems, and Microwave Studio by CST, to see the potential of those softwares to extract electromagnetic parameters such as electric field distributions, S-parameters, and patterns of the specific absorption rate (SAR). Author sets benchmark for this work at 2.45 GHz frequency and concluded that conformal FDTD based solver Quickwave 3-D appeared as quite adequate and beneficial for engineers.

Microwave Heating Modeling Approach

Microwave heating modeling has been performed by trail-and-error procedure. Because of the interdisciplinary nature of microwave processing and complicated interactions of electromagnetism with heat and mass transfer, it is easy to understand why the electromagnetic solvers are solving the microwave heating problem by simplifying the problem with several assumptions such as considering simple microwave oven cavity and solving the problem using Lambert’s law approximation. Calculation of temperature and electromagnetic field distributions inside the cavity and treated product is complicated because of solving coupled governing partial differential equations of electromagnetism with heat and mass transfer. In earlier days, due to the lack of powerful computers and computational techniques, it was impossible to model the coupled partial differential equations (Knoerzer et al., 2008). Recent advances in development of computational techniques and numerical algorithms have made it easy to

develop predictive-modeling, which will describe the real process. Although microwave modeling has been available since the 1980's, it is still in its infancy. Nowadays, in order to design thermal process operations, knowledge about the temperature distribution during heating treatment inside a microwave cavity is required. Government regulators require information on temperature distribution of the food product to regulate and approve the process design and scale-up the process to market. Computer aided modeling can be a tool to meet the requirements (Knoerzer et al., 2008). The challenge is how soon researchers can learn and adopt the modeling theory and technology in a simple and holistic way to make an improvement in microwave food products and processes.

Cornell University

Modeling in domestic microwave oven heating was pioneered by a group of scientists lead by Dr. Ashim K. Datta at Cornell University. His research group is instrumental in developing modeling techniques for microwave oven heating. In his lab, research on microwave heating modeling evolved from analytical approaches to numerical approaches. Effect of geometric shape and applied power were systematically studied for model food (Chamchong and Datta, 1999a; 1999b). To improve the heating uniformity in microwave heating, the rotation of the load and combination of heating methods were described as important. During only 30 s heating of potato slab, the heating uniformity of the rotated load has increased by 37- 43% while compared to the stationary load. It was observed that heating uniformity of the rotated load does not improve in different planes along the vertical axis of the potato. Thus, it was suggested that heating uniformity can be achieved better in different profiles when the system is designed to move the food top and bottom (Geedipalli et al., 2007). Datta and Ni (2002)

studied the possibility of incorporating infrared and hot air with microwave heating to reduce moisture build up in a surface profile at the same time increasing the surface temperature. When comparing the combination heating with microwave-only heating, combination heating provides an opportunity to alleviate inherent problems of pressure-driven moisture build-up at the surface of high moisture foods. Ni et al. (1999) studied the moisture loss due to evaporation and related that to heating uniformity. In this study, authors concluded that when the surface area increases for a given volume, the uniformity of heating increases but the total moisture loss reduces. Finite element based ANSYS software primarily used in their research work. Sterilization of solid foods using microwaves was modeled using numerical techniques (Zhang et al., 2001). Using the time-temperature history and first order thermal kinetics, spatial distributions of thermal-time representing the sterilization process was calculated.

Warsaw University of Technology

Finite difference time domain based numerical methods are more popular in application of solving electromagnetic equations. A research group at the Institute of Radioelectronics, Warsaw University of Technology, Poland has developed a software platform for solving microwave power problems. The developed software (QuickWave 3D) is capable of modeling rotating and horizontally moving foods while heated in a microwave oven. Celuch and Gwarek (2000) summarized the advanced features of the FDTD method in microwave power applications. Authors have discussed the conformal geometry models, field excitation techniques, and parameter extraction procedure techniques. A main advantage of the recent algorithm development is that conformal FDTD meshing helps to design curved sloped and boundary edges of complicated food

shapes. QuickWave 3D software can be easily coupled with external software to solve the multiphysics of microwave heating. Kopyt and Celuch (2006) have presented studies on coupling the FDTD based software with FVTD and FEM based softwares.
This hybrid technique of solving microwave power problems was necessary for accurate modeling. To improve the heating rates in microwave food products, susceptors, a thin metal film placed inside the food packages was recently used. Modeling a microwave heating problem with susceptors adds more complexity to problem solving since metal properties would be influenced by the electromagnetic field. Typically, the susceptor's thickness is about 10 μm. In addition to the complexity of designing such a small thickness, the susceptors are semi-transparent to the electromagnetic fields at microwave frequency. Celuch et al. (2009) have discussed the possibility of modeling microwave heating with the presence of susceptors. Kopyt and Celuch (2003; 2007) have demonstrated the coupling of electromagnetic solver with two separate external thermal solvers. Accuracy of the model prediction was observed to be similar in both cases.

Optimization of Modeling

Before validating a microwave heating model, simulation of microwave heating needs to be optimized for electromagnetic and computational parameters. Electromagnetic models of microwave power problems are subjected to numerical error unless the parameters of electromagnetic fields and computational variables are optimized. Therefore, the complex interactions of electromagnetic fields with food need to be subjected to numerical optimization process. This optimization process for each electromagnetic and thermal parameter can be easily done using a computational platform. To be able to develop the electric field patterns and calculate accurate power

absorption during each heating time step in electromagnetic simulation, electromagnetic field iterations need to reach steady state (Kopyt and Celuch, 2003). It is important to choose the correct heating time step (Δt) at each thermal iteration to determine the convergence and the rate of convergence of the simulation (Celuch et al., 2006).

The choice of time step should be neither too big nor too small. In case of a too big heating time step, immediate divergence of the temperature fields would occur, whereas in case of a too small heating time step, the convergence of temperature fields would be reached but at the expense of a longer simulation time. Mesh size optimization is important for obtaining better simulation results. Reducing the mesh size by half brings the space discretization errors down by a factor of four. However, it should also be mentioned that the computing time will increase 16-fold and memory occupation will increase 8-fold. Electromagnetic simulation in a dielectric material typically requires about 8 to 10 cells per wavelength (Akarapu et al., 2004). The magnetron (microwave source) is an imperfect device which changes its operating frequency depending on reflection coefficient (S_{11}) and even jumps from one operating frequency to over a tens of MHz (Buffler and Risman, 2000). The instantaneous frequency emitted by a magnetron in a microwave oven depends on two parameters: The cathode-anode voltage and the high frequency output impedance of the magnetron which is set by the load (Ghammaz et al., 2003). Yakovlev (2006) mentioned that typically the deviation range of the magnetron operating frequency is about 50 MHz. Therefore, it must be important to study the reflection coefficient over a frequency band to ensure stability in the operation and efficiency of the microwave system.

Summary

There are several published reports on microwave heating modeling. However, the heat transfer models have not been integrated to assess food safety and risk assessment. Most researchers consider the cavity as a simple box with defined applied microwave energy. In reality, modern microwave oven design has many intriguing elements inside the cavity to change the electric field distribution. Therefore, the design platform should have the option for designing such intriguing microwave geometry. Numerical methods applied for microwave power problems are subjected to dispersive errors which makes the simulation solutions unrealistic. Therefore, the numerical methods and variables of microwave oven should be optimized with external optimizer tools. A single modeling platform should be developed to take care of complete heat and mass transfer involved in microwave heating instead relying on coupling different numerical softwares for solving those heat and mass transfer equations. The definition of the model parameters should be well-outlined in each modeling tool in order to define the correct value of the parameters for the simulation. It is highly necessary to develop feed-back control modules for modeling tools to re-work the simulation results for multiple constraints of variables.

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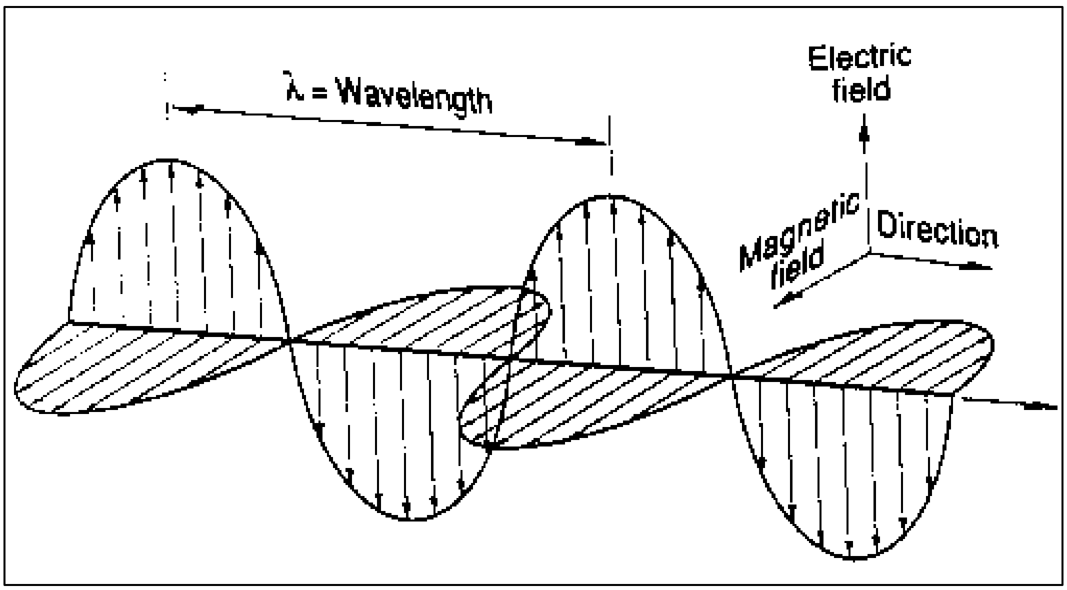

Figure 2.1. Direction of electromagnetic field propagation with electric and magnetic field.

Courtesy: http://www.tutorvista.com/physics/electromagnetic-radiation-field

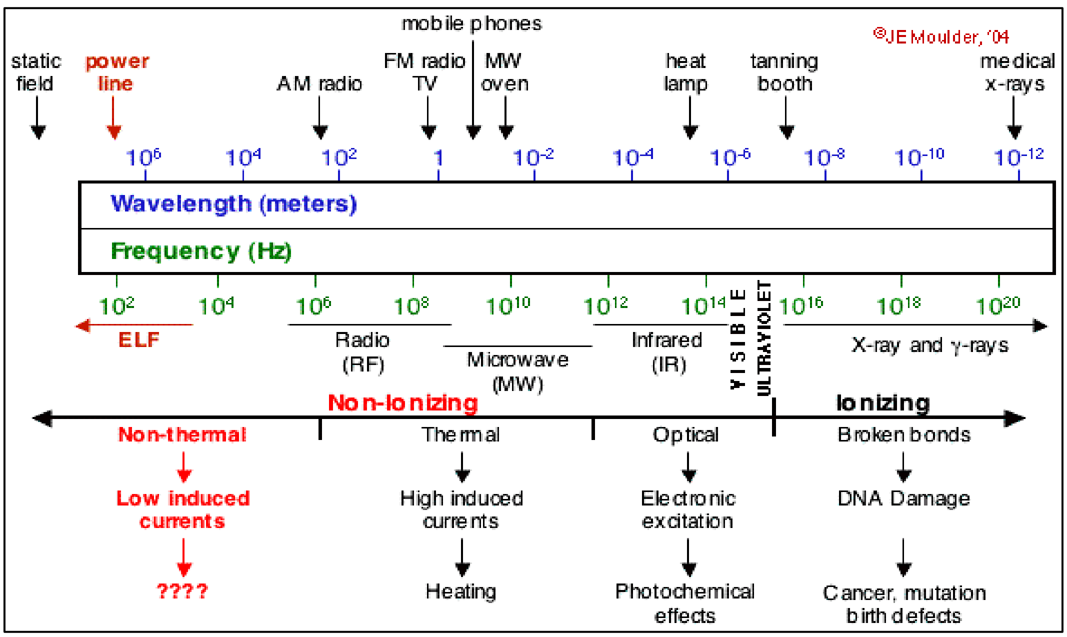

Figure 2.2. Electromagnetic spectrum.

Courtesy: University of Virginia, Charlottesville

http://faculty.virginia.edu/consciousness/new_page_5.htm

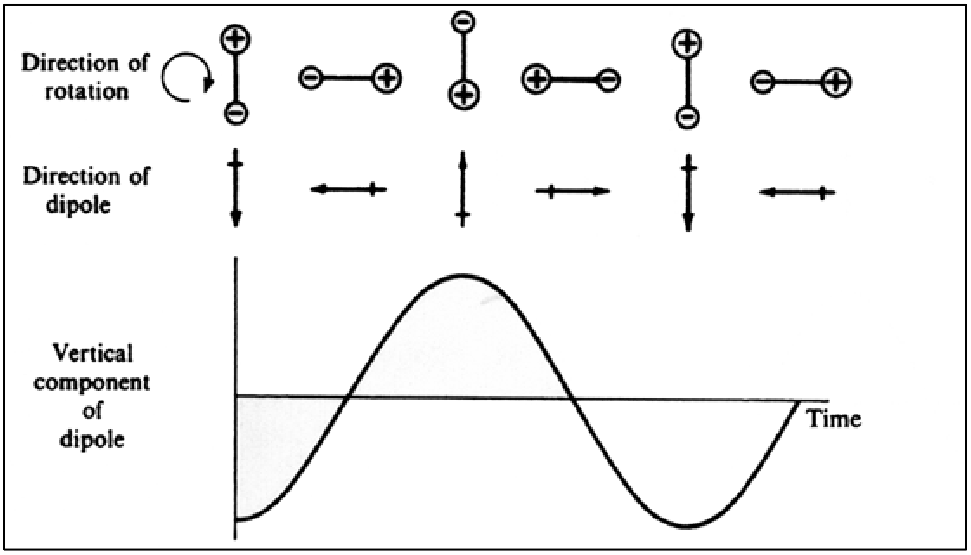

Figure 2.3. Variation of microwave propagation in time.

Courtesy: University of Guelph, Guelph, Canada.

http://131.104.156.23/Lectures/CHEM_207/CHEM_207_Intro.htm

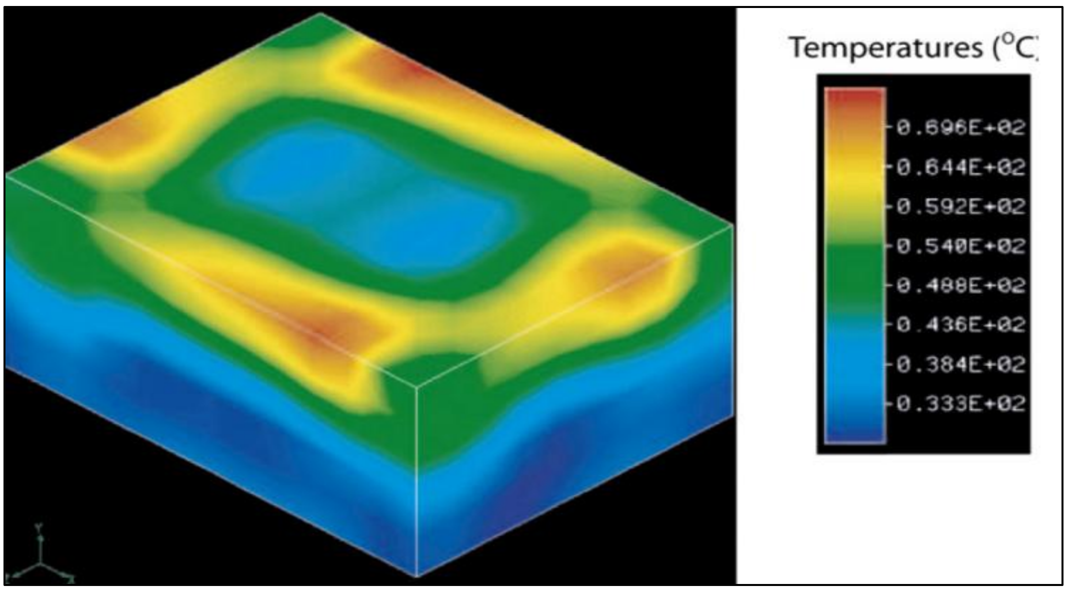

Figure 2.4. Non-uniform distribution of temperature in microwave heated gel.

Courtesy: Geedapalli et al., 2007

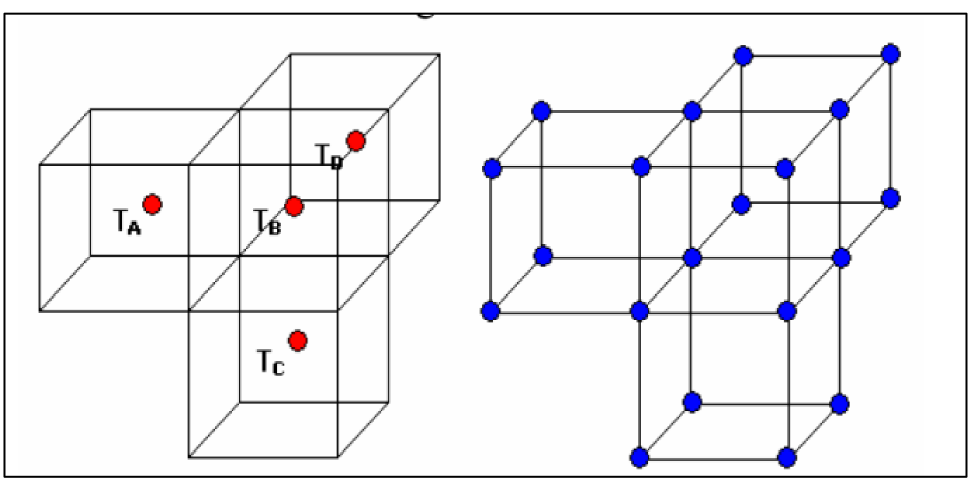

Figure 2.5. Description of temperature calculation in discretized mesh using FDTD (left) and FEM (right) methods.

Courtesy: Kopyt and Celuch, 2004.

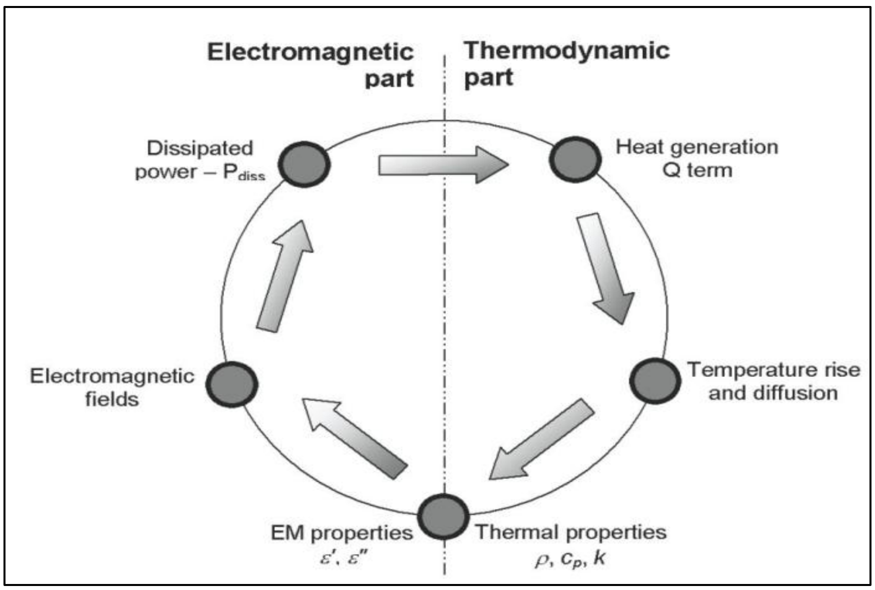

Figure 2.6. Schematic flow chart of coupling electromagnetic and thermal fields.

Courtesy: Kopyt and Celuch, 2007.

Table 2.1. Summary of recent microwave heated product outbreaks.

Product (Company)	Pathogens	Month and Year	Illness impact	Geography of impact	Source
Frozen chicken nuggets	*Salmonella* Heidelberg	March 2003	23 cases	British Columbia, Canada	Leitch, 2008
Banquet pot-pies (ConAgra Foods)	*Salmonella* I 4, [5], 12;i:-	October 2007	401 cases	41 states, USA	Leitch, 2008
Frozen meat pizza (General Mills)	*E.Coli* O157:H7	November 2007	-	10 states, USA	USDA-FSIS, 2007
Frozen pre-browned stuffed chicken (Chicken Kiev and Chicken Cordon Blue of Milford)	*Salmonella*	October 2008	32 cases	12 states, USA	Leitch, 2008
Marie Callender's cheesy chicken & rice (ConAgra Foods)	*Salmonella* Chester	June 2010	29 cases	14 states, USA	USDA-FSIS, 2010

Table 2.2. List of numerical methods available for modeling microwave power problems.

Numerical Method	Advantages	Limitations	Applied software	Applied research work in microwave power engineering
Finite Difference Time Domain (FDTD)	• Ability to obtain wideband results. • Quick implementation on parallel computers. • Good at modeling inhomogeneous and complex materials. • Computational memory required less.	▪ Errors are dispersive for larger time steps. ▪ Difficult to model thin metal pieces. ▪ Difficult to model materials with frequency dependent properties.	➢ Quickwave 3D 7.5 ➢ Empire XCcel 5.40 ➢ XFDTD 7.0 ➢ FIDELITY 3.0	Ma et al. 1995 Mechenova and Yakovlev, 2004. Celuch and Gwarek, 2007 Kopyt and Celuch, 2003 Kopyt and Celuch, 2004 Kopyt and Celuch,2007 Tilford et al. 2007 Wäppling-Raaholt et al. 2002 Chen et al.2008 Wappling-Raaholt et al. 2006
Finite Element Method (FEM)	• Good at handling complex geometries. • Can handle wide variety of engineering problem. • Easy to implement frequency, thermal, pressure, and force dependent material properties. • Best method for modeling resonant cavities.	▪ It obtains only approximate solution. ▪ Large computational memory required. ▪ Absorbing boundary required for radiation problem.	➢ HFSS 12.0 ➢ Multiphysics 12.1(ANSYS) ➢ COMSOL Multiphysics 4 ➢ Abaqus 6.8 ➢ LS-DYNA (also available in MOM) ➢ EMAS (Ansoft Corp.) ➢ NASTRAN ➢ ALGOR ➢ TWODEPEP (ANSYS)	Kopyt and Celuch, 2004 Kopyt and Celuch,2006 Ehlers and Metaxas, 2007 Zhang et al. 2001 Zhang and Datta, 2003 Akarapu et al. 2004 Pandit and Prasad, 2003 Huo and Li, 2005 Zhou et al. 1995
Transmission Line Method (TLM)	• Analysis is performed in time domain. • Absorbing boundary condition can be easily modeled. • System explicitly solved.	▪ Requires more computer memory than FDTD method.	➢ MEFiSTo-3D Pro 2 ➢ Micro-Stripes 5.6	-

Finite Volume Method (FVM)	• It is well suited for implementing in unstructured meshes. • Electromagnetic field values calculated for a small volume which represents more accurate value of the small domain. • It is well suited for flow dynamics equation solving.	▪ Dispersive errors more in surface integrals.	➢ Fluent 13.0 ➢ EMC2000-VF ➢ FLOW-3D 8.2 ➢ CFX 4.3 ➢ PHOENICS	Kopyt and Gwarek, 2004 Kopyt and Celuch,2006 Kopyt and Celuch,2007 Verboven et al. 2003 Dincov et al. 2004
Method of Moments (MOM)	• It can be used to solve a wide range of equations involving linear operations. • It is highly useful method to solve large and dense matrix equations.	▪ It is only best suited to solve for linear equations not for non-linear problems.	➢ CONCEPT II 8.0	-
Boundary Element Method (BEM)	• Accurate modeling of infinite and semi-infinite domains. • Discretization required only for boundary not for entire domain.	▪ It does not model well for inhomogeneous or complex materials. ▪ Not good for modeling the problems that combine small details geometries with larger objects. ▪ Practical application not well established.	➢ LS-DYNA	Huo and Li, 2005

Table 2.3. List of numerical solvers available for modeling electromagnetic and thermal fields.

Simulation package (Electromagnetic and Thermal)	Numerical method	Features	Vendor	Applied research work in microwave power problem	Applications
High Frequency Structure Simulator (HFSS) 12.0*	FEM	• Automated solution process. • Fast and accurate s-parameter extractions. • Automatic mesh generation and adaptive refinement. • Domain decomposition (a job can be distributed into multiple network computers). • Adoption of curvilinear elements and mixed element orders.	Ansoft Corp. www.ansoft.com	-	▪ Microwave and radio frequency analysis ▪ Signal integrity and chip development
Multiphysics 12.1**	FEM	• Unified simulation environment for solving multi –physics disciplines. • Importing CAD geometries. • Support for parallel processing. • Support for dissimilar mesh interface between physics models. • Includes non-linear geometric effects.	ANSYS Inc. www.ansys.com	Yakovlev,2001a Geedipalli et al., 2007	▪ High frequency electromagnetic analysis ▪ Thermal and fluid flow analysis ▪ Structural analysis ▪ Circuit design ▪ Acoustics
Microwave studio 5.0*	FIT	• Perfect boundary approximation. • Multilevel subgriding scheme. • Optimization strategies for multiple parameters.	Computer Simulation Technology (CST) www.cst.com	Yakovlev,2001a Akhtar et al. 2008	▪ Microwaves and radio frequency ▪ Statics and low frequency ▪ Biomedical ▪ Signal integrity
Empire XCcel 5.40*	FDTD	• Frequency dependent loss modeling. • 3D arbitrary shape import/export. • Multi-core CPU supports. • Object parameterization.	IMST, GmbH www.imst.com	-	▪ Microwave and radio frequency component design ▪ Antenna design

		• 3-D video display of field distributions.			▪ Circuit design ▪ Automobile industry
XFDTD 7.0*	FDTD	• GPU acceleration for fast computing. • Script library to automate the modeling. • Complete parameterization control. • Customizable results browser. • Designed to run Windows, Mac OS X, and Linux platform (only EM software compatible to all platform)	Remcom Inc. www.remcom.com	-	▪ Antenna design ▪ Microwave circuits design ▪ Wireless communications ▪ Lens design
COMSOL Multiphysics 4.0**	FEM	• Global definition of model variables. • Streamlined model builder. • In-built model library for common applications. • Sweeping parameter geometry. • Options for parallel computing. • More boundary conditions options for thermal analysis.	COMSOL Inc. www.comsol.com	Curet et al. 2006 Romano et al. 2005 Knoerzer et al. 2008	▪ Chemical Engineering ▪ Microwave and radio frequency power engineering ▪ Acoustics ▪ Earth science ▪ Batteries and fuel cell design
QuickWave 3D 7.5**	FDTD	• Conformal FDTD meshing. • Parameterization of model geometry. • Coupling to computational fluid dynamics software. • Importing CAD figures. • Options for multi-simulation. • S-parameter extraction.	Qwed Sp. Z.o.o. www.qwed.com.pl.	Mechenova and Yakovlev, 2004 Celuch and Gwarek, 2007 Kopyt and Celuch, 2004 Kopyt and Celuch, 2003 Yakovlev,2001a Tilford et al. 2007 Chen et al.2008 Knoerzer et al. 2008	▪ Microwave power engineering ▪ Antenna design

ANSYS Fluent 13.0***	FVM	• Unstructured mesh can be adopted for complex objects. • Dynamic and moving mesh adoption. • Parallel processing with other CFD platforms. • Options for exporting simulations in data and animations format.	ANSYS Inc., www.ansys.com	Kopyt and Gwarek, 2004 Kopyt and Celuch,2006 Kopyt and Celuch,2007	▪ Fluid flow analysis ▪ Thermal analysis ▪ Acoustics
Abaqus 6.8***	FEM	• Structural finite element analysis (FEA) (same model information can be used for multiple physics). • Direct coupling to 3rd party software and independent-code.	Dassault Systems www.simulia.com	-	▪ Structural Analysis ▪ Automobile Industry ▪ Electrical circuit analysis ▪ Flow dynamics ▪ Acoustics

FDTD – Finite Difference Time Domain Method; FEM – Finite Element Method; FVM- Finite Volume Method; FIT- Finite Integration Technique. * - Electromagnetic solver; ** - Electromagnetic and thermal solver; *** - Flow dynamics solver.

CHAPTER III

COUPLED ELECTROMAGNETIC AND HEAT TRANSFER MODEL FOR MICROWAVE HEATING IN DOMESTIC OVENS

Abstract

Microwave (MW) ovens are used extensively for heating a variety of not-ready-to-eat food products. It is vital to achieve target temperature uniformly throughout the food to inactivate foodborne pathogens to assure safety. Non-uniform heating of foods in microwave ovens is the major concern in assuring microbiological safety of such products. The non-uniform heating of foods in domestic microwave ovens is due to complex interactions of microwaves with foods. A comprehensive coupled electromagnetic and heat transfer model was developed using finite-difference time-domain based numerical method to understand the complex interaction of microwaves with foods. Simulation parameters such as cell size, heating time step, number of iterations for steady state electromagnetic field were optimized. The coupled model was validated by heating a cylindrical model food (1% gellan gel) for 30 s in a microwave oven (700 W). The model was validated qualitatively by measuring the product temperature profiles on three planes in the gel and compared to the thermal images. Quantitative validation was performed by measuring the temperature of the gel at 12 locations using fiber optic sensors. Model spatial temperature profiles agreed well with the thermal image profiles at 2.45 GHz frequency. The root mean square error values ranged from 0.53 to 4.52°C, with an average value of 2.02°C.

Keywords: Microwave heating, modeling, FDTD method, heat transfer, prediction.

Introduction

Because of rapid and convenient heating offered by microwave ovens, it has become a favorite kitchen appliance in American households. Microwave (MW) heating takes place in dielectric materials due to the polarization effect of electromagnetic radiation at frequencies between 300 MHz and 300 GHz (wavelength (λ) : 0.01-1 m). MW energy interacts with food products and generates heating due to molecular friction caused by dipolar rotation of polar solvent such as water present in food product. The dipolar rotation during microwave heating is caused due to changes in electrical and magnetic fields over discrete time.

Recent foodborne illness outbreaks and recalls associated with microwave heated packaged frozen foods have resulted in the food industry reviewing microwavable food product development. The main issue with most of the non-ready-to-eat foods is the non-uniform heating of foods in a microwave oven. Non-uniform heating in food products heated in a domestic microwave oven is due to: (1) interference of electromagnetic waves resulting in hot and cold spots, and (2) variation in dielectric, physical, and thermal properties of food components, which results in uneven absorption of microwave energy and subsequent heat dissipation. Not-ready-to-eat (NRTE) food products should be cooked thoroughly as some ingredients are not fully cooked and may contain foodborne pathogens. Therefore, temperature of microwave-heated foods must be raised at all locations to temperatures that will ensure inactivation of microorganisms.

A significant difference in dielectric properties of ice and liquid water causes non-uniform heating of frozen foods heated in a microwave oven. Typically, frozen segments of the food absorbs less MW energy (×1000) compared to the thawed food portion because dielectric properties of ice are much less than that of liquid water (Chamchong and Datta, 1999 a, b). In a multi-mode enclosure such as an oven cavity, electric field distribution is highly sensitive to changes in the dielectric and thermal properties of foods. Current methods for designing of foods for microwave heating are based on trial and error. A systematic study and computer simulation of microwave heating of foods allows for proper design of foods to assure microbial safety.

Over the last two decades, with the availability of powerful computational power and development of efficient numerical methods, computer simulation is becoming a promising tool to understand microwave heating. Extensive modeling efforts have been made to simulate microwave heating using simple analytical approaches (Watanabe et al., 1978) to computational approaches solved using numerical methods.
Researchers have made assumptions to simplify the problem and reduce the computational time. These simplifications in modeling have not captured real scenarios of microwave heating. For example, instead of modeling Maxwell's equation, several researchers simplified the problem by using Lambert’s law, which calculates dissipated power by assuming that the energy decays in the food exponentially from the material surface to center in a single dimension (Campañone and Zaritzky, 2005; Chamchong and Datta, 1999a, b; Chen et al., 1993; Khraisheh et al., 1997; Zhou et al., 1995). Lambert’s law does not represent the true electromagnetic field distribution inside the MW oven cavity completely (Datta and Anantheswaran, 2001). There have been several studies in

the past compared the Maxwell's equation with Lambert's law equation in predicting temperature field of microwave heating (Yang and Gunasekaran, 2004; Curet et al., 2006; Liu et al., 2005). Liu et al. (2005) stated that although Lambert's law is not appropriate for microwave power processing, its simplified numerical results are comparable with the experimental methods. Maxwell's equations are more accurate than Lambert's law in calculating power dissipation in a food material (Yang and Gunasekaran, 2004).

Localized microwave heat dissipation in the foods is diffused by conduction and convection inside and outside the food (Ohlsson et al., 1974; Basak and Ayappa, 1997). The dynamic physical situations cause rapid changes in material properties, which in turn make the problem non-linear. Therefore, the non-linear problem of microwave heating needs to be solved by coupling electromagnetic and heat transfer equations.
Model that couple electromagnetic and thermal equations to calculate temperature field of microwave-heated foods have been reported (Dincov et al., 2004; Geedipalli et al., 2007; Wäppling-Raaholt et al., 2002; Zhang and Datta, 2000, 2003). These models are solved iteratively using various numerical methods such as finite-difference time-domain (FDTD) (Tilford et al., 2007) and finite element method (FEM) (Zhang and Datta, 2000; Curcio et al., 2008). Several techniques, potentially capable of making the temperature field more uniform have been modeled, including: rotation of the load (Kopyt and Celuch, 2003), mode stirrers (Plaza-Gonzalez et al., 2005), sample movement (Pedreno-Molina et al., 2007), design of the load and/or its container (Wappling-Raaholt and Moret, 2006). Geedipalli et al. (2007) modeled the heating of a rotating raw potato in a microwave oven. In this model, they assumed constant dielectric properties of the potato and studied the effect of rotation while the object is at the center of the turntable.

Most of the microwave modeling research did not focus on optimizing the simulation parameters and does not describe the selection of model. Solving for electromagnetic equations require optimization of electromagnetic parameters such as frequency, electric field strength, and reflection from the cavity (Mechenova and Yakovlev, 2004). Xiaowei et al. (2010) recently developed a procedure for optimizing and calculating electromagnetic field distributions in microwave oven cavity with a specific MW excitation power. It is crucial to develop a computer model which is less susceptible to numerical errors (arising from poor discretization of time and space domain). Therefore, use of numerical simulation of microwave heating with optimized model parameters can provide an accurate prediction of time-temperature profile.

So far, researchers have assumed that a microwave oven is just a simple cavity in which the port is located at certain place of cavity wall. A closer 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 systematic simulation studies. In modern microwave ovens, geometric features such as metal bumps, dimples, turntable crevices, and input port configuration have been introduced to improve heating uniformity. Each of these features of the microwave oven can dramatically change the electric field distribution inside the cavity. Therefore, a simulation model should include all the features rather than considering as the oven as a simple cavity with a waveguide.

In this study, a comprehensive coupled electromagnetic (EM) and heat transfer model was developed using a commercial software Quickwave v7.5 (QWED Sp.z o.o., Warsaw, Poland) based on finite-difference time-domain method. Electromagnetic and computational parameters of microwave heating such as heating time step, cell size,

frequency and electric field strength were optimized and used for model validation. The specific objectives of this study were to:

i. develop a holistic coupled electromagnetic and heat transfer model for domestic microwave heating using finite-difference time-domain (FDTD) based numerical method.
ii. optimize the electromagnetic and computational parameters of the developed model, and
iii. validate the developed model using a food system.

Materials and Methods

Electromagnetic field equations

The microwave heating of a food material inside the oven is governed by a set of four Maxwell's equations.

$$\nabla \times E = j\omega\mu H \qquad (3.1a)$$

$$\nabla \times H = -j\omega\varepsilon_0\varepsilon^* E \qquad (3.1b)$$

$$\nabla . E = 0 \qquad (3.1c)$$

$$\nabla . H = 0 \qquad (3.1d)$$

where E and H are the time-harmonic electric and magnetic fields, respectively. $\nabla\times$ is the curl operator that describes rotation of a vector field in 3-dimensional space, $\nabla.$ is the divergence operator that measures magnitude of a field at given point, ω is the angular frequency (rads/s), ε_0 is the free space permittivity (8.854×10^{-12} F/m), ε^* is the complex dielectric permittivity, and μ is the permeability (H/m). The boundary condition of

metallic waveguide walls are considered as perfect electric conductors, where the following boundary condition applies

$$E_{tangential} = 0 \qquad (3.2)$$

The microwave power absorbed in a food material is proportional to the dielectric loss factor (ε'') and square of electric field strength. An electromagnetic wave losses its energy when travelling through a lossy dielectric medium. The part of the electromagnetic power was converted into thermal energy within the medium. Conversion of electromagnetic energy into thermal energy is governed by the following equation (Goldblith, 1967).

$$P_v = 2\pi f \varepsilon_0 \, \varepsilon'' E^2 \qquad (3.3)$$

where P_v is the dissipated power per unit volume (W/m^3), f is the frequency of electromagnetic wave (Hz), ε'' is the relative dielectric loss factor, ε_0 is the permittivity of free space (8.854×10^{-12} F/m), and E is the electric field strength (V/m) in food. The dielectric loss in a material due to electric conductivity (σ, S/m) is given by:

$$\varepsilon'' = \frac{\sigma}{2\,\pi\,\epsilon_o f} \qquad (3.4)$$

Heat transfer equations

The microwave dissipated power term (P_v, W/m^3) is considered as source term in transient heat transfer equations given by:

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + P_v\,(x,y,z,t) \qquad (3.5)$$

where ρ is the density (kg/m^3) , C_p is the specific heat capacity at constant pressure (kJ/kg °C) , k is the thermal conductivity (W/m °C) , and T is the temperature (°C) at time t.

The surface of the food exchanges heat with surrounding air by convention expressed as

$$-k\frac{\partial T}{\partial n} = h\,(T - T_a) \qquad (3.6)$$

where 'n' represents the normal direction to the surface, h is the surface convective heat transfer coefficient (W/ m^2/°C), T_a is the ambient temperature (°C) and T is the transient temperature (°C).

When evaporative losses from the surface are significant, the evaporative losses term in heat transfer equations needs to be included. In general, the evaporative loss is considered as minimal when surface temperature of the food below 70°C, hence it can be negligible. Heat loss to the air from the load was approximated by assuming heat transfer coefficient of value 10 W/m^2/°C which is quite often used in natural convective heat transfer in air (Tong and Lund, 1993). To make sure this assumption is valid we turned off the air going inside the cavity, which insured that natural convection is taking place at air-material inference. If the air flow goes into the cavity, then the simple convective heat transfer boundary is not valid on the entire air-object interface as the surfaces in front of the air will have higher heat transfer coefficient than the surfaces opposite to it (Verboven et al., 2003). To model with airflow to the cavity, we need to solve the energy and momentum transfer equations for entire cavity.

Simulation model development

Differential form of electromagnetic equations, Maxwell's equations, for calculating electric field (E) distribution inside the cavity with irregular objects as load cannot be solved merely by analytical methods. Therefore, dynamically varying electromagnetic fields inside the cavity need to be solved using numerical methods. Several numerical techniques are available to solve the Maxwell's equations to get power dissipation term inside the load. With the advent of powerful computing technologies and efficient numerical methods such as finite-difference time-domain (FDTD) method and finite element method (FEM), it is possible to solve the Maxwell's equation. In this study, conformal FDTD based electromagnetic software, QuickWave 3D v7.5 (QWED Sp z o.o, Warsaw, Poland) was used to solve the coupled electromagnetic and heat transfer model. Basic heating module of the software was used to predict transient temperature in load. The main reason for choosing Quickwave 3D software was its efficient electromagnetic field simulation and ability to parameterize the model domain and properties. As with other commercial softwares, modeling requires creating geometric model, assigning material properties, meshing, selecting solver parameters, and post-processing as outlined in Figure 3.1.

Model geometry

In QuickWave software, the geometry of the model can be developed using the text enabled parameterized macros called user defined object (UDO) script. This feature allows the user to define the model dimensions in a script file. The file execution in the software creates the entire model geometry. In this study, a UDO script was customized to create the required microwave oven model with all the features such as crevices, metal

bumps, waveguide, port and magnetron as coaxial feed in a single executable file format. This special UDO feature becomes handy when there is a need to study microwave heating characteristics of the same object in different types of microwave ovens. Figure 3.2 shows geometric model developed using UDO script for 700 W rated power (629 W available power) microwave oven (Sharp Electronics Corp., New Jersey, USA) with an operating frequency of 2.45 GHz. The microwave oven (395 × 420 × 253 mm) included a magnetron, a turntable, a waveguide, crevices (bottom of the cavity) and a metal bump. The port that provides microwave energy to the cavity was located on top of one side of the microwave oven cavity. The port was connected to a magnetron through a waveguide on the other side of the cavity. The waveguide had cross-sectional dimensions of 80 mm (width) × 40 mm (height) and a length of 290 mm. A 10 mm thick glass turntable (dielectric constant of 6 with zero dielectric loss factor) was located at the bottom of cavity. Figure 3.2A shows the geometric model that has the power source as a rectangular port feed, whereas the Figure 3.2B shows the same geometric model with magnetron as a coaxial feed to the waveguide.

Input variables

QuickWave 3D software has two functional parts: Editor and Simulator. The Editor part defines the geometry of the microwave oven. It is also used to define simulation input parameters such as excitation mode, waveform, frequency, electric field strength, medium properties, meshing, and enabling post-processing data. The Simulator is a conformal FDTD solver, which solves electromagnetic and thermal fields. A starting point in defining the simulation inputs is to provide the medium properties. Each medium in the computation domain is defined with electromagnetic and thermal

properties. Electromagnetic and thermal properties of the medium are defined in a text file format called parameterized macro object (pmo) file and properties are defined as a function of independent variable such as temperature or enthalpy. The choice of an independent variable depends on the physical state of food material subjected for microwave heating. For example, in the state of freezing to thawing, providing the medium properties as function of temperature is not desirable. During this phase change, enthalpy in the medium increases much more while temperature remains nearly constant. Therefore, the medium properties should be defined as a function of enthalpy density. Simulations are performed directly for the enthalpy field as a non-linear model, which means that enthalpy field was updated every iteration instead of temperature. Using the enthalpy and temperature relation in the pmo file, the new temperature field is linearly interpolated.

Coupled simulation

Solving coupled non-linear Maxwell's equations and heat transfer equations requires iterative computational techniques to perform the simulation. Differential form of electromagnetic field equations are applied to each grid for calculating electric field strength based on properties assigned for that grid and adjacent grids. The solution of electromagnetic equations requires a large number of iterations for obtaining steady state field at each time step. The steady state electric field is reached, when the difference of electric field strength calculated at two consecutive iterations at any point in the domain is less than 0.25% of the electric field strength calculated in previous iteration (Quickwave, 2008). In solving for field distributions in a small-enclosed space like a microwave cavity, the metal walls of the model provide a perfect electric conductor

boundary for the solution regime. The interactions of electromagnetic field with the conducting walls yield zero electric field intensity at wall surface. The calculated electric field strength (E) is applied as an input to determine the dissipated power density (W/m^3) using Eqn.3.3. In heat transfer analysis, new enthalpy fields (H^{new}) are updated in every time step using the following relation:

$$H^{new}(x,y,z) = H^{old}(x,y,z) + P_v(x, y, z)\,\Delta t \qquad (3.7)$$

where Δt is the heating time step (s), P_v is the average power density (W/cm^3), H^{old} is the enthalpy density field of previous time step (J/cm^3) , and H^{new} is the enthalpy density field of current time step (J/cm^3). The new temperature field (T^{new}) in the medium is interpolated using the updated enthalpy.

$$T^{new}(x,y,z) = T\,[H^{new}(x,y,z)] \qquad (3.8)$$

In the current time step, thermal properties of the medium are updated with respect to change in the temperature field. As a sequence, new EM properties are calculated based on the new temperature field and used to calculate new electromagnetic fields and microwave power source term. This cyclical process continues until a desired heating time is reached. A flow chart given in Figure 3.3 describes the execution of the above-mentioned coupled process.

Post-processing

The temperature field of the entire computational domain is saved at every time step. Simulated spatial temperature profiles and discrete-point temperatures were extracted using a routine developed in MATLAB R2010a (The MathWorks Inc., Massachusetts, MA, USA). The post-processing option in the editor window was

enabled to collect scattering parameters in a range of 2.4 to 2.5 GHz frequency at 5 MHz interval.

Experimental Studies

Magnetron power

Power output of a magnetron is required to calculate electric field strength (E). The International Electrotechnical Commission (IEC) method involves heating of 1,000 g water load for 60 s in a glass container for calculating power output of domestic microwave ovens. This protocol assumes that there is no reflection of microwave energy from the cavity and all the power delivered by the magnetron is fully absorbed by the load. This assumption is valid as a large amount of water (a highly lossy medium) is used as a load in the microwave oven. Power output of a microwave oven is calculated using the following equation (IEC, 1999).

$$P = \frac{C_{pw} m_w (T_2 - T_1) + C_{pg} m_c (T_2 - T_0)}{t} \quad (3.9)$$

where P is the microwave power output (W), C_{pw} is the specific heat of water (4.186 J/g °C), m_w is the mass of water (g), C_{pg} is the specific heat of glass container (0.55 J/g °C), m_c is the mass of container (g), T_0 is the ambient temperature (°C), T_1 is the initial temperature of water (°C), T_2 is the final temperature of water (°C),and t is the total heating time (s).

Three replications were performed with the interval of 6 h between replications allowing the magnetron to cool down to room temperature. The average microwave power output calculated was 629 W, which is 90% of original rated power.

Model food preparation

A homogeneous, cylindrical shaped gellan gel was used for model validation. To evaluate the accuracy of the model, it was desired to have a model food with consistent dielectric and thermal properties. One percent gellan gum powder (Kelcogel, Kelco Division of Merck and Co., San Diego, CA), a fermented polysaccharide plant tissue powder, was dissolved in deionized water gradually and the solution was heated to 90°C in about 15 min. $CaCl_2$ (0.17%) was added to the hot gellan gum solution to form a firm gel. Hot gel solution was then poured into a cylindrical container and allowed to cool at room temperature for 30 min to ensure solid gel formation (Birla et al., 2008). The prepared gel was stored at ~4°C in a closed container. The cylindrical gel had a diameter of 80 mm with a height of 50 mm (volume of 251.42 cm^3).

Dielectric properties

There are several methods available to measure dielectric properties of agricultural and biological materials. Venkatesh and Raghavan (2004) extensively reviewed the available methods to measure dielectric properties. The dielectric properties of 1% gellan gel was measured using an Agilent Technologies™ N5230A PNA-L Vector Network Analyzer (VNA) attached to an open-ended coaxial high temperature probe (Agilent 85070E-020) with a two-port electronic calibration (ECal) module (Agilent, Model N4691-6004). Only one port of the VNA's was used and calibrated using the ECal module, and then the probe was subsequently calibrated using the references air/short/water protocol before each measurement session (Blackham and Pollard, 2002). The VNA was configured to take measurements at 201 linearly spaced points between 10 and 3000 MHz frequency. Dielectric properties were measured from 10 to 80°C at every

10 °C interval. Three readings were taken at each temperature point and the average reading was reported. Figure 3.4 shows the relationship of dielectric properties with respect to temperature. As the temperature increases, dielectric constant decreases linearly whereas dielectric loss factor decreases exponentially. The dielectric properties of 1% gellan gel as a function of temperature can be predicted using the equations given in Table 2.1.

Thermophysical properties

The heat transfer equation uses thermal and physical properties in calculating transient temperature field. Thermal and physical properties are considered as isotropic which means that properties do not change with 3-dimensional direction. In addition to dielectric properties, the input file for simulation was provided with thermal conductivity, specific heat, and density. Thermal properties of the gellan gel and glass turntable used in this study are given in Table 2.1.

Microwave heating

The gellan gel samples stored in a refrigerator were removed from the container and left outside for 4 h to equilibrate to ambient temperature. A gel sample was placed in the center of the glass turntable (366 (D) × 10 (H) mm). The sample was subjected to 30 s heating with full power operation without any rotation of the turntable. The experiment was triplicated at 6 h interval to ensure the cold start of magnetron each time.

Temperature recording

Transient temperature at twelve points was recorded using fiber optic sensors (4-channel reflex signal conditioner, accuracy ±0.8°C, Neoptix Inc., Quebec, Canada) as

shown in Figure 3.5. Because, the instrument had only 4-channels to measure the temperatures, the experiments were repeated three times to get transient temperatures at 12 locations. To visualize spatial variation of temperature in gellan gel after heating, a thermal imaging camera (SC640, accuracy ±2°C, FLIR systems, Boston, MA) with a resolution of 640× 480 pixels was used to record thermal image profiles of three layers. Immediately after MW heating, the thermal images of top and bottom of gel cylinder were taken using the camera. Then, the sample was sliced horizontally in the middle (25 mm from top) to obtain image at the middle plane. The camera parameters such as emissivity, distance between the lens and the object, and ambient temperature were set before the experiments. The distance between the lens and the object was set at 37 cm and kept constant throughout the experiments. A stand-alone software, FLIR ThermaCAM™ Researcher v2.9, was used to acquire thermal images of the heated gel samples.

Results and Discussion

Solution of electromagnetic field is prone to numerical errors when appropriate simulation parameters are not set correctly. Therefore, it is critical to conduct a study to determine optimum simulation parameters to minimize the numerical errors. In this study, simulation variables such as number of iterations to reach steady state, cell size, heating time step, magnetron frequency, electric field strength, electromagnetic mode and power input were studied to identify their optimum values. The simulations were performed on a Dell Precision 690 workstation with an operating memory of 24GB RAM running on Quad-core Intel Xeon clocked at 2.93 GHz frequency processor. Figure 3.6 shows a flow chart of the parameter selection process performed in this study.

Iterations for electromagnetic steady state

Solving electromagnetic field equations typically requires a large number of iterations to obtain steady state electromagnetic field strength values, which do not change with subsequent iterations. It is an important parameter for accurate prediction of temperature (Kopyt and Celuch, 2003). The electric field will stabilize with increasing iterations and therefore the temperature at any point in the domain will stabilize. In this study, simulations were carried out with increasing number of electromagnetic periods(N_p) (amount of time needed to complete one cycle of electromagnetic wave while propagating in medium = 1/frequency = 0.40 ns) from 50 to 450 with the interval of 50 periods to find minimum number of periods needed for stable temperature. The relationship of electromagnetic periods (T_p) to the number of iterations is described in the following relation:

$$N_p \times T_p = N \times dt \qquad (3.10)$$

where N is the number of iterations needed for reaching a steady state, and dt is the electromagnetic time step (ns). The dt is automatically calculated by the software by taking account of the smallest cell size in the computational domain to obey the Courant stability criteria. For a 3-D problem, the electromagnetic time step has to fulfill the following condition

$$dt = \frac{a}{c \times r} \qquad (3.11)$$

where a denotes the effective size of the smallest cell in (m) calculated $\sqrt{\frac{dx^2+dy^2+dz^2}{3}}$, dx, dy, dz denote the sizes in x, y, z direction of the smallest cell, c is the speed of light

(3×10^8 m/s), and r is a stability factor which should be equal to or greater than three for 3D problems. Using the Eqn. 3.10, each electromagnetic period (T_p) is multiplied by N_p and then divided by electromagnetic time step (dt), which was 0.00166 ns (calculated by the software) to find the number of iterations for the corresponding period.

Figure 3.7 shows that with an increasing number of iterations, the temperature increases and reaches steady state after certain number of iterations which means that no significant change in temperature occurs at all four selected locations in the load. After 200 periods, the change in temperature was negligible at the center of the model domain (location 2). In the other three locations in the domain, the temperature stabilizes. Therefore, it was concluded that electromagnetic steady state has reached at 200 periods (51,012 iterations) and this value was used in the rest of the simulation.

Heating time step

Appropriate selection of heating time step (Δt) is an important factor in balancing the computation time and accuracy of temperature prediction (Celuch et al., 2006). The choice of time step should be neither too big nor too small. In the case of a too big heating time step, immediate divergence of the temperature fields would occur, whereas in the case of too small, the convergence of temperature field would be reached but at the expense of longer simulation time. Therefore, to optimize Δt, the simulations were performed for the total heating time of 30 s with time steps ranging from 1 to 30 s. Average dissipated power in the gellan gel load was calculated for each time step. Normalized power absorption (NPA) was defined as a ratio of average simulated dissipated power to the power absorbed by the 1000 g of water load experimentally calculated using IEC method (Zhang and Datta, 2003).

$$\text{NPA} = \frac{P_{\text{simualted}}}{P_{\text{IEC method}}} \tag{3.12}$$

When the value of NPA does not change with further refining of the time step, then the simulated temperature is considered independent of the time step. Figure 3.8 shows that increasing time steps from 4 to 30 s results in a decrease in the NPA value. Reducing the time step from 4 to 1 s does not change the NPA value much. Therefore, the time step could be selected somewhere between 4 and 1 s. In this work, time step of 2 s was further used in the simulation in order to have sufficient number of predicted temperature points to compare with experimental temperature profile.

Cell size

Cell size optimization is an important step in obtaining reasonable simulation results. Reducing the cell size by half brings the space discretization errors down by a factor of four. However, it should also be mentioned that the computing time will increase by almost 16 times and memory requirement will increase by 8 times (QuickWave, 2008). The QuickWave software manual suggests that 12 cells per wavelength in the air (λ = 12.22 cm) domain is good enough for cell independent results. The FDTD method rule of thumb (Eqn. 3.13) suggests to use ten cells per wavelength in the dielectric medium (Pathak et al., 2003).

$$\text{Cell size} \leq \frac{c}{10\, f \sqrt{\epsilon}} \tag{3.13}$$

where f is the frequency (Hz), c is the velocity of light (3×10^8 m/s), and ϵ is the permittivity of the medium (for gel it is ~78).

However, electromagnetic simulation in a dielectric material (gellan gel in this study) typically requires about 8 to 10 cells per wavelength. The wavelength of microwaves in gel is 13 mm and therefore the cell size should be less than 1.3 mm. In this study, cell size in the air domain was set at 5 mm (for example cavity size in x direction is 395 mm which gives 79 cells in air). Figure 3.9 shows the meshing scheme used in this study in 2-dimensional direction in x-y (top view) and y-z (front view) planes. In the gellan gel domain, the effect of cell size along the x, y and z direction in the range of 1 to 6 mm on power absorption was studied. The simulations were performed with 2.45 GHz frequency sinusoidal excitation (meaning that EM wave had a single frequency) to study the effect of cell size on the normalized power absorption.

Figure 3.10 shows the effect of cell size on normalized power absorption in the gel. The cell size interval from 1 to 4 mm did not have much variation in microwave power absorption. However, the normalized power absorption in the load drops drastically from 0.78 to 0.64 when cell size changes from 4 mm to 5 mm cell size. Table 3.2 summarize the information of number of cells, memory required, normalized power absorption, and % difference. Changing the cell size from 1 to 3 mm gave more or less the same normalized power absorption and percent difference error was much smaller than 2% (Table 3.2). However, the normalized power absorption calculated for 1 mm (0.84) was slightly higher than the NPA at 2 and 3 mm (0.83 and 0.81, respectively). Therefore, 1 mm cell size in gellan gel was selected for model validation.

Electromagnetic mode

An electromagnetic wave travels with certain patterns (modes) in the waveguide governed by the frequency and waveguide dimensions. When the power is excited at one

end of the waveguide, the electromagnetic waves would assume traverse electric (TE) or traverse magnetic (TM) modes based on cross-section of the waveguide. However, when the waveguide dimensions are short and not in regular shape, such modes do not fully develop in the waveguide. So far, in the literature only TE (most often TE_{10}) and TM modes have been used to assign at port boundary assuming the waveguide is rectangular and infinite long. While simulating, microwave field distribution scattering parameters (S_{11}) provides a measure of reflected power to the magnetron power output to the cavity were also simulated in a frequency range of 2.4 to 2.5 GHz. This frequency range covers the frequency spectrum of a domestic magnetron. The dimensions of the port allows either TEM or TE_{10} modes and will not allow the TM mode to develop. Therefore, both TEM and TE_{10} modes were evaluated in this study. Figure 3.11 compares the simulated scattering parameters calculated in two input port conditions viz. co-axial feed (TEM) and TE_{10} mode. In case of the TE_{10} mode, the reflected power is slightly higher than that of TEM mode throughout the frequency spectrum. It gives the indication that in TEM mode electromagnetic energy couples much better than TE_{10} mode with the load. Interestingly in both type of feed conditions, the deep resonance (least value of s11) was found to occur at the same frequency, which is at 2.46 GHz. The co-axial feeding in a microwave oven represents actual scenario. Therefore, in this study TEM mode was used for model validation. In our microwave oven, the waveguide is relatively large and rectangular and therefore simulation using either mode should produce similar results. In modern microwave ovens, the waveguides are short and often not in rectangular shape and therefore TEM mode is more appropriate than other electromagnetic modes.

Electric field strength

In a microwave oven, a magnetron generates electromagnetic waves and feeds into the cavity through a waveguide. The magnetron output frequency and power depend on the impedance of the heating load placed on the turntable. It is essential to know the exact magnetron power output for providing correct value of electric field strength (E) at the feeding port. Value of E was estimated empirically by (Soltysiak et al., 2008):

$$E = \sqrt{\frac{2 \times P_m}{(1-|S_{11}|^2)}} \qquad (3.14)$$

where E is the electric field strength (V/cm), P_m is the power output of a magnetron (W), and S_{11} is the reflection coefficient as a function of frequency.

The impedance mismatch of the load leads to reflect some energy back to the magnetron, which can be seen in the plot of reflection coefficient versus frequency (Figure 3.11). The original IEC standard suggests using 1000 g of water load. As the gel mass was 250 g, the IEC method was modified to calculate microwave power absorption in 250 g of water load, which had the same 0.17% salt content as that of the gellan gel. The microwave power calculated for 250 g of water load was 508.11 W. The S_{11} parameters extracted for 250 g of water as a function of frequency is shown in Figure 3.12. The deepest resonance for this load size is found at 2.458 GHz frequency (S_{11} = 0.243). Using Eqn.3.17, the electric field strength (E_1) is calculated as 32.90 V/cm for 250 g water load at 2.458 GHz frequency.

To validate that the electric field strength calculated using the empirical Eqn. 3.14, the calculated electric field strength (E_1) at 2.458 GHz frequency was applied to simulate 250 g of water and power absorbed in the water load was calculated from

simulation results. The calculated power can be used to adjust the electric field strength so that the new electric field strength will make the simulation energy absorbed by the load equal to the energy absorbed by the load measured experimentally using the modified IEC method. As power is proportional to the square of the electric field strength, the following relationship is used to determine the new electric field strength so that energy absorbed by the load in simulation matches the energy absorbed the load measured experimental. The electrical field strength (E_1 = 32.90 V/cm) was used in the simulation, which resulted in the power absorption ($P_{similuated}$). The new electric field strength (E_2) was determined to match the power determined by modified IEC method ($P_{IEC\ method}$) was calculated using the following relationship:

$$\frac{P_{IEC\ method}}{P_{simulated}} = \frac{{E_2}^2}{{E_1}^2} \qquad (3.15)$$

The calculated (E_2) value was then used in the gellan gel simulation. The above correction procedure was repeated for different frequencies, because the power absorption and reflecting power varies with magnetron operating frequency.

Magnetron frequency

Initially, monochromatic frequency of 2.458 GHz was used as input to the model with sinusoidal waveform excitation; however mismatch of predicted and observed temperature profiles prompted us to evaluate the effect of frequencies on the heating pattern. The instantaneous frequency emitted by a magnetron in a microwave oven depends on two parameters: cathode-anode voltage and the high frequency output impedance of the magnetron which is set by the load (Ghammaz et al., 2003). Changes in dielectric properties with temperature causes change in the load impedance, which in

turn shifts the frequency of the magnetron. The frequency shift not only changes the heating rate but also changes the field distribution (Celuch and Kopyt, 2009). Yakovlev (2006) mentioned that a typical magnetron operating frequency deviates about 50 MHz.

Figure 3.12 shows the deep resonance at 2.458 MHz for 250 g gel load. Stipulated frequency for household magnetrons is 2.45 GHz. Therefore, the computer simulations were performed with sinusoidal excitation for three monochromatic frequencies: 2.450, 2.455, and 2.458 GHz individually. Simulated temperature profiles obtained for these frequencies were compared with the experimental temperature profiles and root mean square error (RMSE) was calculated as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_p\text{-}T_0)^2} \tag{3.16}$$

where T_p is the predicted temperature, T_o is the observed temperature, and n is the number of data points on the time-temperature profile. Figure 3.13 shows the spatial temperature profiles collected at three planes for the three frequencies (2.45, 2.455 and 2.458 GHz) compared with the experimental profile. It is quite evident from Figure 3.13 that locations of hot and cold spots changes with change in magnetron frequency.

Model Validation

After establishing the model and selecting the appropriate model simulation parameters, the simulated spatial and temporal profiles were compared with the experimental profiles. Model parameters used for validation study are shown in Table 3.3. A separate simulation was performed by exactly using those parameters as input to the model.

Spatial temperature profile

Spatial simulated temperature profiles of the gellan gel cylinder at three planes (z = 0, 25, and 50 mm) were compared with experimental heating profiles obtained using the thermal imaging camera. Figure 3.13 shows the simulated and experimental temperature profiles obtained at three planes. It is evident that simulated temperature profiles were higher than the experimental profiles. The major cause of the error could be the time lapse between end of heating and imaging. However, the heating patterns of experimental profiles at top (z = 0 mm) and bottom (z = 50 mm) planes match those simulated profiles at 2.45 GHz frequency. The middle image (z = 25 mm) has a smudge effect on experiment profiles that may be due to slicing of the gellan gel sample. Because of the smudge effect, heating pattern in the middle thermal image implies more uniform heating. Zhang and Datta (2000) developed a coupled electromagnetic and heat transfer model for microwave heating of potato cylinder to 15 s heating. They had collected spatial temperature profiles at three planes (top, bottom and front).
The predicted spatial profiles of their study at top and bottom planes heating pattern were not close to the experimental profiles. They reported that the maximum temperature difference at top and bottom planes are 4°C and 12°C, respectively. The reason for not having the close match in heating patterns at top and bottom planes is that when the temperature reaches above 70°C, surface cooling effect would become dominant in high moisture food (more than 80% moisture content food). Gellan gel contains 99% water. However, in our study, when the temperature reaches above 70°C, the predicted profiles at top and bottom planes are much closer to the experimental profiles, when compared to results reported by Zhang and Datta (2000). Similarly, Wäppling-Raaholt et al. (2002)

developed a combined electromagnetic and heat transfer model for heating a rectangular model (TX 151 gel) food to 50 s in microwave combination ovens. Even though, they reported that the maximum temperature achieved in the top plane using simulation agreed well with the maximum temperature observed on the thermal image, the observed temperature pattern on the top plane was profoundly different from the simulated profile. Overall, spatial profiles calculated in this study are closer (in terms of maximum temperature and heating patterns) to the experimental IR images than these previous two studies.

Time-temperature profile

Temporal profiles obtained using fiber optic sensors at twelve discrete points were compared with the simulated temporal profiles. Figure 3.14 compares the observed and simulated temperatures on the top plane at four locations. Even though, the time-temperature profiles were measured at five locations for the middle plane, only time-temperature profiles of four locations were showed in Figure 3.15 due to space constraints. Similarly, Figure 3.16 shows the time-temperature profiles for three remaining locations on the bottom plane. It was observed that it took around 2 s for the microwave power to start after the oven switched on. The root mean square error (RMSE) value was calculated using Eqn.3.16 for each location. Standard deviations of three experimental replications calculated for each discrete time point was plotted in the graph. The RMSE values and final temperature difference calculated for 12 locations at three frequencies (2.45, 2.455, and 2.458 frequency) are given in Table 3.4. Those twelve locations were grouped into three categories based on their location in the load. The average RMSE values were the lowest at 2.455 GHz, while it was slightly higher at

2.45 GHz. The spatial temperature profiles (Figure 3.13) at 2.45 GHz matched more closely to experimental profiles and therefore further discussion on temporal profiles will be done only for the 2.45 GHz frequency simulation. The average RMSE calculated for the top plane ($n = 4$; $z = 10$ to 20 mm) temporal profiles were 2.15°C ± 1.76°C. Whereas, the average RMSE calculated at middle plane ($n = 5$; $z = 25$ mm) and bottom plane ($n = 3$; $z = 30$ to 40 mm) are 2.08°C ± 1.34°C and 1.79°C ± 0.89°C, respectively (refer Table 3.4). The RMSE calculated at close to the top surface (Figure 3.14, location 1, $z = 10$ mm) was 4.52°C. In the center of the model domain, the predicted profile was close to the observed profile with the RMSE value of only 1.04°C. The predicted profile at this location falls within the experimental variation throughout heating time. In the bottom plane ($z = 30$ to 40 mm), the RMSE value ranges from 0.78°C to 2.76°C. Here the simulated profile follows the same heating rate and falls within the variation of experimental throughout heating time except location 7 (refer Figure 3.16) where simulation profile deviates from experimental profile. Tilford et al. (2007) developed a simulation model to predict the temporal profiles in cheesy sauce at eight locations of the food. In their study, the predicted temporal profiles falls close to the observed profiles only in shorter processing time and then deviations gets much higher as processing time is increased with the given complex nature of microwave heating and considering implementation of such scenario in modeling, overall model predictions were reasonably good.

Final temperature difference

The final temperature reached in simulation is an important value in food safety issues, because microbial inactivation rate is much faster at higher temperatures than at

lower temperatures. Table 3.4 shows the final temperature difference calculated at twelve locations for three frequencies simulations. At 2.45 GHz frequency, the average final temperature difference at the top plane (n = 4; z = 10 to 20 mm) was 2.82°C ± 2.04 °C. Whereas, the average final temperature difference at the middle plane (n = 5; z = 25 mm) and bottom plane (n = 3; z = 30 to 40 mm) are 3.85°C ± 2.63°C and 3.30°C ± 1.74°C, respectively (refer Table 3.4). It is important to evaluate whether the model over-predicts or under-predicts at various locations to provide guidelines for microbial inactivation studies. Table 3.5 shows final temperature difference, which calculated by subtracting experimental final temperature from the simulated final temperature at each location. The negative sign indicates over-prediction, whereas positive sign indicates under-prediction. In top and bottom plane, most (5 out of 7) of the locations, the model over-predicts the temperature. On the other hand, in middle plane (n = 5; z = 25 mm) the model under-predicts at 4 out of 5 locations. The selection of electric field strength value assured that the total energy absorbed by the gel during simulation is equal to the experimental value. Because there were over-predictions on the top and bottom plane, the average temperature predictions throughout the gel has to converge to the experimental value, it is reasonable to expect that the model will under predict in the middle plane.

Conclusion

A comprehensive coupled electromagnetic and heat transfer model was developed to simulate microwave heating in domestic oven. The conformal FDTD based numerical method was used to solve electromagnetic Maxwell's equations and Fourier heat transfer equations. In this numerical electromagnetic solver, geometry of the model was

constructed using a user defined script format, which facilitates changing microwave oven parameters quickly for further simulations. Effects of various electromagnetic and computational parameters were studied and the procedure for selecting appropriate value for each parameter was discussed. The computational model was then simulated using the optimized parameters for validation of the model for microwave heating of food.
To validate the model, a gellan gel cylinder was heated for 30 s in a microwave oven. Simulated spatial and temporal profiles were compared with experimental temperature profiles. The model predicted spatial profiles at 2.45 GHz frequency agreed well with the experimental profiles. The predicted temporal profiles were close to the observed temporal profiles with the RMSE value of 2.15 °C, 2.08 °C and 1.79 °C at top, middle, and bottom planes, respectively.

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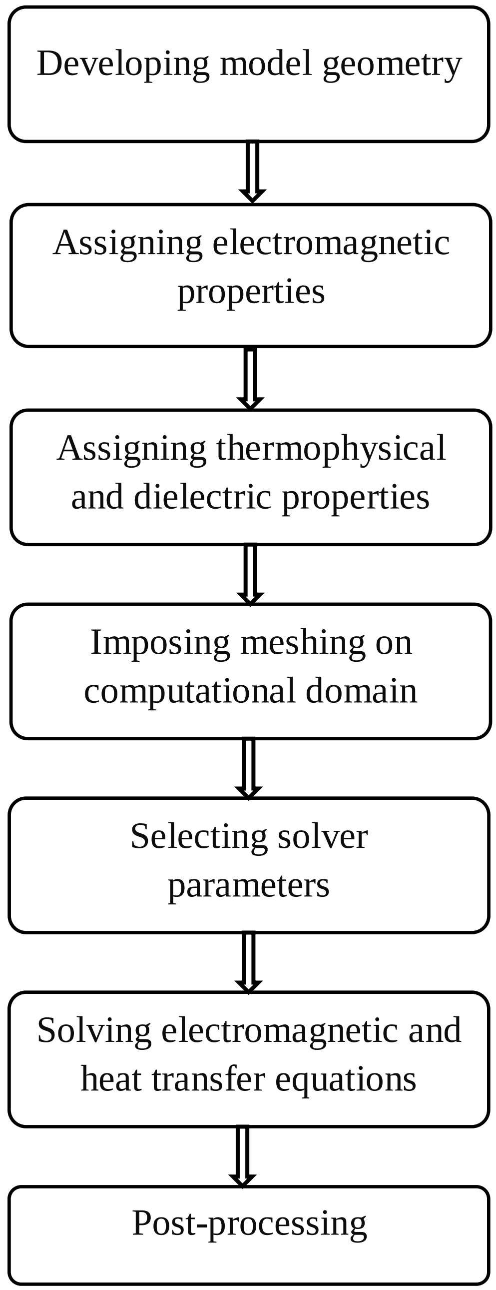
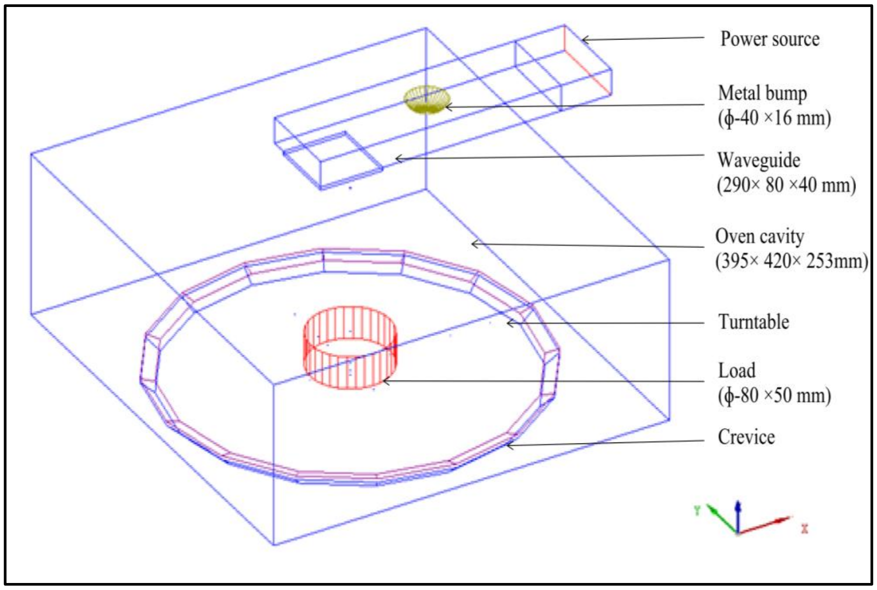
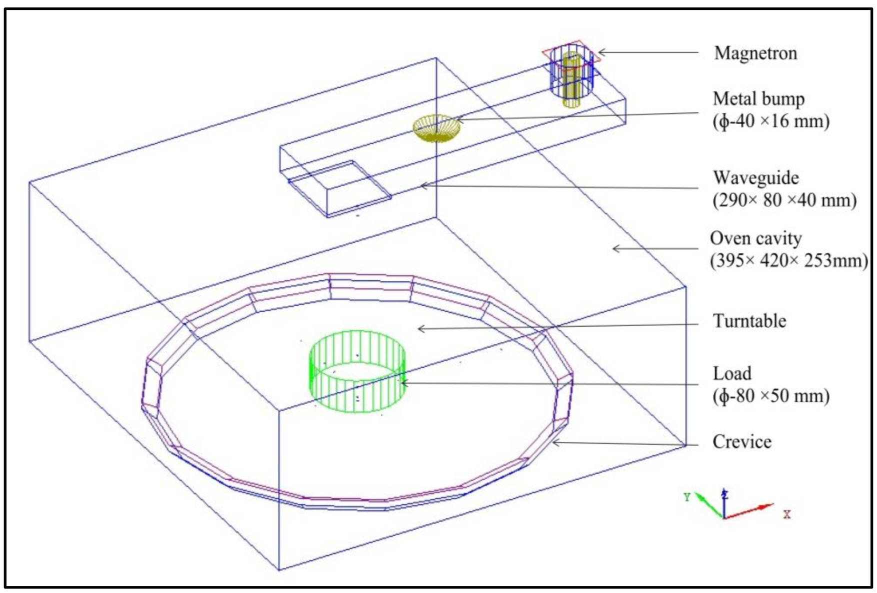


Figure 3.1. Steps for model development.



A. Model with TE10 port feeding.



B. Model with TEM coaxial feed.

Figure 3.2. Geometric model of 700 W rated power microwave oven (Sharp Electronics Corp., New Jersey, and USA) with A) port feeding B) magnetron as coaxial feeing.

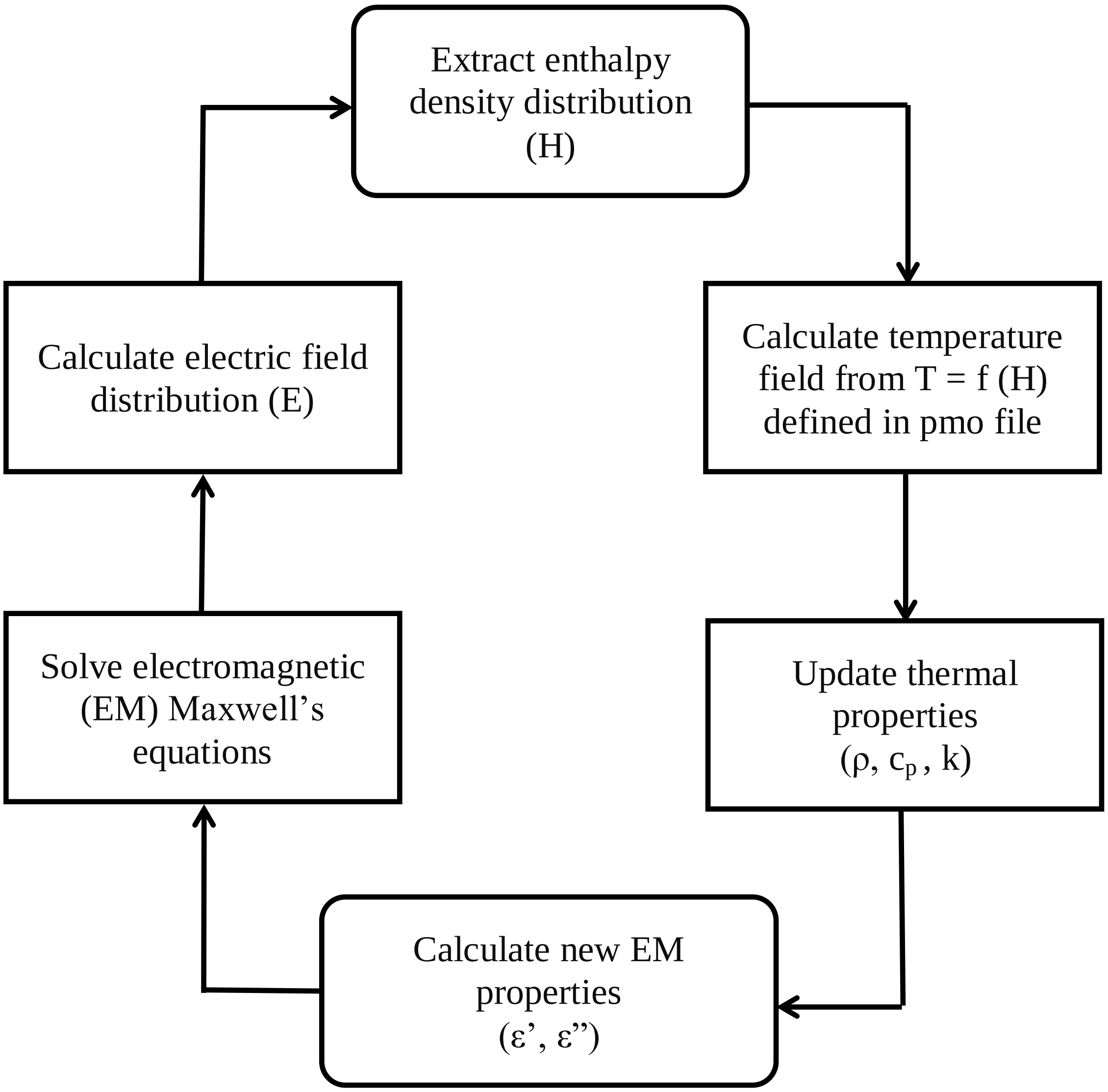


Figure 3.3. Coupling electromagnetic and thermal calculations.

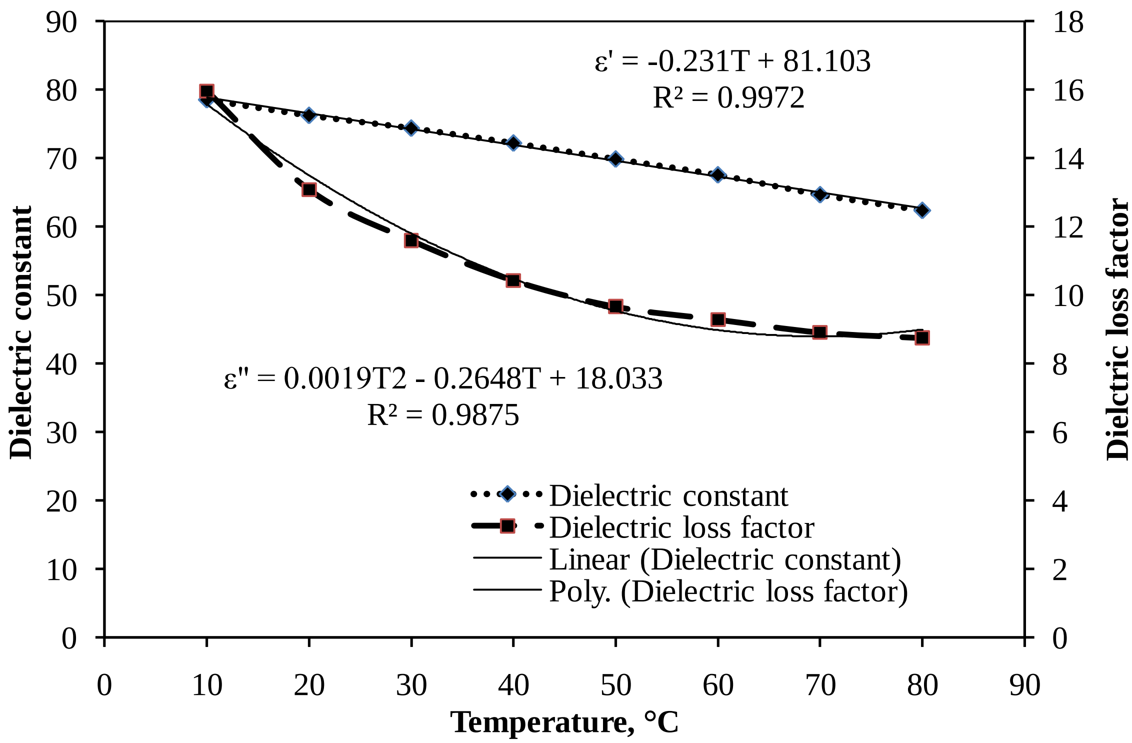


Figure 3.4. Dielectric properties of 1% gellan gel measured at 2.45 GHz frequency.

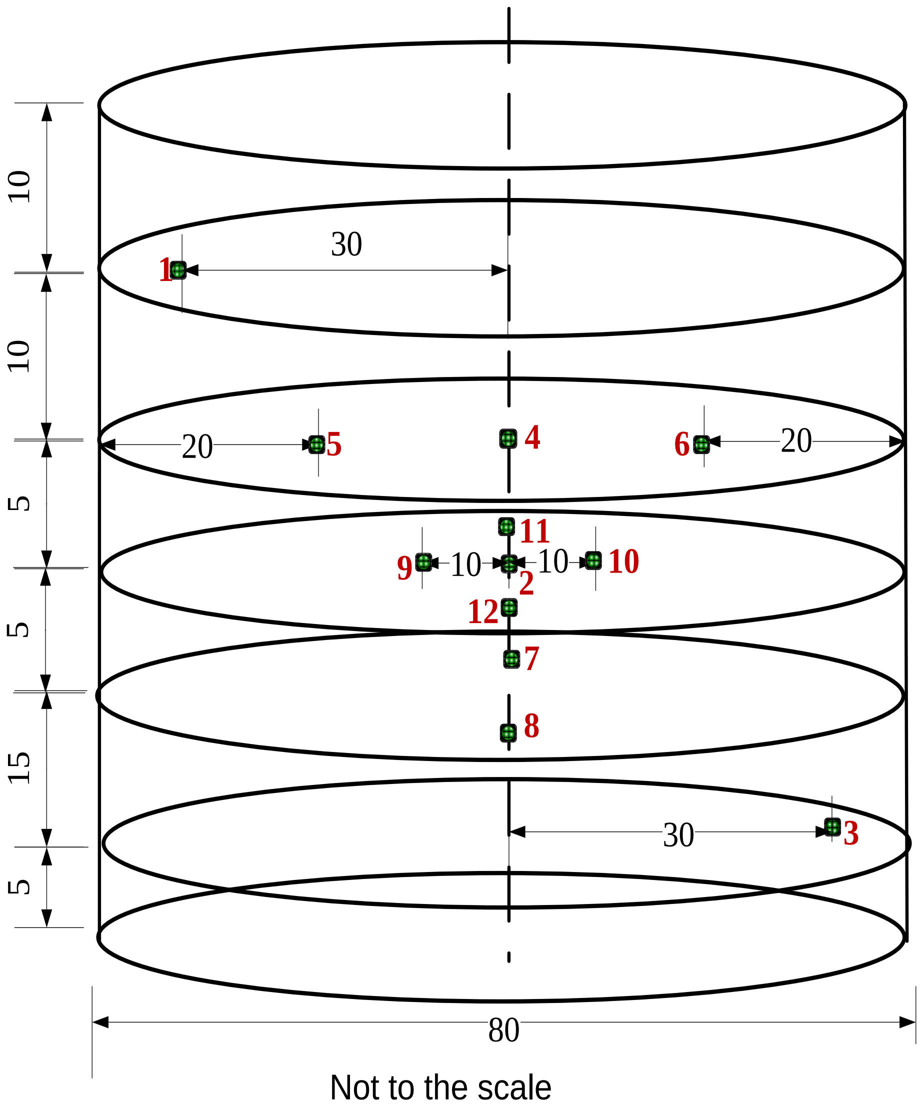


Figure 3.5. Location of the fiber optic sensors in gellan gel cylinder.

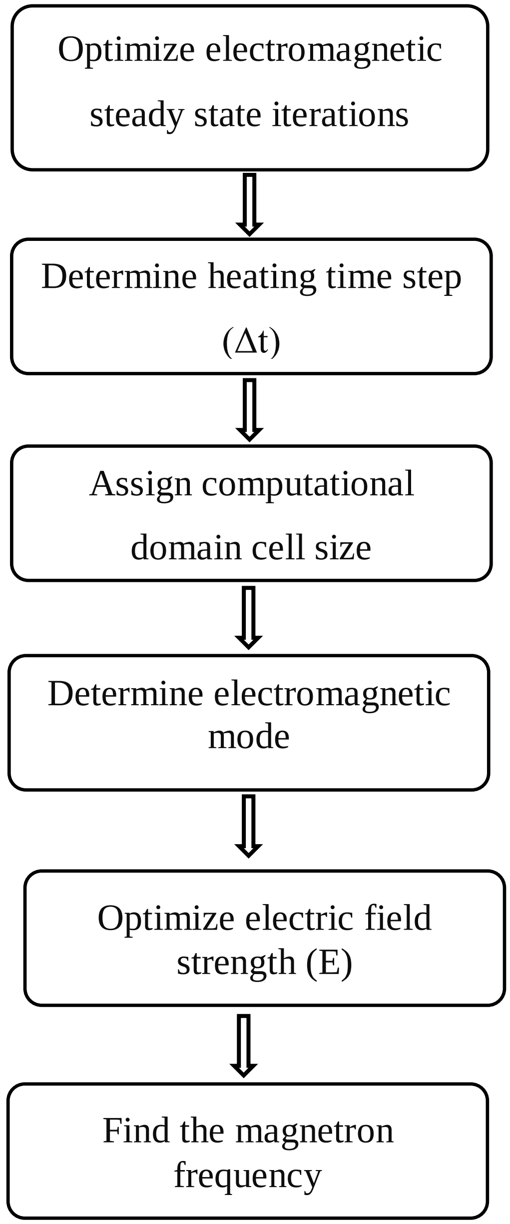


Figure 3.6. Model parameter selection procedure.

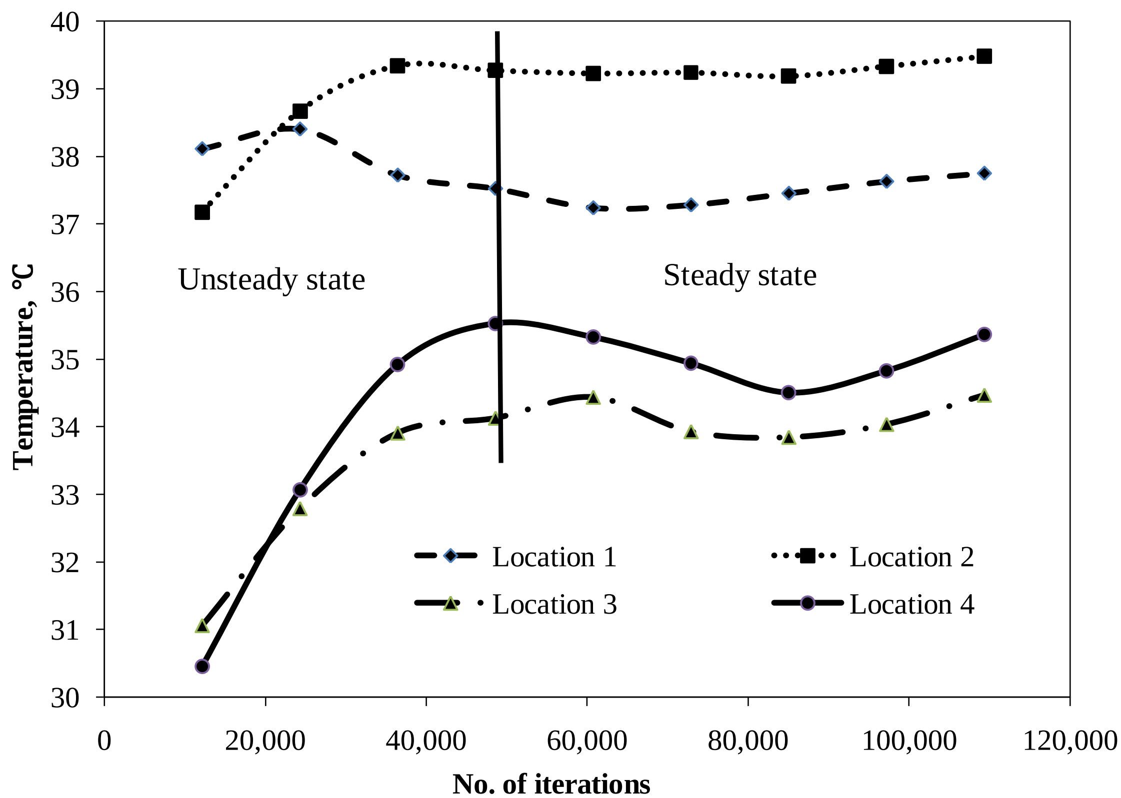


Figure 3.7. Optimization of electromagnetic steady state iterations at four locations in gellan gel.

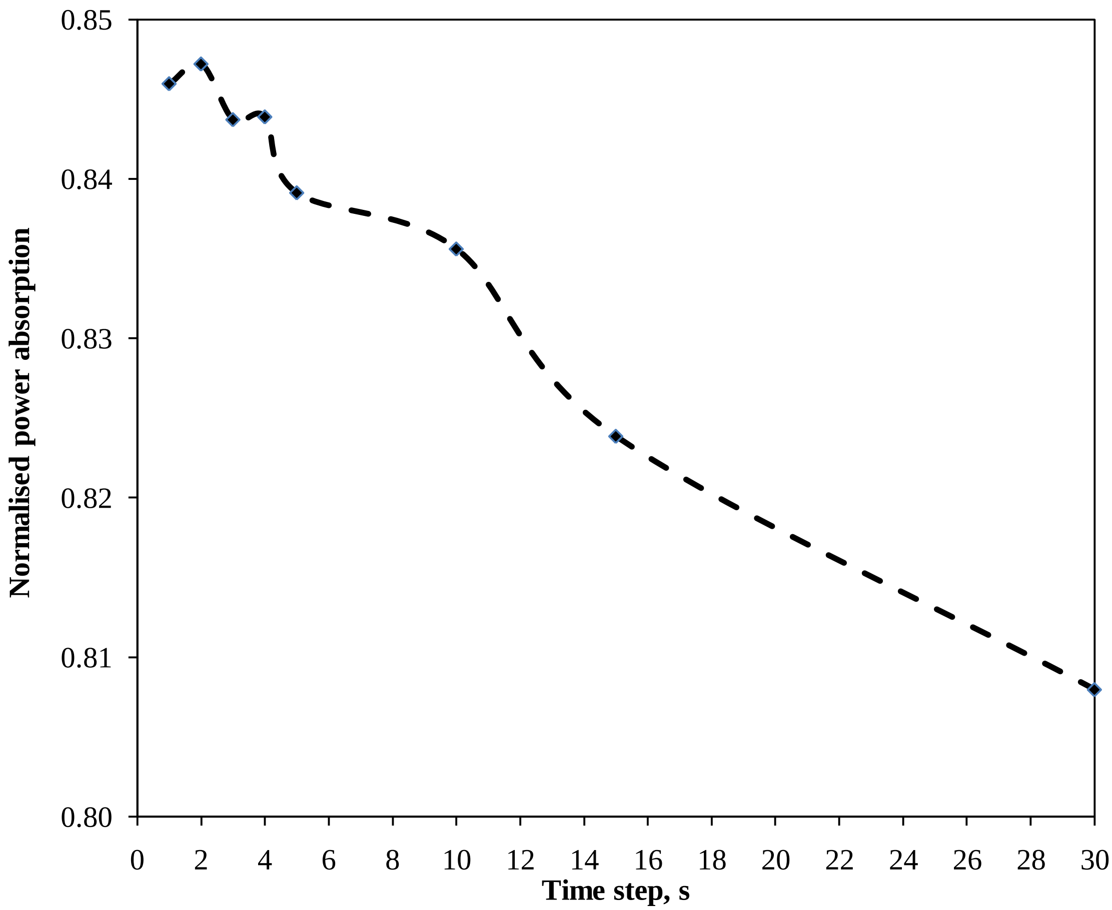
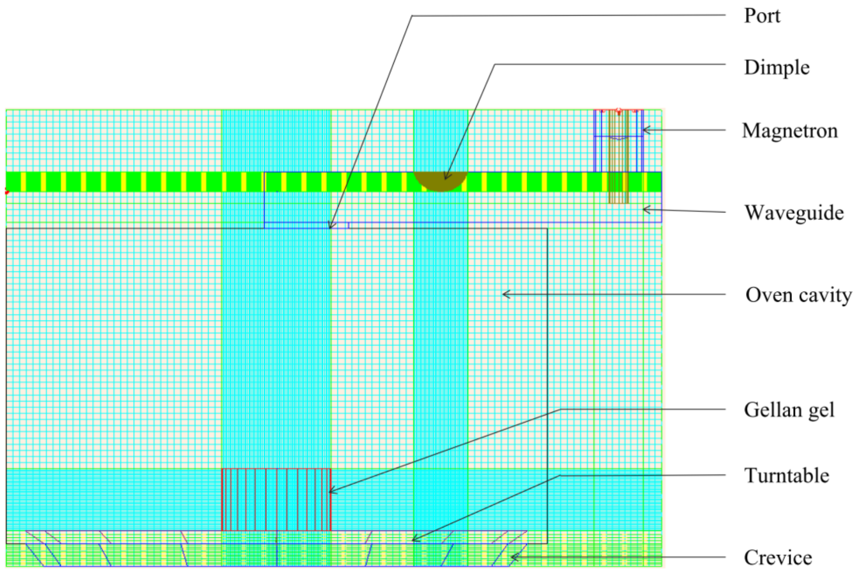
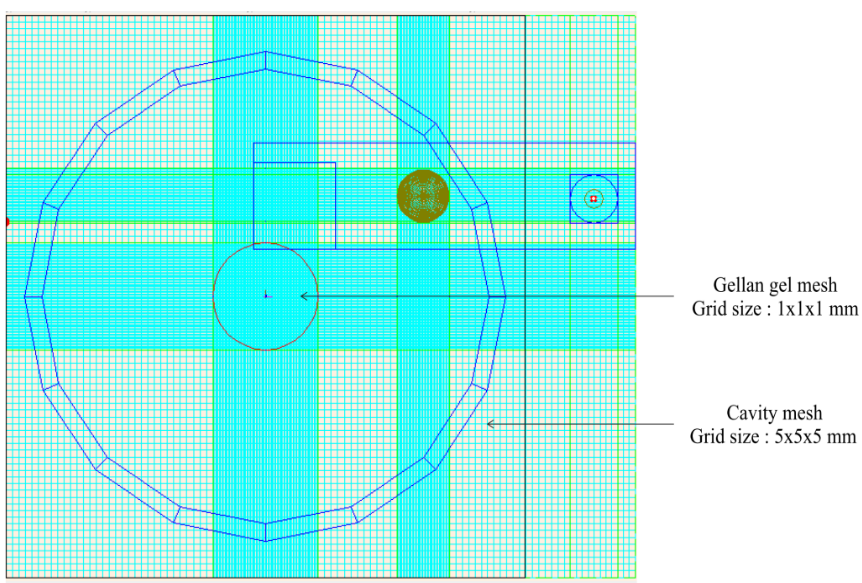


Figure 3.8. Effect of heating time step on power absorption.



a. Front view



b. Top view

Figure 3.9. 2-D view of meshing in the computational domain.

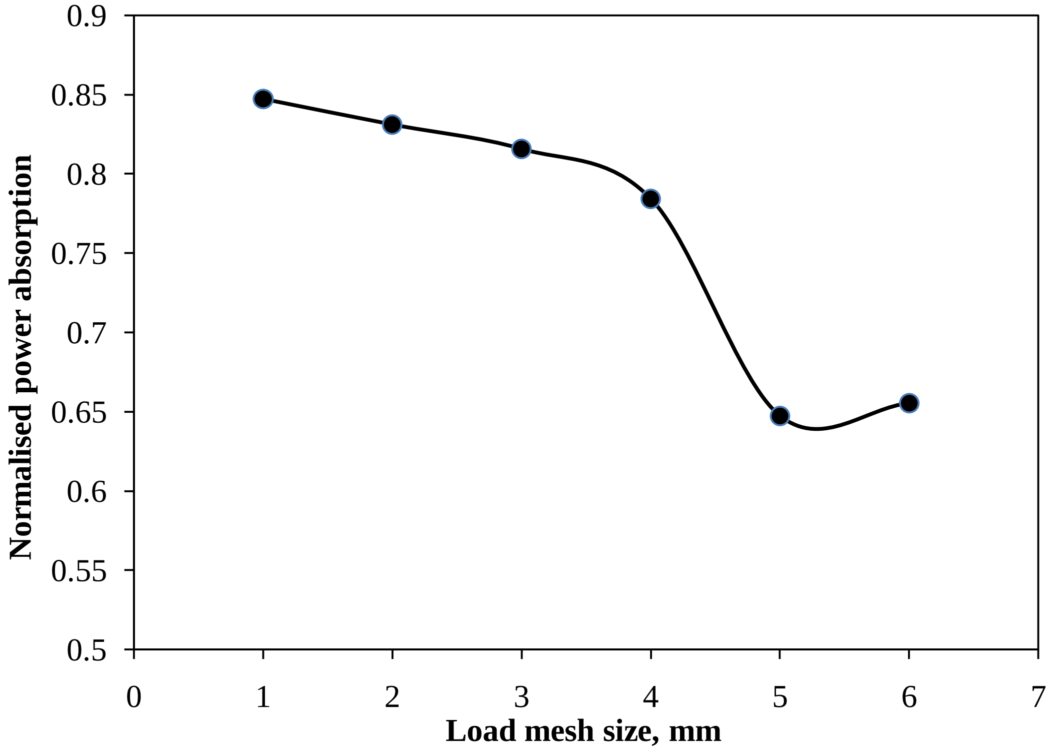


Figure 3.10. Effect of mesh refinement on absorption of microwave power.

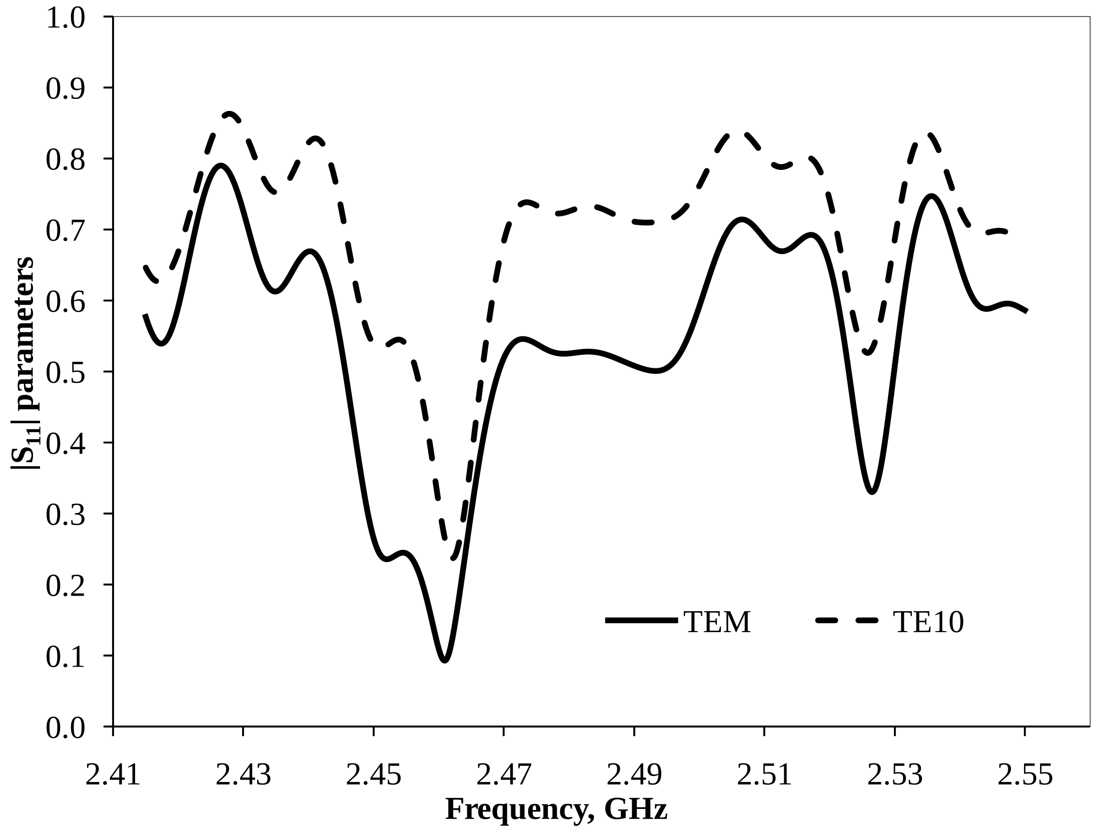


Figure 3.11. Scattering parameter of TEM and TE10 electromagnetic modes extracted from frequency spectrum.

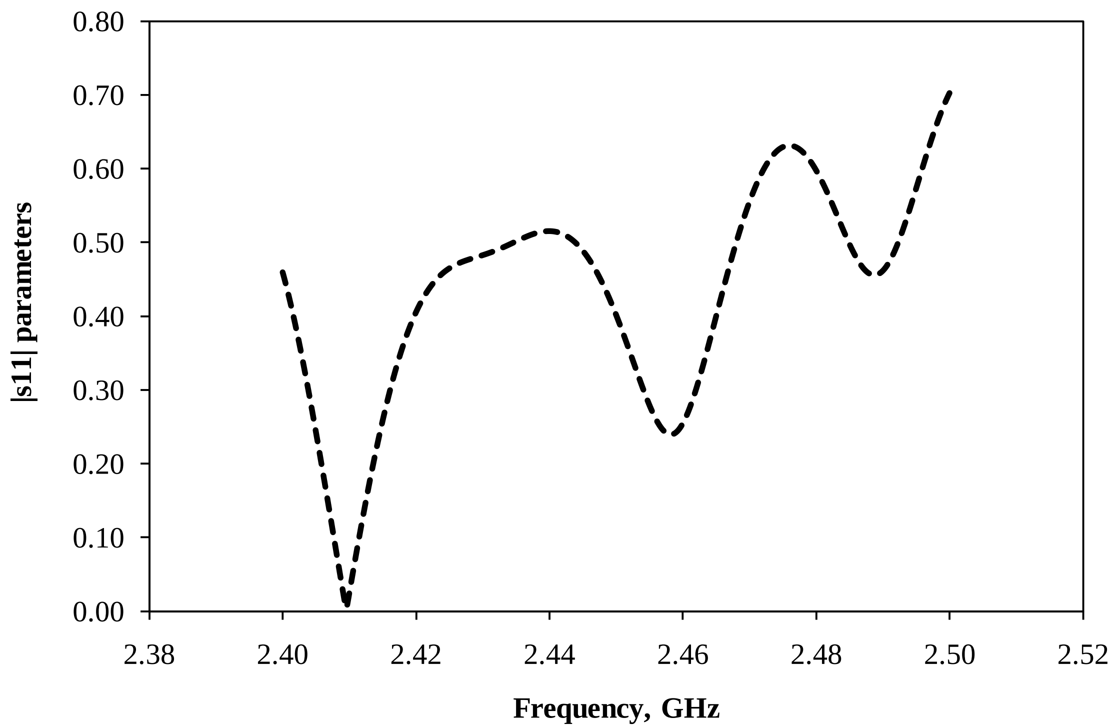


Figure 3.12. Scattering parameter of TEM extracted from frequency spectrum for 250 g of water load.

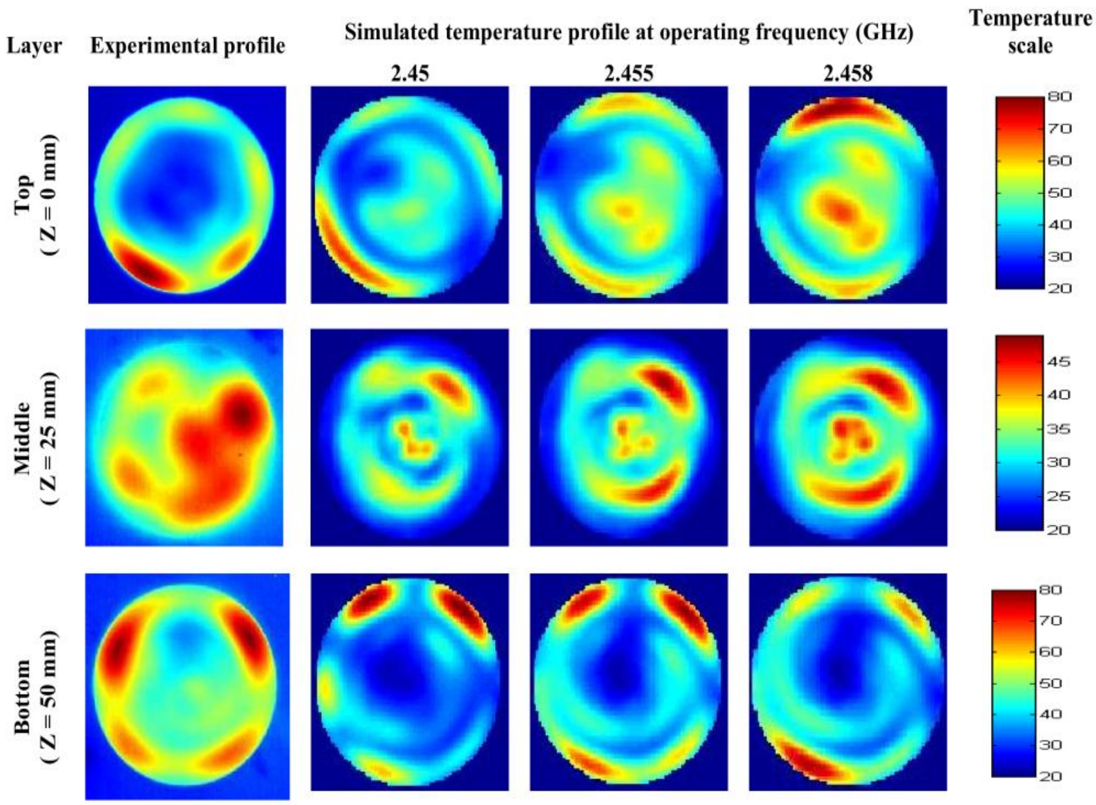


Figure 3.13. Effect of frequency on spatial heating profile of gellan gel cylinder (80 × 50 mm) subjected to 30 s heating in 700 W microwave oven.

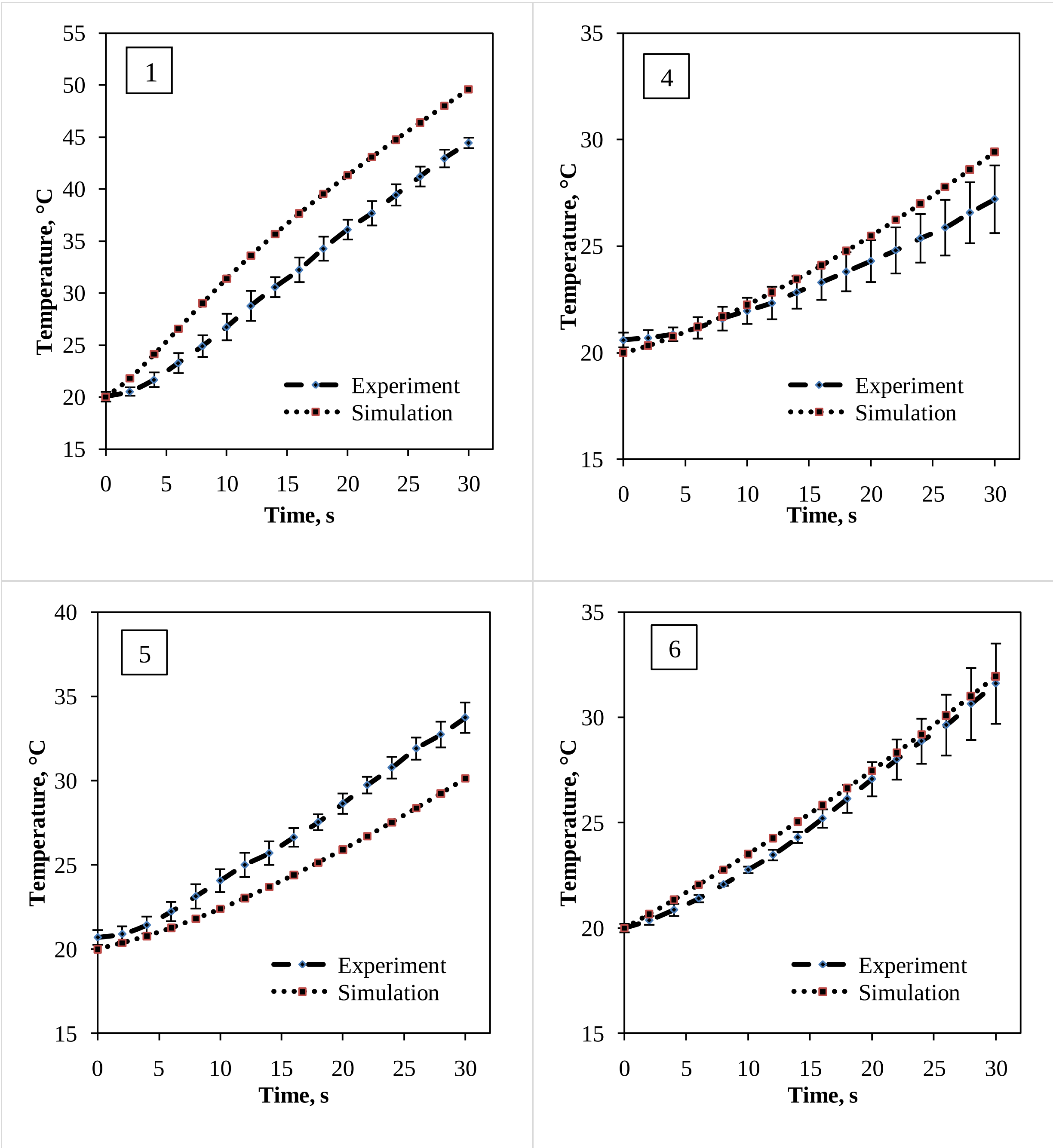


Figure 3.14. Simulated and observed time-temperature profile at four locations of gellan gel subjected at 2.45 GHz (locations from z = 10 to 20 mm).

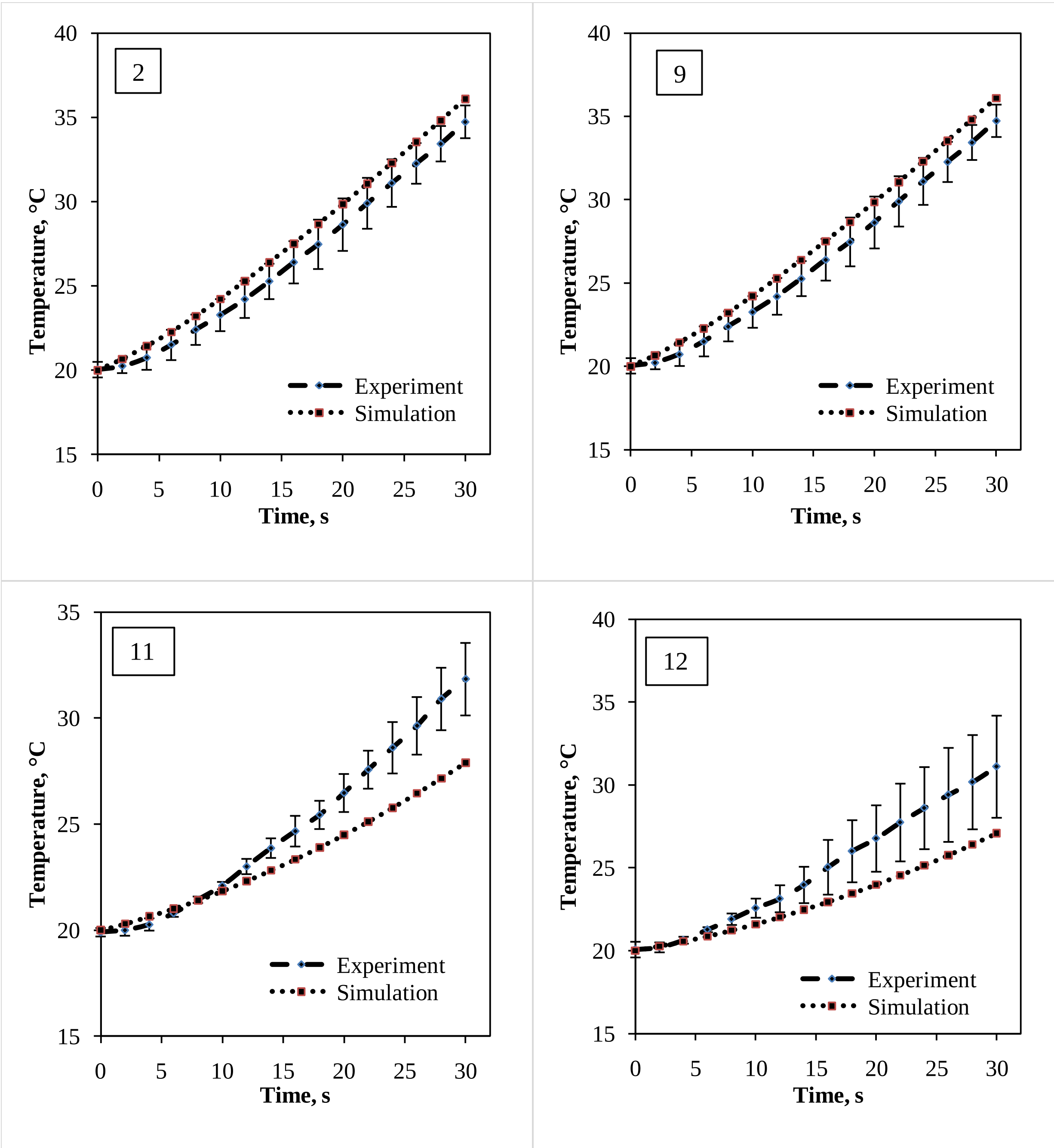


Figure 3.15. Simulated and observed time-temperature profile at four locations of gellan gel subjected at 2.45 GHz frequency (locations at z = 25 mm).

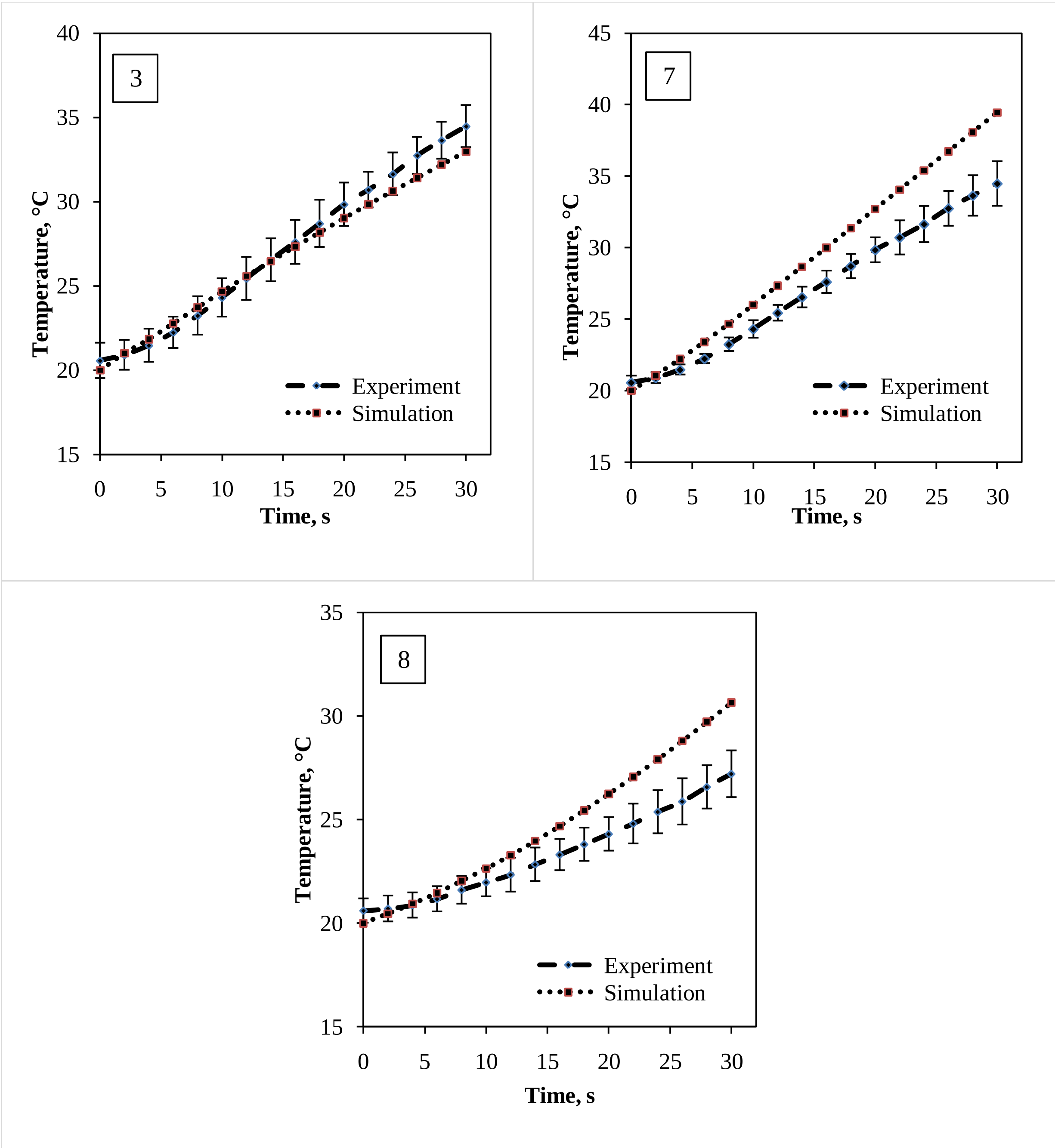


Figure 3.16. Simulated and observed time-temperature profile at three locations of gellan gel subjected at 2.45 GHz (locations from z = 30 to 40 mm).

Table 3.1. Properties of 1 % gellan gel and glass turntable used in the simulation.

Properties	Gellan gel	Glass#
Specific Heat, kJ/kg °C	4.16*	0.55
Density, kg/m^3	1010*	2050
Thermal Conductivity, W/m °C	0.53*	0.1
Dielectric Constant	-0.23T+81.103**	6
Dielectric loss factor	$0.0019T^2$-0.264T+18.033**	0

Source: * Birla et al. 2008, ** In this study, # Quick wave, 2008

Table 3.2. Effect of mesh refining on absorbed power in the gel.

Mesh Size (mm)	Number of Cells	Memory Required (MB)	Normalized Power Absorption	% Difference
1	4,661,376	445	0.847	-
2	2,341,911	223	0.831	1.92
3	1,803,100	172	0.816	1.87
4	1,555,827	148	0.784	3.95
5	1,413,720	135	0.647	19.14
6	1,353,807	129	0.655	1.23

Table 3.3. Selected simulation parameters.

Parameters	Value
EM steady state iterations	36,450
Heating time step	2 s
Mesh size	Air : ($\Delta x = \Delta y = \Delta z = 5$ mm) Gel : ($\Delta x = \Delta y = \Delta z = 1$ mm)
Feed port mode	TEM
Frequency	2.45 GHz
Electric field strength	35.69 V/cm

Table 3.4. Comparison between transient experimental temperature and predicted temperature using 2.45, 2.455 and 2.458 GHz magnetron frequency.

Position	Sensors ID	Magnetron frequency (GHz)					
		2.450		2.455		2.458	
		RMSE (˚C)	$\|\Delta T\|_{final}$ (˚C)	RMSE (˚C)	$\|\Delta T\|_{final}$ (˚C)	RMSE (˚C)	$\|\Delta T\|_{final}$ (˚C)
Top (z = 10 to 20 mm)	1	4.52	5.13	3.85	7.61	4.04	7.75
	4	1.16	2.22	1.77	3.36	2.39	4.44
	5	2.37	3.6	1.23	2.2	0.28	0.25
	6	0.53	0.34	0.24	0.16	0.67	1.21
	Avg.	**2.15**	**2.82**	**1.77**	**3.33**	**1.85**	**3.41**
Middle (z = 25 mm)	2	1.04	1.35	2.83	1.83	4.63	5.97
	9	0.81	1.91	0.74	0.27	1.22	1.58
	10	4.18	8.05	2.46	4.91	1.25	2.71
	11	1.99	3.94	1.72	3.38	1.18	2.33
	12	2.36	4.02	1.59	2.53	0.52	0.34
	Avg.	**2.08**	**3.85**	**1.87**	**2.58**	**1.76**	**2.59**
Bottom (z = 30 to 40 mm)	3	0.78	1.49	1.57	2.42	0.45	0.57
	7	2.76	4.97	4.62	7.89	6.32	10.79
	8	1.82	3.44	1.38	2.75	2.21	4.32
	Avg.	**1.79**	**3.30**	**2.52**	**4.35**	**2.99**	**5.23**
Global average		**2.02**	**3.37**	**2.00**	**3.27**	**2.09**	**3.52**

RMSE = Root mean square error; $|\Delta T|_{final} = abs\,(T_{simulated} - T_{observed})_{final}$

Table 3.5. Final temperature difference of simulated (2.45 GHz frequency) and observed temperature after 30 s of microwave heating.

Position	Sensors ID	Magnetron frequency 2.45 GHz		
		$T_{experiment}$ (˚C)	$T_{simulated}$ (˚C)	ΔT (˚C)
Top (z = 10 to 20 mm)	*1*	*44.43*	*49.57*	*-5.13*
	4	*27.2*	*29.42*	*-2.22*
	5	33.73	30.12	3.61
	6	*31.60*	*31.95*	*-0.35*
Middle (z = 25 mm)	*2*	*34.73*	*36.09*	*-1.36*
	9	33.23	31.31	1.92
	10	36.06	28.01	8.06
	11	31.83	27.89	3.95
	12	31.10	27.08	4.02
Bottom (z = 30 to 40 mm)	3	34.46	32.97	1.50
	7	*34.46*	*39.44*	*-4.97*
	8	*27.20*	*30.64*	*-3.44*

$\Delta T = (T_{experiment} - T_{simulated})_{final}$; italize numbers denotes over- prediction; normal numbers denotes under- prediction.

CHAPTER IV

ASSESSMENT OF NON-UNIFORM HEATING IN DOMESTIC MICROWAVE OVENS

Abstract

Due to the inherent nature of standing wave patterns of microwaves inside a cavity and varying dielectric properties of different components in food, microwave heating produces non-uniform distribution of energy inside the food. Non-uniform heating is a major concern for food safety of not-ready-to-eat (NRTE) foods in domestic microwave ovens. In this study, we present a method for assessing non-uniform heating within domestic microwave ovens. A custom designed container was used to assess non-uniform heating of a range of microwave ovens using a hedgehog of 30 T-type thermocouples. The mean and standard deviation of temperature raise along the radial distance and sector of the container were measured and analyzed. The effect of radial distance of rings and sectors were analyzed using ANOVA to identify the best location for placing food in the turntable. The study suggested that the best location to place food in a microwave oven is not at the center but near the edge of the turntable. Effect of power and cavity size on temperature raise and non-uniform heating were also studied for a range of microwave ovens. As the power and cavity size increases, temperature raise increases, but non-uniform heating decreases. Sectors in the container did not influence temperature raise, but influenced non-uniform heating.

Keywords: Non-uniform heating, Food safety, Thermocouples, Temperature variation.

Introduction

Microwave (MW) heating of food items is rapid, but non-uniform. The issue of non-uniform heating is exasperated in frozen foods due to dramatic differences in dielectric properties of ice and liquid water. Many frozen food products are not-ready-to-eat (NRTE), meaning that they may contain pathogens. It is expected that the final cooking/heating step in the microwave oven assures food safety. Microwave heating produces "hot" and "cold" spots due to complex interaction of electromagnetic fields with food, a lossy material. Because the process time is short in microwave heating, there is not enough time for thermal diffusion to take place between hot and cold spots (Ma et al., 1995). Risman and Celuch (2000) discussed the development of hot and cold spots in a food material and noted the following six factors involved in microwave heating: mode interference, non-resonant diffraction, focusing effect of load, penetration depth limitation, runaway effect, and diverging defrosting effect. Due to non-uniform heating, part of the frozen foods may not be heated adequately in microwave ovens to reach desired temperatures to kill pathogens. For example, 165°F is required to kill *Salmonella* (USDA-FSIS, 2006). If the desired temperature is not reached, the foodborne pathogens, if present in the cold spots, would survive and cause illnesses.

Improving microwave heating uniformity has been a challenge to both microwave oven manufacturers and food processors. Vadivambal et al. (2010) reviewed various studies on microwave heating and identified a research need to improve heating uniformity in microwave ovens. Improving heating uniformity of a microwave food product can be achieved by modifying food composition and geometry (Ryynanen and

Ohlsson, 1996). In past two decades, many serious efforts have been made by researchers to understand the phenomenon of non-uniform heating experimentally and through computer simulation (Wäppling-Raaholt et al., 2006; Knoerzer et al., 2007). Many researchers have looked at different factors that affect the heating uniformity in microwave ovens such as food shape (Chamchong and Datta, 1999b; Zhang and Datta, 2005), size (Vilayannur et al., 1998), location of food in the turntable (Wappling-Raaholt and Ohlsson, 2000), dielectric properties of food (Chamchong and Datta, 1999b; Peyre et al., 1997), and microwave power and cycling (Chamchong and Datta, 1999a). Another promising area that has been looked at improving heating uniformity is the combination of microwave heating with infrared and/or hot air (Datta and Ni, 2002; Datta et al., 2005). The effects of using variable frequencies for microwave heating (Bows, 1999; Kashyap and Wyslouzil, 1977) and the use of mode stirrers (George and Bergman, 2006) on heating patterns have also been studied to improve heating uniformity. Bows (1999) demonstrated that using the variable frequency microwave ovens (VFMO), the mean target temperatures of 50, 75, and 90°C in a spherical shape food (consisting of 90% water with cellulose structure) at the center plane were achieved within 2 min of heating based on combing 8 discrete frequencies between 2.4 and 6.2 GHz than at a single frequency. Kashyap and Wyslouzil (1977) demonstrated a method to improve the heating uniformity in a thermal wet paper by sweeping the frequency of the magnetron over 2450 ± 50 MHz. They found that sweeping the frequency in the range of 2450 ± 50 MHz gives better heating uniformity than using a field stirrer inside the cavity. George and Bergman (2006) demonstrated via modeling that mode stirrers can improve the heating uniformity in a thermal fax paper. Geedipalli et al. (2007) demonstrated through

computer simulation techniques that the rotation of the turntable can improve heating uniformity by 40%.

A method to quantify non-uniform heating is required to understand and evaluate the effect of various factors affecting the heating performance of microwave ovens. Historically, wet thermal fax paper has been used in demonstrating MW heating non-uniformity in domestic ovens (Bradshaw et al., 1997). The problem with this approach is that one has to use it in an empty cavity. In reality, the presence of a food product inside the microwave oven will drastically alter the electromagnetic field. Moreover, this method does not provide a quantitative assessment of heating uniformity. There are microwave active compositions (Atlanta Chemical Engineering, Atlanta, GA) commercially available that change color depending upon the temperature. Colorant used in the composition loses or gains different color depending on temperature under microwave heating. Response time of the colorant to change in temperature is short and the spots are well outlined. The major limitation of this approach is that it is again not a quantitative assessment.

Recently, a chemical marker technique has been used in locating hot and cold spots in industrial microwave sterilization process (Bhuwan et al., 2007). To quantify the color change, the authors developed a computer vision system to measure the temperature inside a model food product. James et al. (2002) developed a methodology for assessing the heating performance of domestic microwave ovens using a set of quick response thermocouples. A 350 g of water poured in a PET tray was used to assess the heating performance in six microwave ovens in the range of 600 to 1000 W. The PET tray (173 × 35 mm) was designed to cover a small region on a turntable. Swain et al. (2008)

developed a test procedure to characterize the performance of domestic microwave ovens for heating of food simulant. They used a food simulant (171× 127 × 35 mm) made of TX151 powder (Weatherford Inc., Aberdeen, Scotland), a hydrophilic polymer and a hedgehog of 39 quick response thermocouples to study the heating performance of domestic microwave ovens. In their study, only seven microwave ovens were considered in the range of power output from 800 to 1000 W. Their study did not include higher power microwave ovens. IEC 60705 standard suggests the use of a square container (228 mm × 228 mm × 30 mm) made of material transparent to microwaves for measuring the performance of microwave ovens (IEC, 1999). The square container consists of 25 compartments in which 1000 g water is poured to measure the microwave heating non-uniformity. The compartment separators have a small hole approximately positioned in center of them to allow water flow from one compartment to another. In this method, a microwave oven's heating uniformity was measured by the difference between highest and lowest temperature raise of 25 compartments over the average temperature raise of 25 compartments. Wang et al. (2008) designed a test rig consisting of an array of 24 plexiglass cups filled with water and an array of 24 thermocouples to assess heating uniformity in a radio frequency heating system. They also used a foam sheet to evaluate heating uniformity of the radio frequency system using an infrared camera. Thermal imaging is an industry standard tool for assessing heating uniformity of a product at the end of the microwave heating process. The only limitation in using a thermal imaging system is that it provides only surface temperatures.

Our long-term goal is to develop a comprehensive risk assessment model to assess the food safety risk of consuming microwaveable foods. The risk assessment model

takes into account of the variation in microwave parameters (power, location of food inside the oven), food composition, layout and its properties (dielectric, thermal, and physical), microbial factors (death kinetics parameters), and consumer behavior (cooking time, standing time, and dose-response curve). The objective of this study is to determine the variation of microwave energy distributed within the turntable. Thus, the information gathered from this study will be fed into the larger risk assessment model. There has been no systematic study previously conducted on the effect of location of food product on a turntable within a microwave oven on non-uniform heating. This study is conducted to assess the variability of microwave energy distribution within a cavity and how placement (location) of a food in the turntable affects temperature raise and non-uniform heating. Specific objectives of this study were to:

i. evaluate the effect of location of a food product in the turntable (radial direction and sector) on heating rate and non-uniformity,
ii. investigate the effect of power and cavity size on heating rate and non-uniform heating, and
iii. assess the repeatability in performance of microwave ovens.

Materials and Methods

Rationale of the study

Temperature raise in a food product at a given location on the turntable of a microwave oven depends on how much microwave energy was received at the location (which depends on microwave parameters) and how much the product absorbs that microwave energy and convert it to heat (which depends on dielectric properties of food).

As the objective was to study the variation of microwave energy distribution within a cavity, we used water as a sample food whose dielectric properties are well known. By using water as the load, this study focuses on evaluating the distribution of microwave energy within the cavity and therefore heating uniformity in water at various locations. It should be noted, however that the turntable was rotating and therefore the microwave energy received at a particular location of food is the cumulative effect of all energy received during microwave heating.

Container description

To get the distribution of microwave energy absorption by water, a round container (300 mm diameter × 100 mm height) made of polypropylene was designed with 36 equal volume compartments (Figure 4.1). The whole container was divided into 36 compartments by using 2 mm thick polypropylene strips (dielectric constant of 2.25), which absorbs a negligible amount of microwave energy compared to water (dielectric constant of 80). The polypropylene strips (thermal conductivity of 0.12 W/m °C) are chosen as they minimize the heat transfer between the water (thermal conductivity of 0. 58 W/m °C) in different compartments. The design of the container ensured that the surface area (44.52 cm^2) of all compartments were the same. There are small gaps at the bottom of the polypropylene strips that separated compartments, which allowed for water to distribute evenly to all compartments. This ensures that each compartment has the same depth and therefore volume of water. Therefore, microwave energy received in various locations can be measured by temperature raise in each compartment after microwave heating. The water in the container was heated for 2 minutes and typical temperature raise was around 9 - 25°C. For short heating time of 2 min, the movement of

water between the compartments due to temperature difference is negligible. In fact, the IEC 60705 method also used a container that has small holes at the center of each strip separating compartments to equalize water volume in all compartments. The container was also designed to cover the entire area of the typical microwave oven turntable.

Experimental procedure

The designed container was used to assess heating uniformity in 19 microwave ovens. Microwave ovens were selected with the rated power ranging from 800 to 1300 W. One liter of water was weighed and poured into the container. Initial temperature of the water was recorded using 30 T-type thermocouples (COCO-005, thickness - 0.125 mm; response time - 1 s; Omega Engineering, Inc., Stamford, CT, USA) mounted on a circular plate, such that they are properly placed in 30 compartments when placed over the container. The water-filled (volume – 27.77 cm^3; depth – 7 mm) container was placed at the center of turntable and subjected to heating for 2 min. Immediately after heating, the container was removed and final temperature of water at each compartment was recorded.

Temperature measurement system

To record the temperature at each compartment, a set of 30 T-type thermocouples connected to the data logger was used. We did not measure the temperature on the outer ring, because it might be influenced by ambient temperature. In addition, our data acquisition system could measure only 30 of them. The 30 thermocouples were fastened at one end in a perforated flexi-glass lid and other end of the thermocouples connected to the USB 2.0 data logger. DASYLab V10.0 software (Measurement Computing Corporation, Norton, MA, USA) was used to acquire the temperature from the data

logger. The schematic diagram of the temperature measurement system is shown in Figure 4.2. By measuring the temperature of water in each compartment after microwave heating, we can estimate the microwave energy distribution at 30 locations.

Measure of non-uniform heating

Coefficient of variation (COV) is used as a measure of non-uniform heating on a percentage scale (Eq.4.1). COV is a dimensionless number that describes variation (standard deviation) in temperature raise as a percentage of average temperature raise in a ring (average temperature of 6 compartments) or sector (average temperature of 5 compartments).

$$\mathrm{COV} = \frac{\sigma_t}{\mu_t} * 100 \qquad (4.1)$$

where COV is the coefficient of variation, σ_t is the standard deviation of temperature variation (°C), and μ_t is the mean temperature raise (°C).

Rings and sectors temperature

The container consists of 5 rings and 6 sectors (30 compartments) is shown in Figure 4.3. To plot a graph that shows the effect of rings on temperature raise, the following steps were followed:

- First, temperature data for two replicates were averaged for each compartment.
- For each ring, the mean, standard deviation, and coefficient of variation of temperature of all compartments within that ring is determined.

- Then, the mean and standard deviation of resultant values (mean temperature raise, standard deviation, or coefficient of variation) is determined for all microwave ovens in that power category.

The temperature raise (average of mean temperature raise in each ring for all microwave ovens in that power category) as a function of radius is plotted. Corresponding standard error of deviations of temperature raise in each ring for all microwave ovens in that category is plotted as error bars. Similarly, the coefficient of variation or standard deviation of temperatures in each ring for all microwave ovens in that power category, which is a measure of non-uniform heating, is plotted as a function of radius. Corresponding values are then plotted as a function of radius. A Similar procedure was followed to plot a graph to show the effect of sectors. The depiction of a ring and sector in the container is shown in Figure 4.3

t-statistic

Two tailed t- statistic was performed to assess the repeatability in performance of the microwave ovens. For this test, two replications final temperature at each compartment (total of 30 compartments) in a microwave oven were used as statisitic. Two replicates of temperature recording were performed in each microwave oven with the interval of 4 h. A 4 h duration between replicates allowed the magnetron to cool down to room temperature. We hypothesized that there was no variation in absorption of microwave energy over time. The t-test was conducted with 95% confidence interval for all 19 microwave ovens.

Statistical analysis

The experimental design is split-split plot design. For this analysis, temperature raise (difference between final and initial temperature) in each compartment was used as a dependent variable. The main plot factor for the analysis was 19 microwave ovens and sub-plot factor was 2 replications. Split-split plot consisted of a factorial design consisting of two factors namely radius and sectors. A schematic split-split design plot used in this study is shown in Figure 4.4. The SAS program for this model is given in the Appendices. Total observations considered for the model was 1140 (19 microwave ovens × 30 compartments (5 rings and 6 sectors) × 2 replications).

Results

Before statistical analysis, several graphs were created to visualize the effect of rings, sectors, power, and cavity size on heating rate and non- uniformity. For these graphs, the 19 microwave ovens were grouped into three power categories based on their rated power level as shown in Table 4.1.

Effect of radial distance on heating rate and non-uniformity

Heating rate can be measured by averaging temperature raise on all compartments in a given radial distance (a particular ring), as the time of heating was 2 minutes for all trials. Non-uniform heating can be measured by coefficient of variation of temperature raise in all compartments in a given radial distance. Because the turntable was rotating in all trials, the effect of sector on temperature raise in each compartment within a given radial distance should be minimal. Figure 4.5 shows a general trend of heating rate in all three categories of the ovens tested in this study. In general, temperature raise in the

outer rings (15-25°C) were much higher than that in the central ring (9-13°C). Therefore, a food item placed on the edge of the turntable will heat faster than if it were placed on the center of the turntable.

An interesting trend to note in Figure 4.6 is that the coefficient of variation increases as the radial distance increases until a radial distance of 10 cm and then it decreases. This trend indicates that the variation in temperature within the load at the center of the turntable to 10 cm radius of turntable is higher than the variation in temperature of the load when placed on the edges. It was found that non-uniform heating (3.8 – 9.7%) is higher until 74% of the radial distance of rings from center of the turntable. The reamining 26% of the radial distance of the rings found to be acheieving more uniform heating (2.2 -7.7%). Thus, it is extremely beneficial to place the load the edge of the turntable, because it not only receives more electromagnetic energy, but also provides better heating uniformity.

Effect of sectors on heating rate and non-uniformity

We studied the effect of a sector within a cavity on average temperature raise and non-uniform heating. The whole turntable or the circular container was divided into 6 sectors at 60 degrees interval. Within each sector, there were 5 compartments at different radial distance. The temperature raise of 5 compartments was averaged to represent the average temperature raise in a sector. Figure 4.7 shows the effect of sectors on average temperature raise in microwave ovens of three power categories. The average temperature raise in three power categories showed that it did not vary much in entire sectors. Average temperature raise in each sector in high power microwave ovens

reached 21°C. Whereas, the average temperature raise in medium and low microwave power categories reached 17°C and 13°C, respectively. There was no observable difference in temperature raise between sectors in all three power categories because the variation along the sector gets averaged when the turntable rotates the food within the cavity.

Figure 4.8 shows the effect of sectors on non-uniform heating in three power categories. The graph clearly shows that first three sectors (0° to 180°) which are half of the container close to the back portion of cavity wall have more non-uniform heating. The other half portion of the container (remaining three sectors from 180° to 360°) which is close to the front cavity wall has less non-uniform heating. For the first three sectors, non-uniform heating varied from 16 % to 21% in all microwave power categories. In other three sectors, non-uniform heating has as linear trend and varied 12 to 16% for all microwave power categories.

Effect of power and cavity size on heating rate and non-unifomrity

The effect of rated power on average temperature raise and non-uniformity from 800 to 1300 W power microwave ovens was studied. Figure 4.9 shows that as the rated power increases for the microwave oven, the average temperature raise of the water increases. The overall average temperature rose from 11 to 23°C as the rated power increases from 800 to 1300 W. It supports the theory that a food product will be getting more heating rate in the higher power microwave ovens than lower power microwave ovens, when it is heated for same amount of time. On the other hand, the non-uniform heating (coefficient of variation) decreases as the rated power increases. The non-

uniform heating at the lower power (800 W) microwave oven was 4% more than that of 1300 W microwave oven. Thus, high power microwave oven heats a food product more evenly than low-powered microwave ovens. On the contrary, the temperature variation in the 1250 W was 2% more than that of 1200 W microwave oven. This might be due to a smaller sample size (n=3) on high power category, when compared to other two categories (n for low = 6; n for medium = 10).

Figure 4.10 shows the effect of cavity size on average temperature raise and non – uniform heating. The cavity size ranges from 0.9 to 2.2 cubic-ft for the selected microwave oven power range of 800 to 1300 W. A 0.9 cubic-ft cavity size microwave oven achieved a temperature raise of 13.0°C. Whereas, the average temperature raise in a 2.2 cubic-ft was 21.1°C. In general, as the size of the cavity increases, the average temperature raise increases. However, the nature of the effect of cavity size on average temperature raise and non-uniform heating was not as linear as the one observed for the effect of power. The 0.9 cubic-ft microwave oven has a non-uniform heating of 12%. Whereas, the higher cavity size (2.2 cubic-ft) has non-uniform heating of 6%. Interestingly, the non-uniform heating dropped steeply from 12 to 4% within difference of 0.1 cubic-ft cavity size at smaller size microwave ovens. While the lowest cavity size had the highest non-uniform heating, no clear trend was observed for effect of cavity size on heat non-uniformity.

Figure 4. 11 shows a linear relationship of microwave oven rated power as a function of cavity size. The relationship indicates that only 58% of variability in cavity size can be explained by microwave oven rated power. For instance, 1100 W rated power microwave ovens had, cavity size ranging from 1 to 1.8 cubic-ft. Obviously, rated

power has a direct effect on temperature raise. In general, the larger power ovens has higher cavity size and vice versa, but the linear relationship has an R^2 value of only 58%. Thus, cavity size has an indirect and weaker effect on temperature raise. Therefore, rated power is a more important factor than cavity size for heating rate and non-uniform heating.

Assessing performance of microwave ovens

The same power microwave oven was subjected to two replicates with the interval of 4 h duration between replicates that allowed the magnetron to cool down to room temperature. A two-tailed t-test was used to compare the replicates.

Out of the 19 studied microwave ovens, only 3 microwave ovens did not have a significant difference in microwave energy absorption over time of operation (refer Table 4.2). Overall, the performance of the microwave oven changed over time. The confidence interval of significant difference microwave ovens (n =16) used to assess which replication contributes to the difference in performance over time. A count of 9 microwave ovens of second replication contributes to the performance difference, whereas, 7 microwave ovens of first replication contributes to the performance difference. A close to same number of microwave ovens falls in both replications in contribution of the performance difference; therefore, it is not evident to mention which replication contributes to significant difference of performance over time rather it is random effect. A number of factors contribute to this random effect on oven performance over time such as input voltage, power.

Analysis of variance (ANOVA)

Using the split-split plot design model, the effects of power, rings, and sectors and interaction effects on average temperature raise were analyzed by analysis of variance (ANOVA). Results from the ANOVA are shown in Table 4.3. The 3-way interaction of power, rings and sectors did not have significant effect on average temperature raise (p= 0.9695). Therefore, the 3-way interaction effect was removed in the model and divided into 2-way interaction effects. It is clearly evident that there was no significant interaction effect of power*sector (p = 0.1655). It was not further analyzed in this study. Significant interaction effects were found for rings*sectors (p = 0.0639) and power*rings (0.0435). These effects are studied in detail.

Interaction effect of rings and sectors on heating rate

The plot of interaction effect of radial distance of the rings and sectors on average temperature raise is shown in Figure 4. 12. The plot shows that average temperature raises unequally among sectors as the radial distance of rings increases except two outer most rings (radius = 12, 13.4 cm). Sector 3 (150°) has the lowest temperature raise (9.4 °C), whereas sectors 1 and 6 (30° and 330°) have much higher temperature raise (24.13 °C, 24.25°C), respectively. This is a clear indication that the sectors did have a significant effect on the average temperature raise (p = <0.0001). The temperature raise in sectors might be influenced by the position of port, where power delivers to cavity. Further investigation of the interaction effect of rings and sectors indicates that there is a significant difference between rings and sectors on temperature raise (p = 0.0639), refer to Table 4.3. Type 3 tests of fixed effects of the split-split model. It was found that there

was no linear or quadratic effect for the two outer most rings (radius =12, 13.4 cm). It was actually a constant trend at the 25°C temperature raise. However, the other three inner most rings (radius = 0, 7.6,10 cm) have a quadratic effect on average temperature raise.

Interaction effect of power and rings on heating rate

The plot of interaction effect of rated power and radius of the rings on average temperature is shown in Figure 4. 13. The plot shows that as power increases the temperature rise at each ring also increases, but, the average temperature rise at two inner most rings (radius = 0, 7.6 cm) do not vary much as the power increases. The split design gives the indication that power and rings interaction is significant ($p = 0.0435$). The two outer most rings (radius = 12, 13.4 cm) have the highest temperature raise (27.99°C, 26.04 °C, respectively) when the power is less than 1200 W and inner most ring (radius =0 cm) has the lowest temperature raise (7.89°C) for all the power levels. Figure 4. 13 shows that after removing 3-way interaction effect, the outer most rings (radius = 12, 13.4 cm) interact with each other at the higher power level (1300 W). Whereas, the other three rings (radius = 0, 7.6, 10 cm) did not intersect each other at any power levels and also follow the same behavior, which is a quadratic effect.

Discussion

A quick and reliable non-uniform heating assessment method was developed. For two minutes of heating 1 liter of water in microwave oven, the temperature raise ranged from 9ºC at the center of the cavity to 25ºC at the edge of the turntable. Just for 2 minutes of heating, the temperature difference can be as high as 16ºC. It was found that

water was heated more uniformly at a higher rate at the edge of the turntable rather than at center of the turntable. More uniform heating was at the edge because the turntable covers a maximum surface area of rotation while absorbing microwave energy. The hot and cold spots inside the food will even out when heated at the edge of the turntable. However, when the food (load) is placed on a small location within a cavity, the distribution of electromagnetic field changes altogether in the cavity, which will alter the entire scenario of power delivery to the cavity. Therefore, further studies must be conducted with a small water load placed at various radial distances and the heating rate and heating uniformity must be assessed. The non-uniform heating is higher until 74% of the radial distance of rings from center of the turntable (3.8 – 9.7%). The reamining 26% of the radial distance of the rings found to be acheieving less non-uniform heating (2.2 - 7.7%). Therefore, it is better to place the food at the edge of the turntable rather than at the center of the turntable for rapid and uniform heating. Swain et al. (2008) studied the heating performance of seven microwave ovens (800 to 1000 W) using 39 quick response thermocouples. The authors considered only low power microwave ovens (n = 7) in their study. The overall non-uniform heating of seven microwave ovens calculated for their study was 8.43% (with a standard deviation of 3.76%). In our study, the overall non-uniform heating of same category microwave ovens (n = 6) was 18.92% (with a standard deviation of 6.4%). The difference can be attributed to different sized loads used; Swain et al. (2008) have measured the temperature variation in a smaller load (171× 127 × 35 mm) as compared to the load used in this study. Additionally, Swain et al. (2008) had more measurements close to the center load (31) than at the edge (8). James et al (2002) studied the heating performance of six microwave ovens using 350 g water. They

measured the temperature variation in a smaller size load in 12 compartments. The overall non-uniform heating of the six microwave ovens was 4.08% (with a standard deviation of 1%) Based on these previous studies and the study in this paper, it could be inferred that for smaller load sizes, there is less spatial variation than for larger load sizes that cover the entire turntable.

Apart from optimizing the best location for placing food horizontally in the turntable to get better heating uniformity, vertical displacement of the load in turntable has also contributed to reducing temperature variation (Wappling-Raaholt and Ohlsson, 2000). The authors studied the effect of vertical displacement of a model food on temperature variation through computational techniques. It was found that an optimal position of the load should be 15mm above the turntable to get better heating uniformity. Therefore, future work can include experimental verification of this computational results by placing the container 15 mm above the turntable to see the effect on heating uniformity

The average temperature raise (heating rate) in three power categories showed that it did not vary much in entire sectors. Average temperature raise in each sector in high, medium, and low power microwave ovens reached 21°C, 17°C and 13°C, respectively. The reason for no observable difference in temperature raise among sectors in all three power categories might be the variation along the sector gets averaged when the turntable rotates the food within the cavity. The non-uniform heating for the first three sectors (close to back cavity wall) varied from 16 to 21% while for other sectors (close to front cavity wall), it varied from 12 to 16%

Rated power of the microwave oven had an effect on average temperature raise and non-uniform heating. The heating rate was 11°C in a 800 W microwave oven while it was 23°C in a 1300 W microwave oven. Non-uniform heating was 8% in a 800 W, while it was only 4% in a 1300 W microwave oven. Therefore, higher wattage ovens provide not only faster heating but also achieve more uniformity. It should be noted that higher wattage ovens are more expensive and probably have higher quality magnetrons and better cavity design to achieve more uniform heating.

The 0.9 cubic-ft microwave oven has a non-uniform heating of 12%. Whereas, the higher cavity size, 2.2 cubic-ft, has a non-uniform heating as 6%. While the lowest cavity size had the highest heating non-uniformity, no clear trend was observed for the effect of cavity size on non-uniform heating. Therefore, cavity size has a weaker effect on non-uniform heating.

Conclusion

A container with multiple compartments was designed to assess the heating uniformity in a microwave oven. The study found that it is better to place the food at the edge of the turntable to achieve higher heating rate and more heating uniformity. Specific conclusions of this study are as follows:

1) Microwave energy distribution increases as the radial distance of the rings increases for all three power categories. The non-uniform heating increases until 10 cm of the radial distance of rings and then it decreases in two outer most rings. This gives the clear suggestion that the food needs to be placed on

the edge of the turntable to achieve a higher heating rate and more uniform heating.

2) A 13 °C higher heating rate was achieved for high power microwave ovens, in comparison to low power microwave ovens. Non-uniform heating in high power microwave ovens is less than low and medium power microwave ovens. It is concluded that foods can be heated with a higher heating rate and less non-uniform heating in high power microwave ovens.

3) Microwave energy distribution did not vary along the sectors for all three power categories. But, non-uniform heating in the first three sectors (0° to 180°) which represent the half portion of the container closer to back cavity wall ranges from 20% to 16%. In contrast, the remaining three sectors 180° to 360° closer to front cavity wall had a non-uniform heating of 15%. Interaction effect of sector with power as well interaction of rings with sector were not significant ($p = 0.1655$; 0.0639, respectively).

4) It was found that 16 microwave ovens did have a significant effect on performance over time out of 19 microwave ovens. But, when removed the effect of power, rings and sectors on replication, microwave oven performance did not have significant effect ($p = 0.6121$). Any interaction of the power and rings with replication were also not significant ($p = 0.9359$ (power × rep); $p = 0.2243$ (rings ×rep)). Overall, the performance of the microwave ovens did not change over the time on power deliverance and absorption of in load.

5) Microwave power levels and radial distance of the rings significantly effect heating rate (p values of 0.0001 and <0.0001, respectively). Interaction of power and radial distance of the rings have a significant effect on heating rate ($p = 0.0435$) which means that heating rate increases as radial distance of the rings increases with respect to increase of the microwave oven power.
6) The interaction effect of radial distance of the rings and sectors was not significant ($p = 0.\ 0639$) which means that heating rate increases as the radial distance of the rings increases irrespective of the sector.

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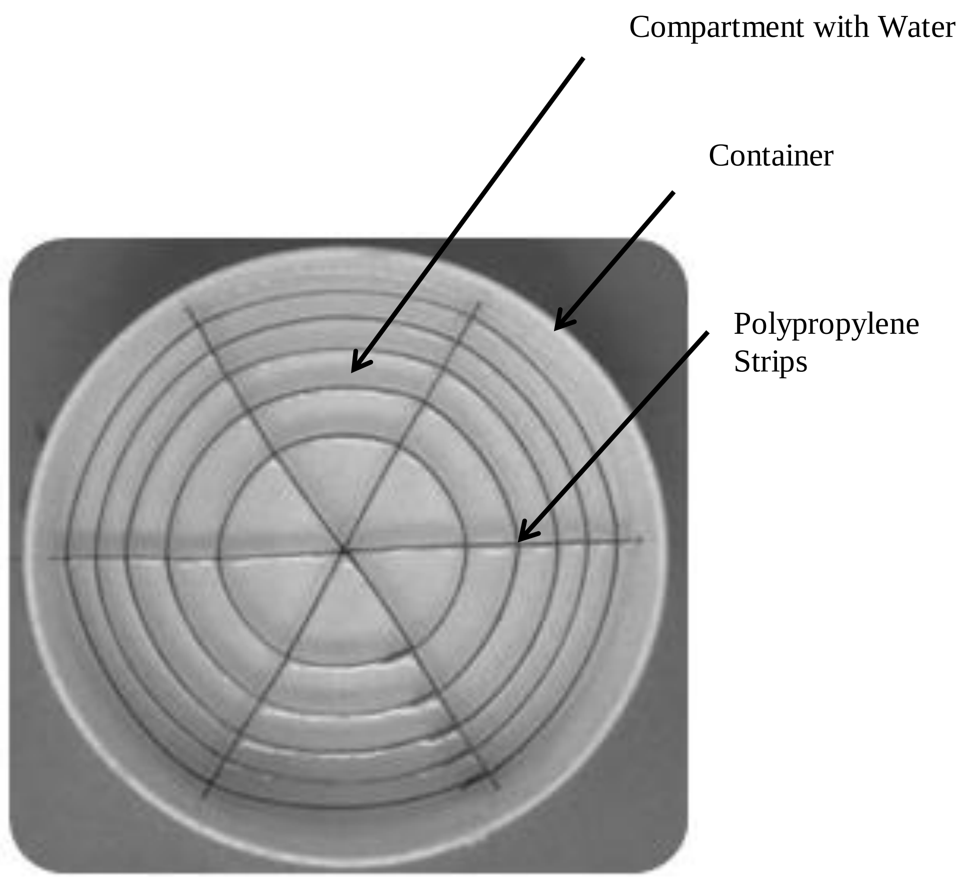


Figure 4.1. A container with multiple compartments to assess non-uniform heating.

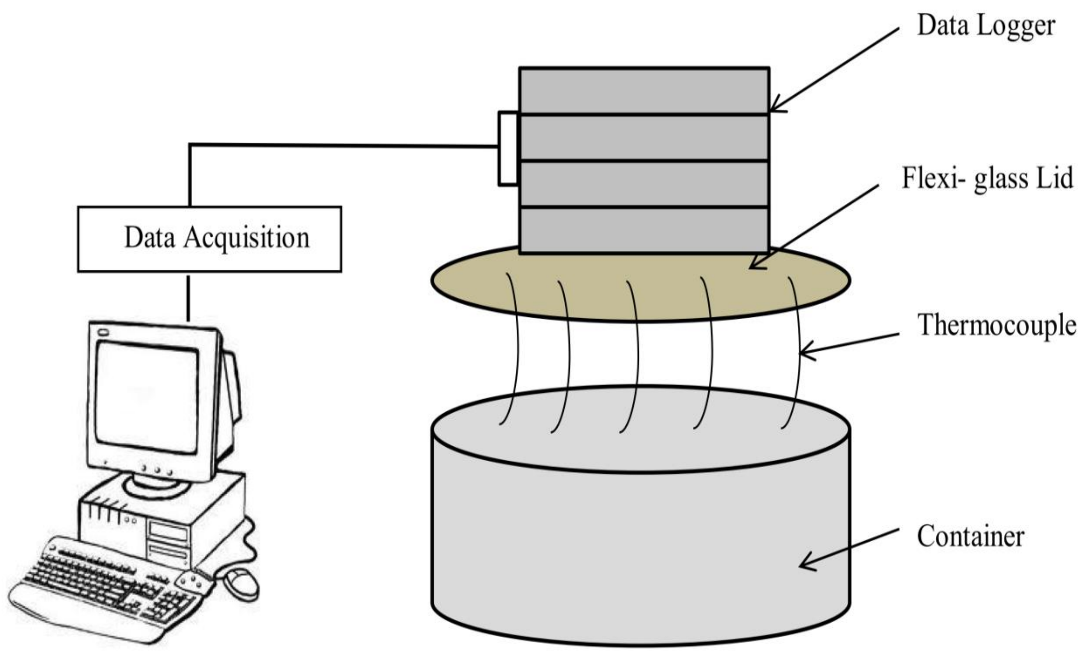


Figure 4.2. Schematic diagram of the data acquisition system.

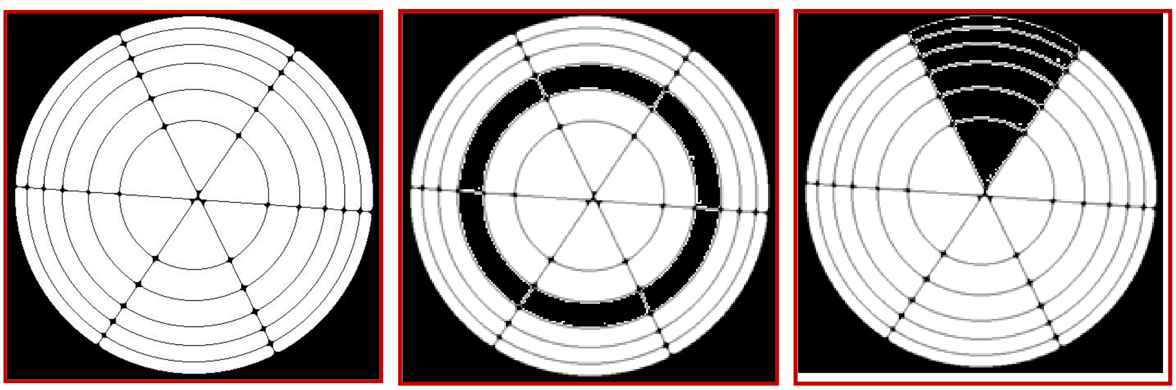


Figure 4.3. Depiction of a ring and a sector in container with a ring of radial distance of 12 cm from center of the container (black portion in center image) and a sector of 60 to 120 degree (sector starts from first quadrant of the container; (black pie portion in right side image).

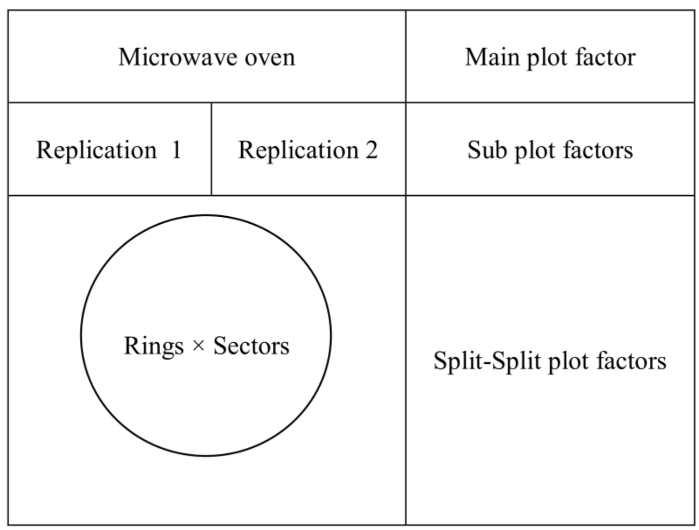


Figure 4.4. Split-Split design plot.

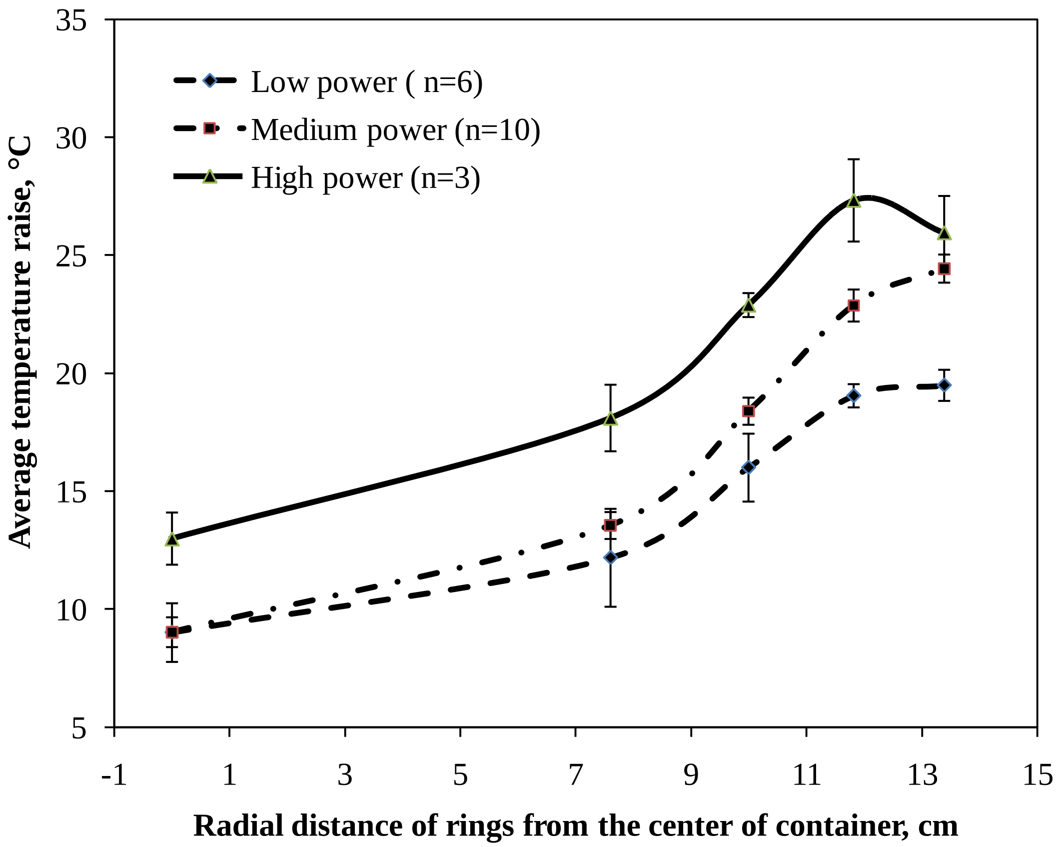


Figure 4.5. Effect of radial distance of rings on average temperature raise (heating rate) in low, medium and high power microwave ovens (error bar indicates the standard error of deviations of temperature raises).

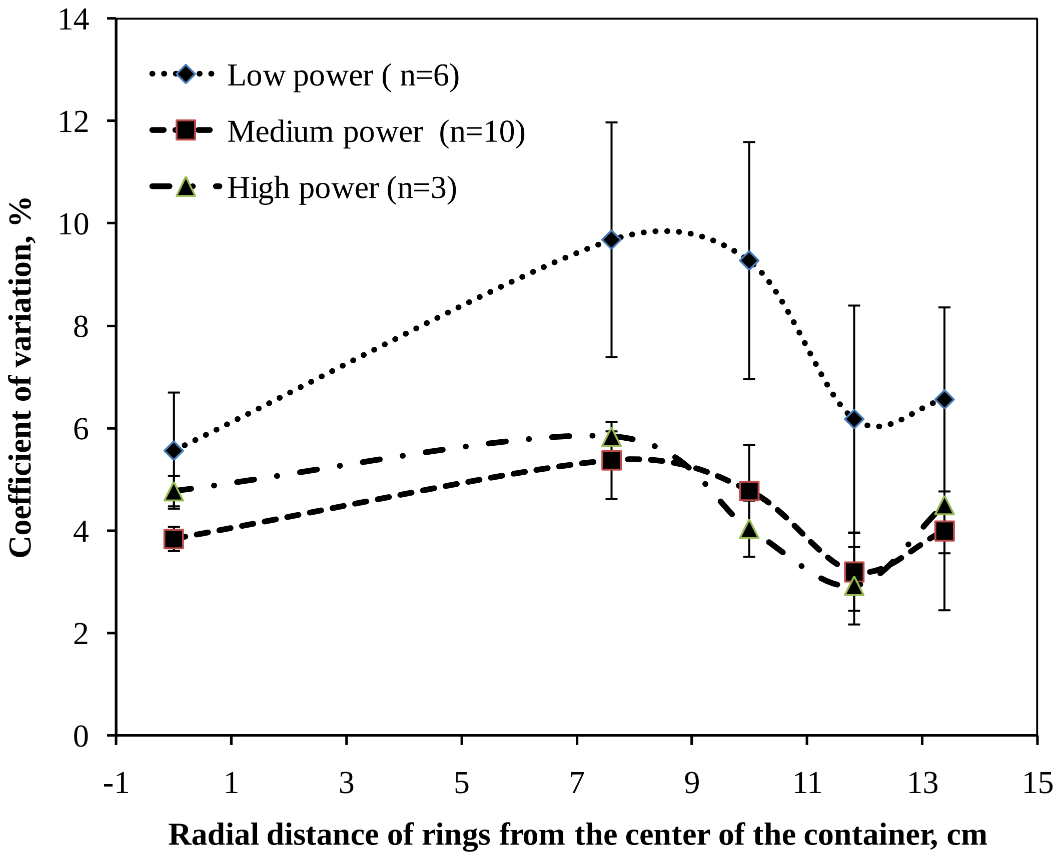


Figure 4.6. Effect of radial distance of rings in non-uniform heating for low, medium and high power microwave ovens (error bar indicates the standard error of deviations of COV).

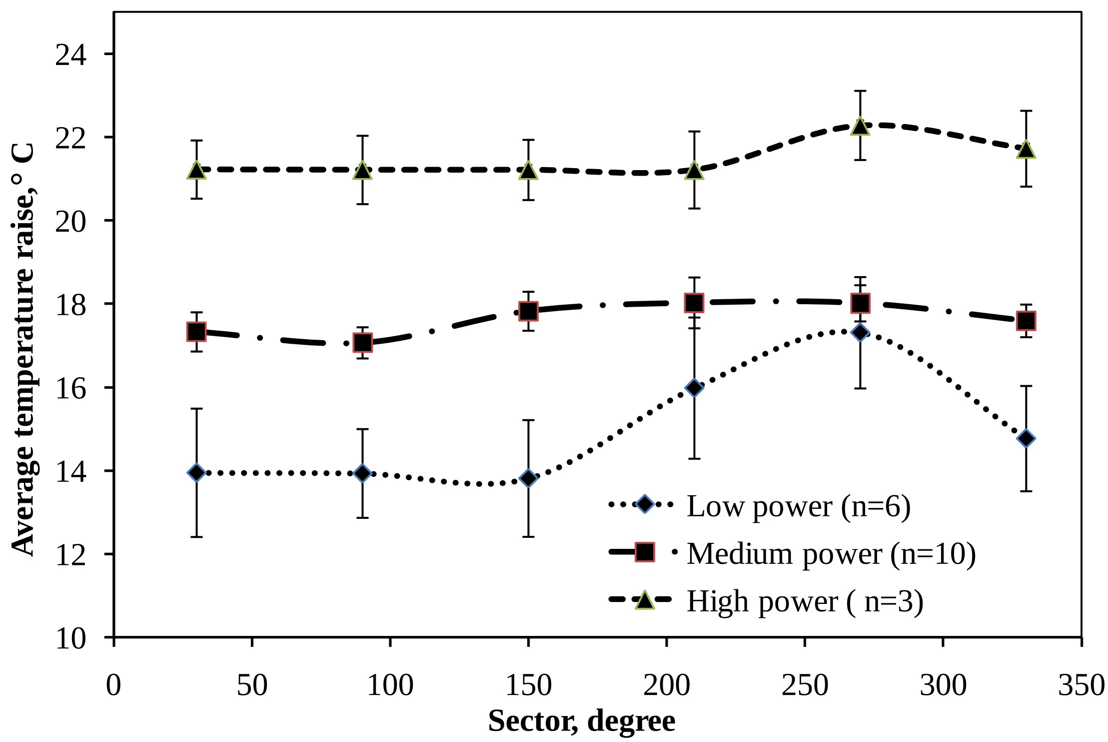


Figure 4.7. Effect of sectors on average temperature raise in low, medium and high power microwave ovens (error bar indicates the standard error of deviations of temperature raises).

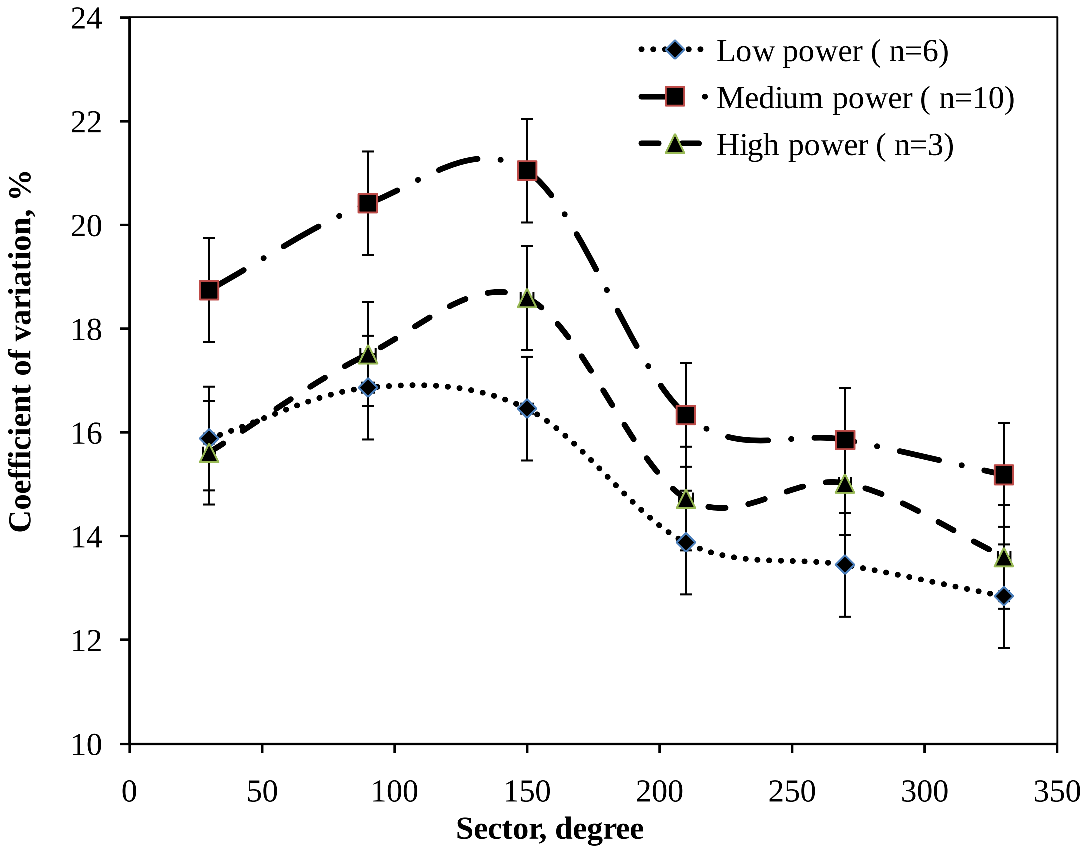


Figure 4.8. Effect of sectors on non-uniform heating in low, medium and high power microwave ovens (error bar indicates the standard error of deviations of COV).

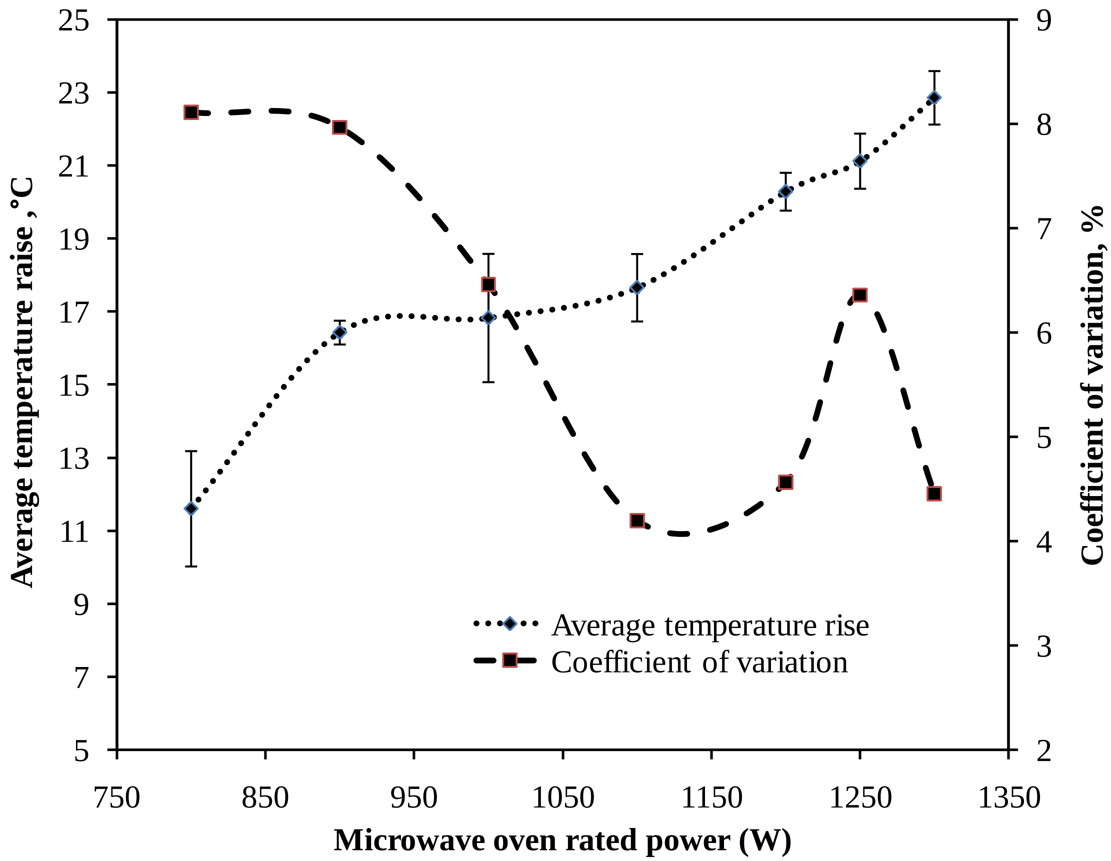


Figure 4.9. Effect of microwave rated power on average temperature raise and non-uniform heating.

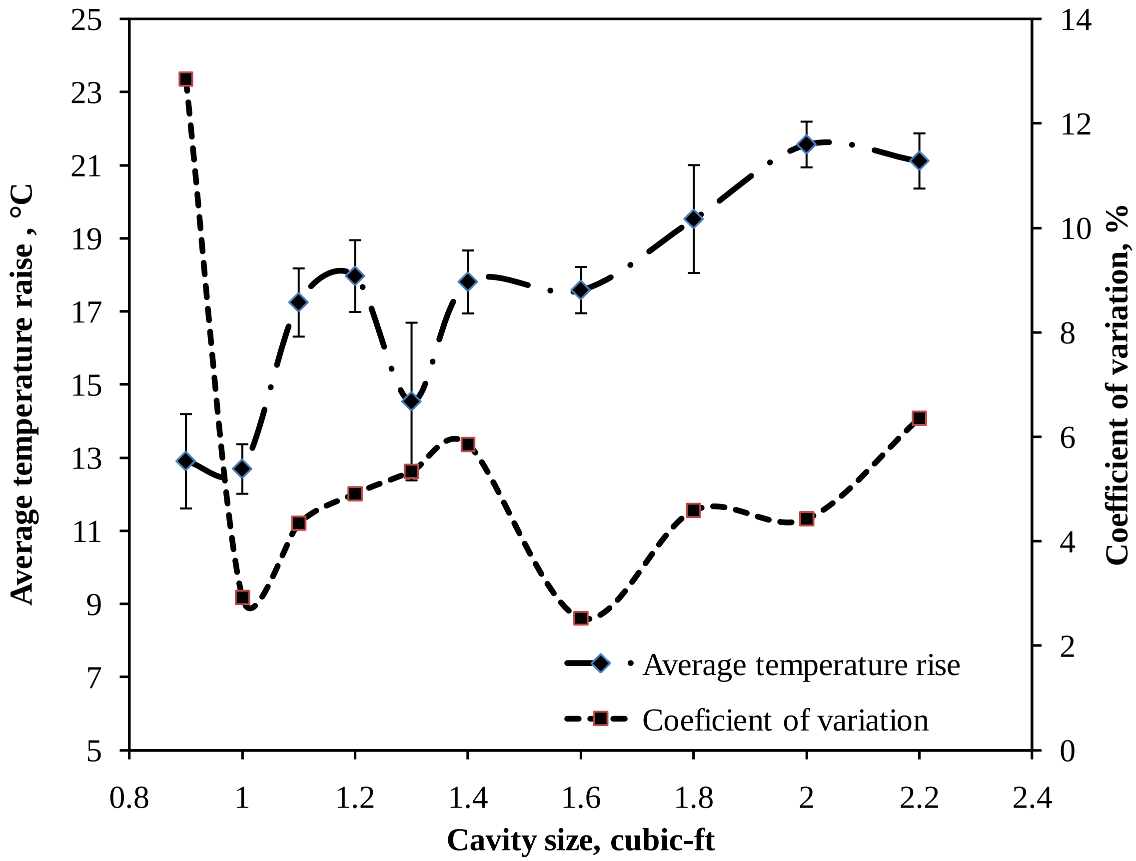


Figure 4.10. Effect of cavity size on average temperature raise and non- uniform heating.

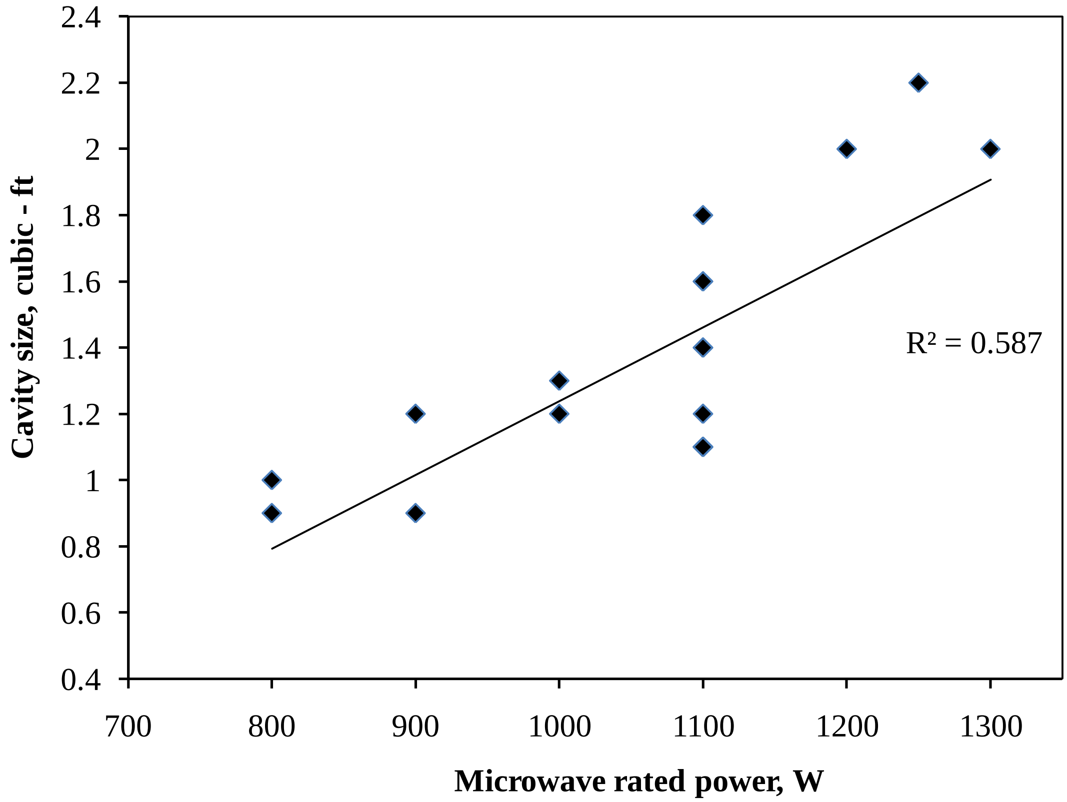


Figure 4. 11. Linear relationship of microwave rated power against cavity size.

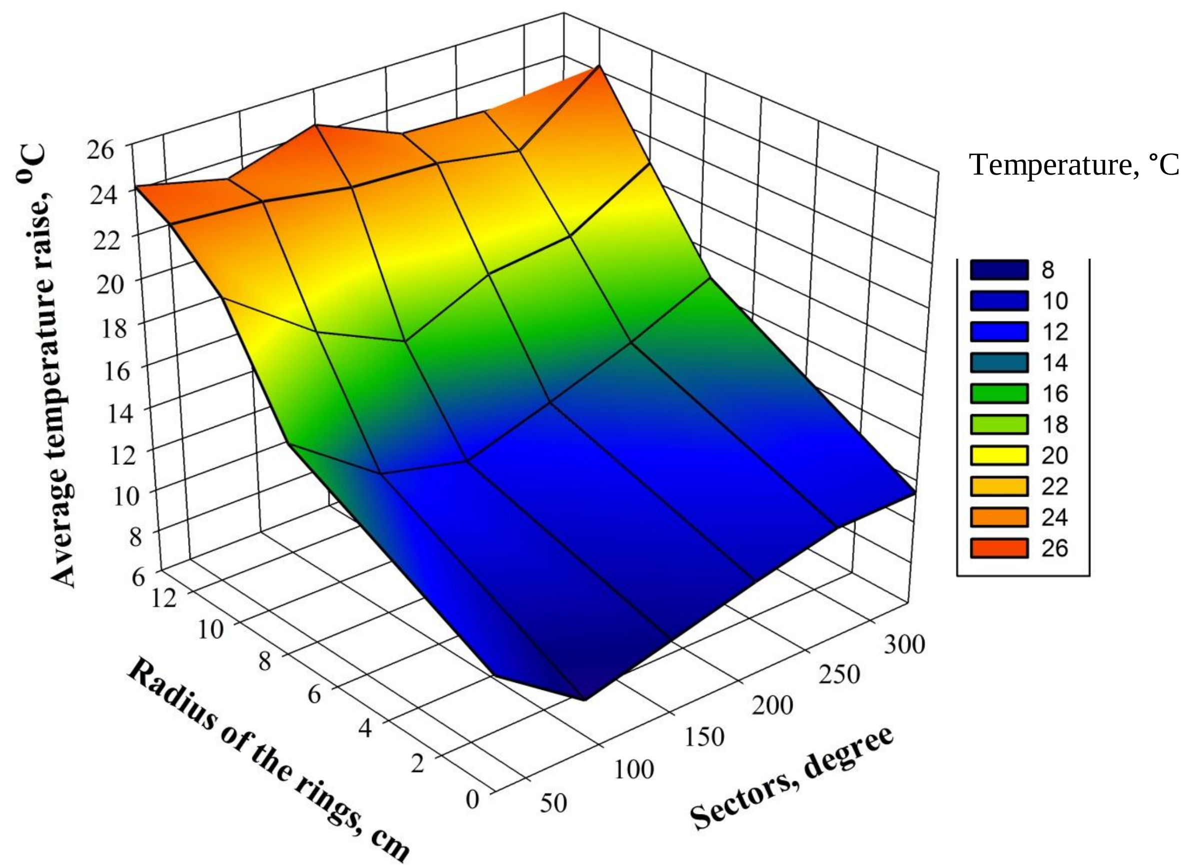


Figure 4. 12. Interaction plot of effect of radius of the rings and sectors on average temperature raise.

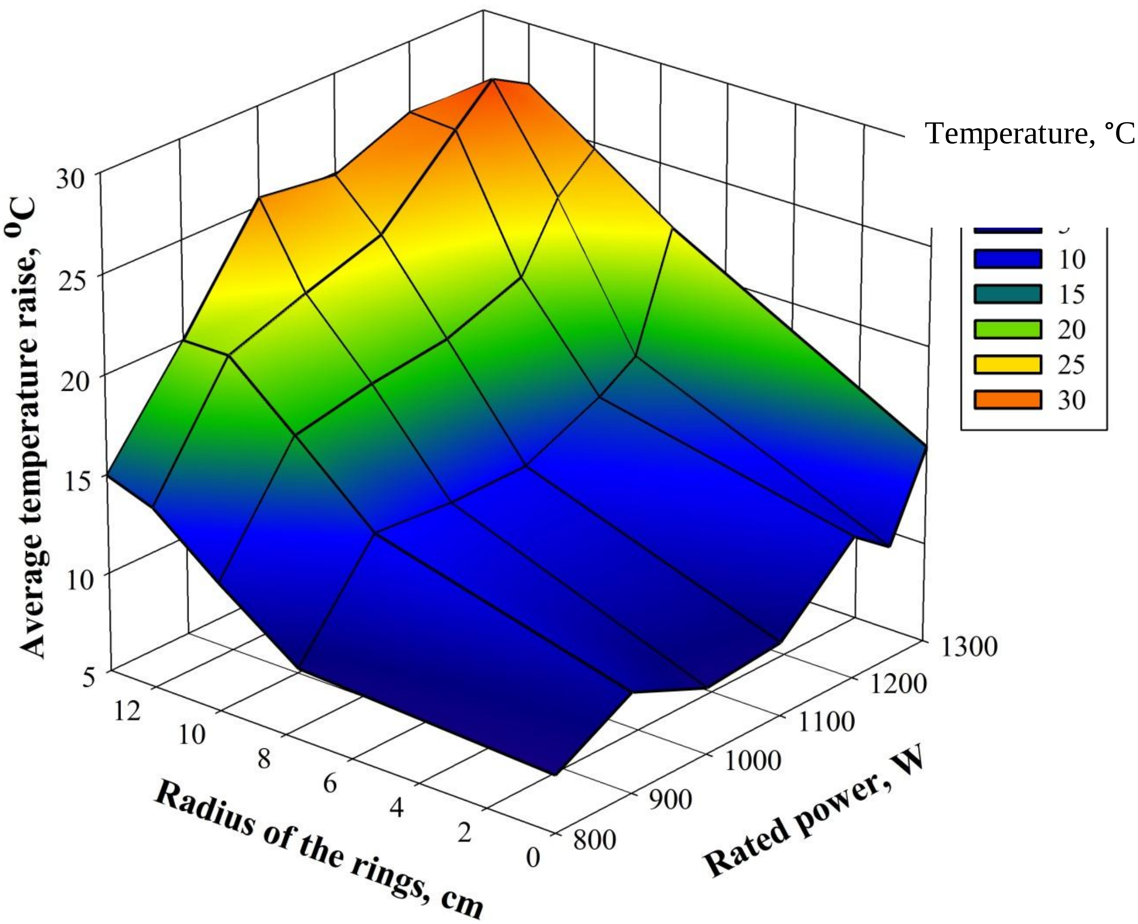


Figure 4. 13. Interaction plot of effect of rated power and radius of the rings on average temperature raise.

Table 4.1. Classification of microwave ovens based on power category.

	Low Power	Medium Power	High Power
Power Range	800-1000 W	1050-1100 W	1200 -1300 W
Number of Ovens	6	10	3

Table 4.2. Statistical significance t-test for each microwave oven.

Microwave Oven	Confidence Interval		t-stat	Std. Deviation (°C)	p-value
10 [a]	0.142	1.415	2.501	1.705	0.018
24 [a]	-5.867	-1.147	-3.039	6.320	0.005
114 [a]	-1.461	-0.456	-3.903	1.345	<0.001
119 [b]	-1.820	2.103	0.147	5.253	0.883
123 [a]	2.537	3.561	12.177	1.371	<0.001
124 [a]	-2.787	-1.049	-4.515	2.326	<0.001
126 [a]	-3.038	-1.205	-4.736	2.454	<0.001
127 [a]	1.237	2.933	5.030	2.270	<0.001
128 [a]	0.104	0.687	2.782	0.779	0.0094
129 [a]	-1.607	-1.017	-13.202	0.577	<0.001
130 [a]	0.387	1.037	4.486	0.870	<0.001
131 [a]	0.674	2.261	3.782	2.125	<0.001
132 [b]	-1.892	0.745	-0.889	3.531	0.381
133 [a]	-1.427	-0.661	-5.572	1.026	<0.001
134 [a]	0.862	2.584	4.093	2.306	<0.001
135 [a]	1.112	1.965	7.379	1.142	<0.001
137 [a]	0.031	1.432	2.138	1.875	0.041
140 [b]	-2.580	0.445	-1.442	4.051	0.159
141 [a]	-1.926	-0.145	-2.380	2.384	0.024

a – significant effect ($p \leq 0.05$)   b-not significant effect ($p > 0.05$)

Table 4.3. Type 3 tests of fixed effects of the split-split model.

Effect	NUM DF	Den DF	F-Value	p>F value
Rep [b]	1	24	0.26	0.6121
Power [a]	6	24	7.67	0.0001
Rings [a]	4	48	80.06	<.0001
Power*Rings [a]	24	48	1.79	0.0435
Power*Rep [b]	6	24	0.29	0.9359
Rings*Rep [b]	4	48	1.48	0.2243
Power*Rings*Rep [b]	24	48	0.74	0.7804
Sector [a]	5	775	5.99	<.0001
Power*Sector [b]	30	775	1.25	0.1655
Rings*Sector [b]	20	775	1.53	0.0639
Power*Rings*Sector [b]	120	775	0.76	0.9695

a – significant effect ($p \leq 0.05$)   b - not significant effect ($p > 0.05$)

CHAPTER IV

SUMMARY AND RECOMMENDATIONS

Coupled electromagnetic and heat transfer modeling of microwave heating is an important tool in understanding system performance and issue of non-uniform heating. Non-uniform heating is a major concern for food safety especially in not-ready-to-eat (NRTE) foods. Several variables contribute to non-uniformity of heating including variables associated with the microwave oven, food properties, and consumer practices. Thus, these variables affecting microwave heating need to be incorporated into a risk assessment model to identify the events leading to illness and their effects on eventual food safety risks. Risk assessment model determines the microbial population dynamics at each and every step of processing. In case of risk assessment of microwaveable food products, the steps include storage in freezers, cooking in a microwave oven including standing time, consumption, and dose-response. A microbial death kinetics model can be used to determine the destruction during cooking and standing time; however, this model requires a time-temperature profile. To determine the time-temperature profile, an accurate heat transfer model is required.

In this study, a comprehensive coupled electromagnetic and heat transfer model was developed to simulate microwave heating in a domestic oven. Maxwell's electromagnetic equations and Fourier's heat transfer equations were solved simultaneously using the conformal FDTD based numerical solver, QuickWave 3D software. The protocol for developing coupled model included creating the geometry of oven, optimization of simulation parameters, simulation, and validation of the model.

Simulation temperature results obtained using optimized parameters were compared with the experimental temperature profiles of 1% gellan gel cylindrical model food. The gel cylinder was placed on a stationary turntable and subjected to 30 s of heating in a 700 W rated power microwave oven. In the experimental work, spatial and temporal profiles were collected using a thermal imaging camera and fiber optic sensors, respectively. The predicted temperature profiles of the mathematical model were validated with the experimental profiles. Model spatial profiles were in good agreement with thermal imaging profiles qualitatively. Time-temperature profiles of the simulation were validated with the experimental study in 12 discrete locations of the model food. Quantitative validation of time-temperature profiles showed that average root-mean squared error of 12 locations of the model food was 2.02°C.

In this study, a method for assessing heating uniformity within domestic microwave ovens was developed. A custom designed container was used to assess heating uniformity of a range of microwave ovens using a hedgehog of 30 thermocouples. The variation of average temperature raise and heating non-uniformity along the radial distance and sector of the container was studied. For two minutes of heating 1-liter of water load in microwave ovens, the temperature raise ranged from 10ºC at the center of the cavity to 25ºC at the edge of the turntable. For just for 2 minutes of heating, the temperature difference can be as high as 15ºC. It was found that water will get more uniform heating at the edge of the turntable rather than at center of the turntable when the container was allowed to rotate. Thus, it is better to place food at the edge of the turntable rather than at the center of the turntable for rapid and uniform heating.

The developed test method can be used for performance testing of a range of microwave ovens.

Effects of rated power and cavity volume on average temperature raise and heating non-uniformity were also studied for a range of microwave ovens. High power microwave ovens, as expected achieved higher temperature raise, which is 13°C more than low power microwave ovens. Non-uniform heating in high power microwave ovens is lower than low and medium power microwave ovens. It can concluded that foods can be heated more rapidly and more uniformly in high power microwave ovens. Larger size cavity (2.2 cubic feet) achieved a higher temperature rise, 7°C more than the smaller size cavity (0.9 cubic foot) and had 6% less non-uniform heating than the smaller size cavity.

A study was also conducted to see the effect of sectors on temperature raise and non-uniform heating. Temperature raise does not vary along the sectors in low, medium and high power microwave ovens. Absorption of energy in sectors is uniform because the turntable is rotated during heating. But, non-uniform heating increases in the first half of the sectors located close to back cavity wall (sectors 0° to 180°) and then decreases in the second half of the sectors located close to front cavity wall (sector 180° to 360°).

A statistical model was developed to understand the interaction effects of radial distance of rings and sectors to identify the best location for placing food on a turntable. The power of the microwave oven and radial distance of the rings had an interaction effect. Temperature difference in the two outer most rings had a significant interaction with power levels but there is no such interaction for the inner three rings.

Recommendations for Future Research

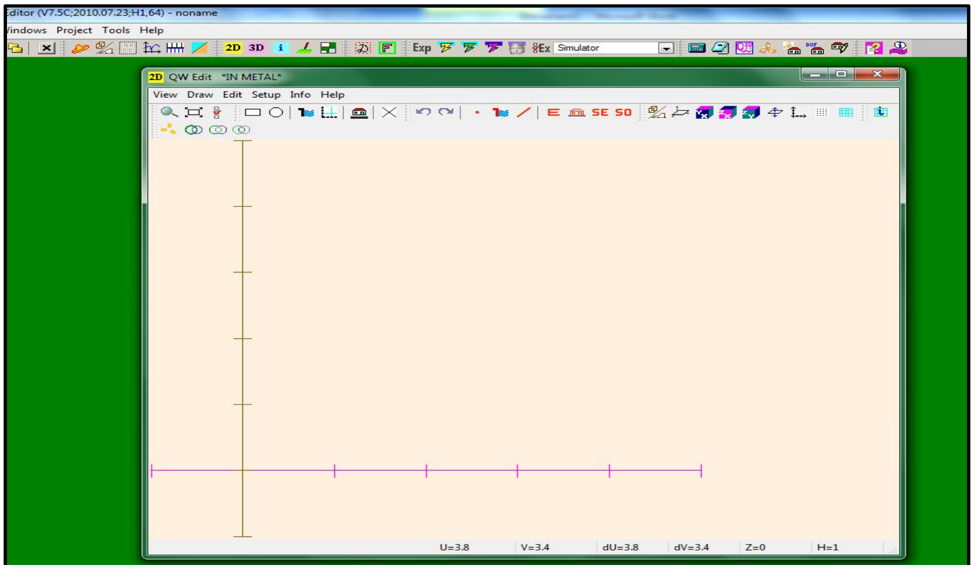
- In this study, the microwave heat transfer model was developed assuming no evaporative losses from the load. This assumption is only valid for short microwave heating periods in which the product temperature does not go beyond 70° C. In reality, air flow inside the cavity induces evaporative heat and mass losses at the interface of food and air. To include the mass and momentum transfers in numerical computation, it is recommended that the present model include the Navier-Stoke's equations with the convective boundary condition at the air and food interface.
- Rotation of food while heating in microwave ovens is known to enhance heating uniformity. In the current model, the load was placed stationary on the glass turntable to reduce the computational time to optimize the simulation parameters. In QuickWave 3D software, simulation of rotating load is an in-built function. Therefore, rotation effects can be easily simulated with optimized simulation parameters. It has been patented by Cho (Article: Microwave oven having vertically reciprocable turn table, US Patent No: US 5667714) that moving the load vertically inside the cavity would improve the heating uniformity better than rotating horizontally. Therefore a systematic study could be undertaken to study the effect of moving load in vertical and horizontal planes.
- The model has been validated with single component and assuming no phase change occurring during heating. However, NRTE foods contain heterogeneous components and they undergo phase changes. Therefore, it will be necessary to improvise the model to take this factor into account.

- The developed model can be used to study the effect of physical and thermal properties of NRTE foods on heating uniformity. This will help food product developers to design foods to minimize food safety concerns. Similarly, effects of frequency, a microwave oven parameter, on heating profiles needs to be studied systematically to give the option for developing variable frequency microwave ovens.
- The ultimate goal would be to develop a website, where a food processor can select a list of various microwave ovens and design the package shape and product layout using the built-in CAD software, and then change ingredients which would automatically adjust food properties and can simulate microwave heating. So, food processors could do a virtual microwaveable food product development, before they market the product. This will be a useful tool for microwave oven design engineers, food product development personnel, government regulatory agencies and most importantly for consumers.
- Susceptors, a thin metal film, has been used with NRTE foods to improve heat transfer effects and evenness of heating food. This is a promising study which could be characteristically studied for different packaging materials to find the optimized and suitable susceptors design and material for microwave application.
- Heating uniformity assessment was conducted with the water load that covered most of the turntable surface and came up with the recommendation to place the food at the edge of the turntable. However, when the food (load) is placed on a small location within a cavity, the distribution of electromagnetic field changes altogether in the cavity, which will alter the power delivery scenario. Therefore, further studies must

be conducted with a small water load placed at various radial distanced and the heating rate and heating uniformity must be assessed.

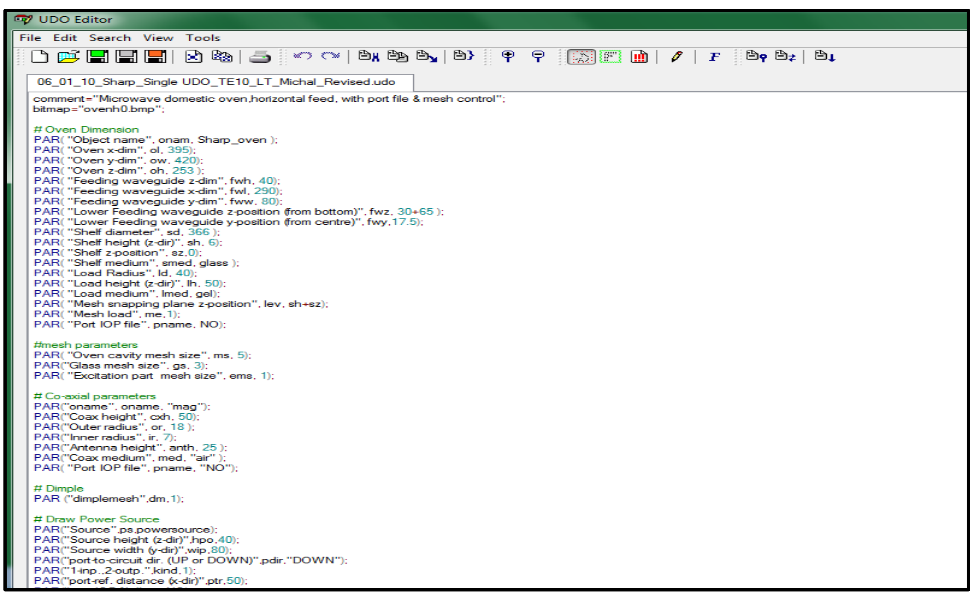
APPENDICES

A.3.1. Steps to develop microwave-heating model in Quickwave 3D software.



Quickwave 3D & V2D editor empty window

Path: Windows start menu/ All programs/ Quickwave/ QW 3D & V2D Editor



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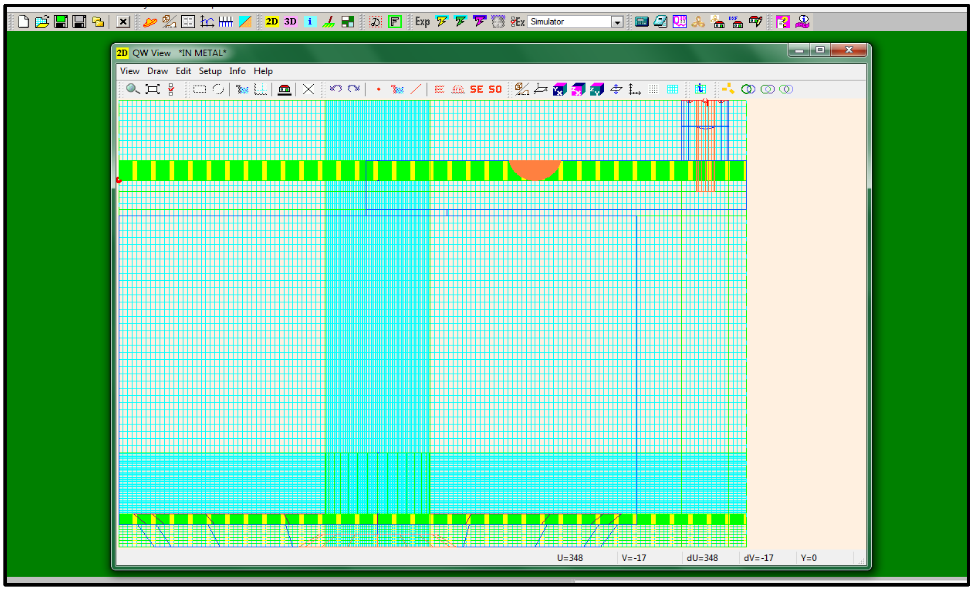

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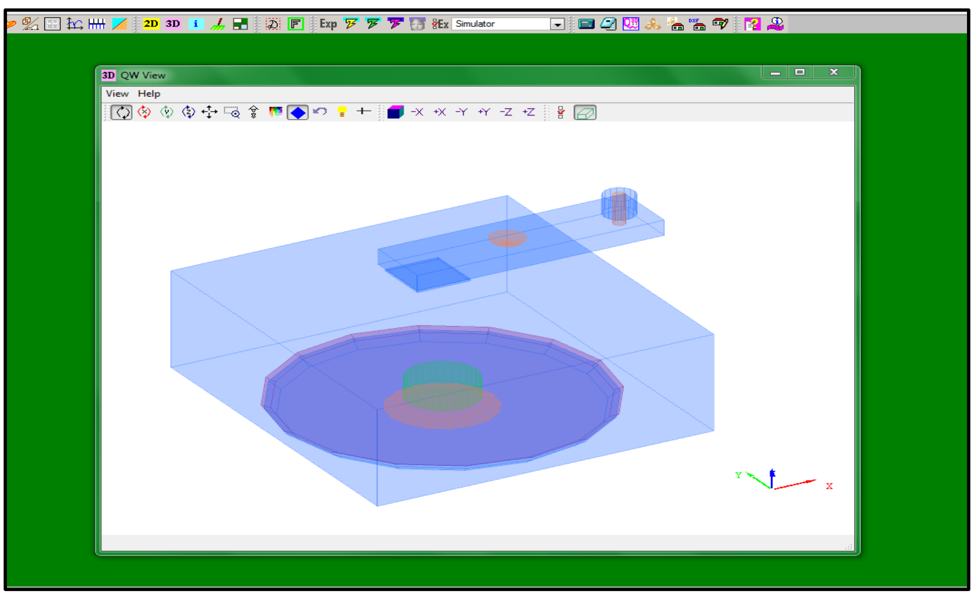

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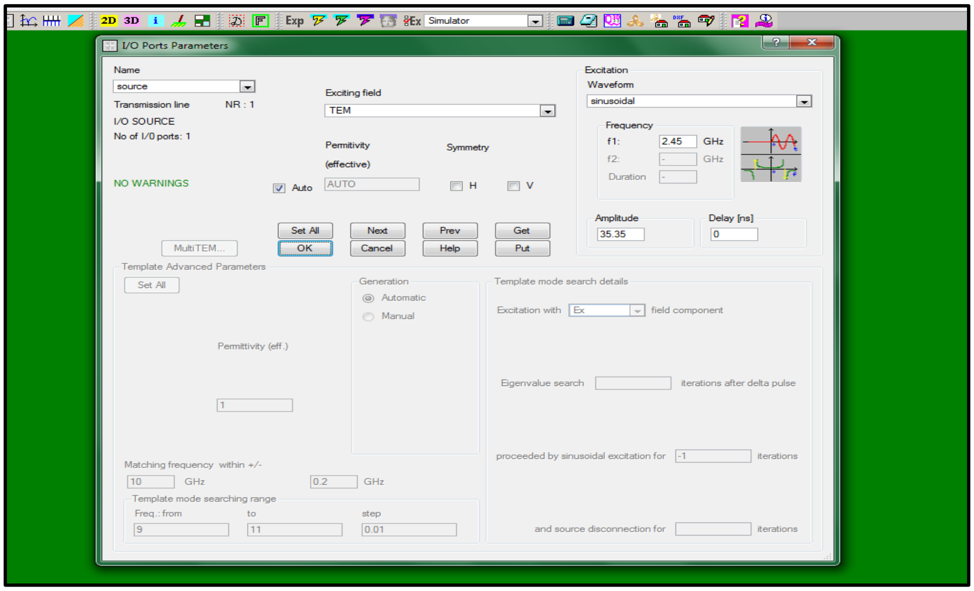

Port parameters editing window

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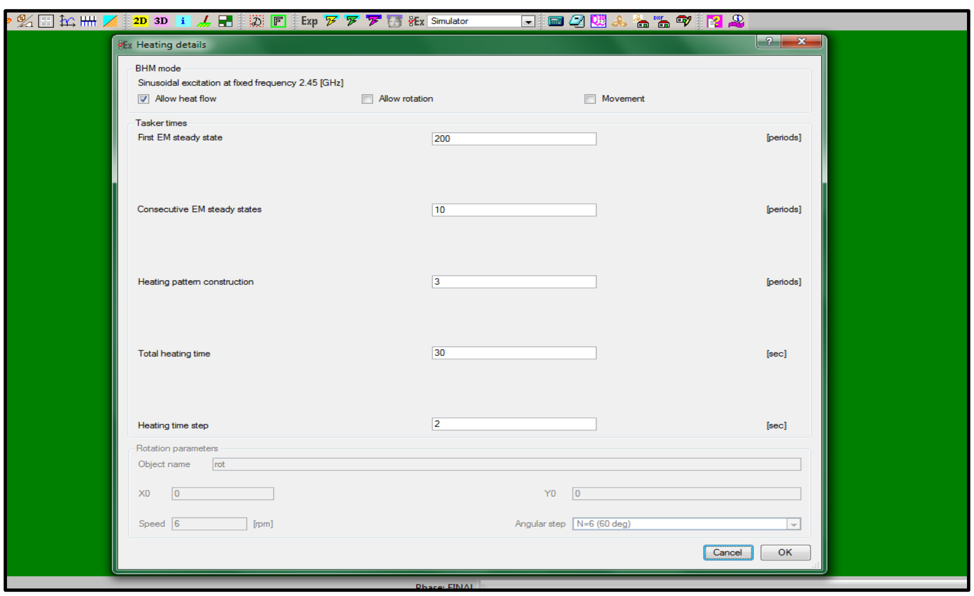

Heating details editing window

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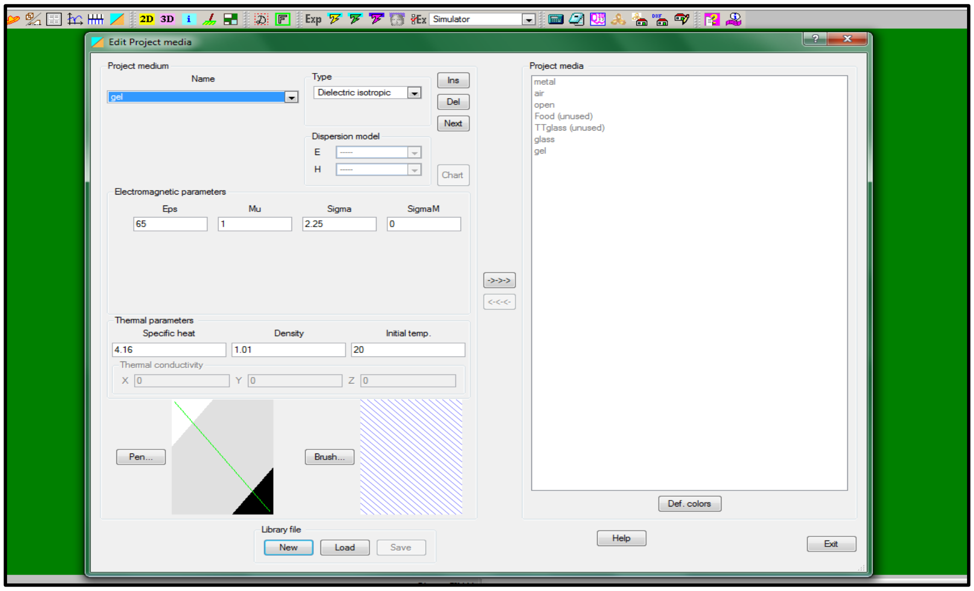

Project medium (properties) editing window

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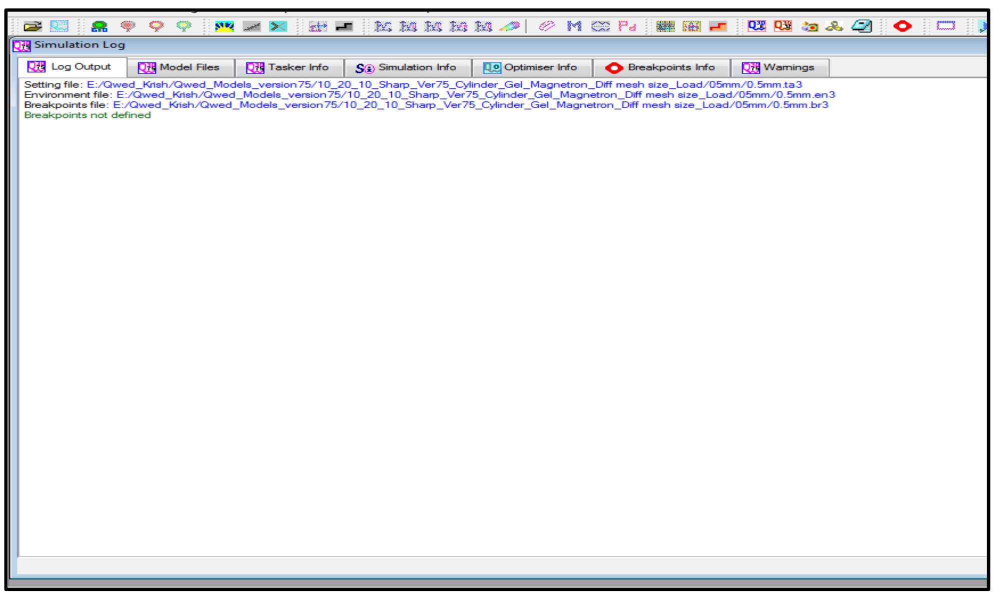

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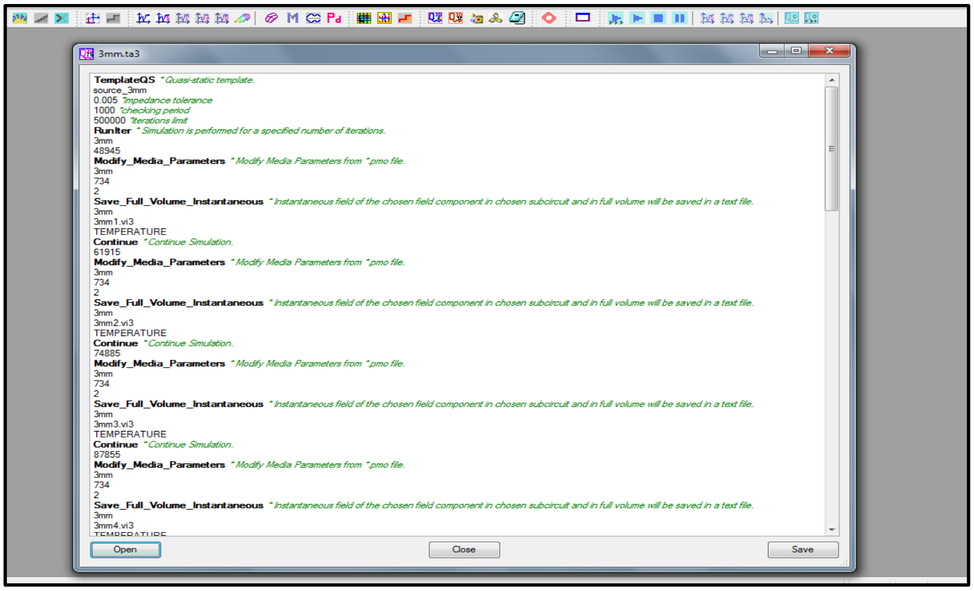
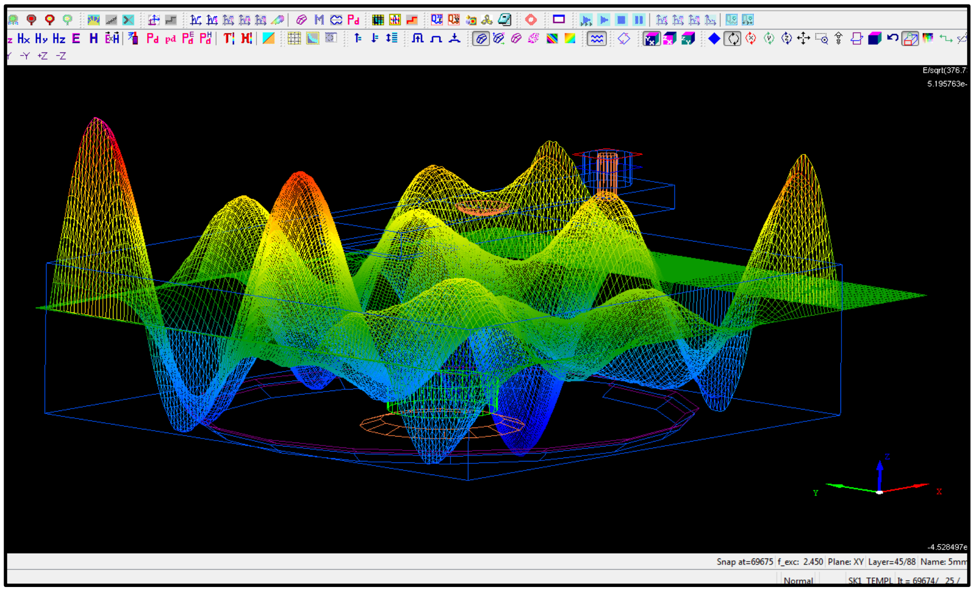


Quickwave 3D & V2D simulator tasker file (exported file information) window

Path: Quick Wave 3D Simulator/ View/ Edit Ta3 File

Quickwave 3D & V2D simulator log file (current simulation information) window

Path: Quick Wave 3D simulator/ View/ Simulation Log



Quickwave 3D & V2D simulator electric field distribution window

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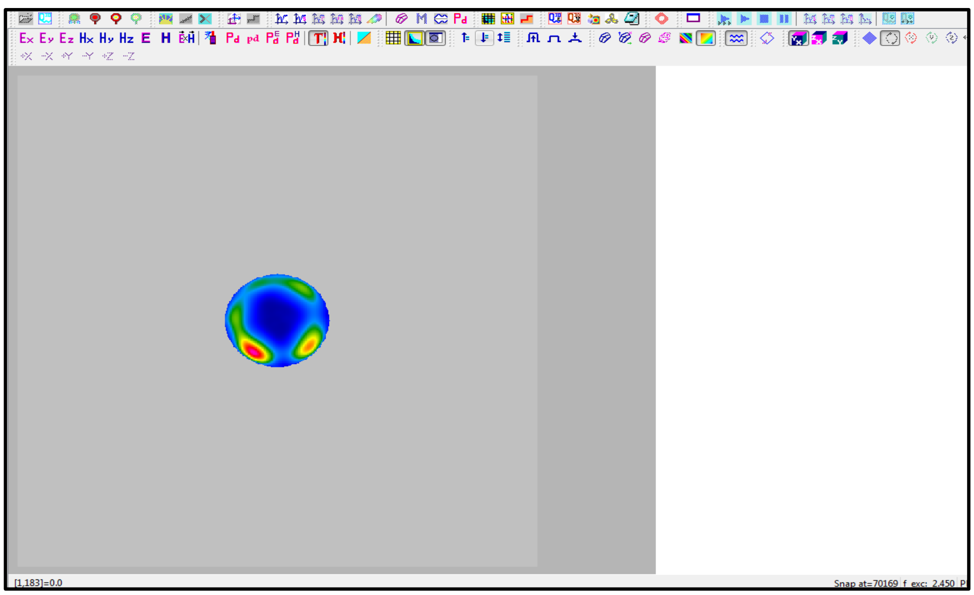

Quickwave 3D & V2D simulator temperature field window

Path: Quick Wave 3D simulator/ View/ Fields/ T/ Continuous mode

A.4.1. A sample SAS code used for split-split model design.

```
option pageno=1;
data A;
input oven power      Cavity Rep     Rings   sector  Tin      Tfinal;
Tdiff=Tfinal-Tin;
cards;

::::::::::::::::::::::::::::::::::::::::::::::::::::

Data


::::::::::::::::::::::::::::::::::::::::::::::::::::

;
run;
proc print;run;

Proc sort data=A;
by Rep Power Rings sector;
run;
proc means data=A;
by power rep rings sector;
var Tdiff;
run;


Proc mixed data=A covtest;
Class  Power Rings oven sector rep;
Model Tdiff=rep Power Rings Power*Rings rep*power rep*Rings rep*Power*Rings
Sector Power*sector rings*sector power*rings*sector;
random oven(Power rep) oven(power rings) oven(rep power rings);
lsmeans  power*rings;
ods output lsmeans=lsm;
run;

axis1 value=(h=1) label=(h=1 'Outer to Inner Ring');
axis2 value=(h=1)  label=(h=1 angle=90'Temperature') ;
axis3 value=(h=1) label=(h=1 'Distance') ;
axis4 value=(h=1) label=(angle=90 h=1 'Covariance of Between Ring effects');
legend1 value=(h=1)label=(h=1 'From Time');
symbol1 color=blue interpol=join l=1 value=square;
symbol2 color=green interpol=join l=2 value=circle;
symbol3 color=red interpol=join l=20 value=triangle;
symbol4 color=black interpol=join l=3 value=plus;
```

```
symbol5 color=blue interpol=join l=4 value=star;
symbol6 color=red interpol=join l=5 value=dot;
symbol7 color=green interpol=join l=5 value=cross;
run;
proc gplot data=lsm;
        plot estimate*Rings=Power /vaxis=axis2 haxis=axis1 ;
        plot estimate*Power=Rings /vaxis=axis2 ;
Run;


******************************************** sector ********;
Proc mixed data=A covtest;
Class  Power Rings oven sector rep;
Model Tdiff=rep Power Rings Power*Rings rep*power rep*Rings rep*Power*Rings
Sector Power*sector rings*sector power*rings*sector;
random oven(Power rep) oven(power rings) oven(rep power rings);
lsmeans  sector*rings;
ods output lsmeans=lsm;
run;

axis1 value=(h=1) label=(h=1 'Sectors');
axis2 value=(h=1)  label=(h=1 angle=90'Temperature') ;
axis3 value=(h=1) label=(h=1 'Distance') ;
axis4 value=(h=1) label=(angle=90 h=1 'Covariance of Between Ring effects');
legend1 value=(h=1)label=(h=1 'From Time');
symbol1 color=blue interpol=join l=1 value=square;
symbol2 color=green interpol=join l=2 value=circle;
symbol3 color=red interpol=join l=20 value=triangle;
symbol4 color=black interpol=join l=3 value=plus;
symbol5 color=blue interpol=join l=4 value=star;
symbol6 color=red interpol=join l=5 value=dot;
symbol7 color=green interpol=join l=5 value=cross;
run;
proc gplot data=lsm;
        plot estimate*sector=rings /vaxis=axis2 haxis=axis1 ;
        plot estimate*rings=sector /vaxis=axis2 haxis=axis1 ;
Run;
```