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Mathematical and Computer-Based Models for Optimizing Microwave Heating Processes of Frozen Oysters

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MATHEMATICAL AND COMPUTER-BASED MODELS FOR
OPTIMIZING MICROWAVE HEATING PROCESSES OF FROZEN
OYSTERS

A Dissertation

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ABSTRACT

Consumers with full-time jobs prefer microwavable-frozen-meals for convenience when lack time to cook. Microwaves do not require a medium for heat transfer and provide quick heating even in low thermal conductivity foods, which does not occur in conventional heating. The main problem in utilizing microwave-heating for cooking is the non-uniform temperature distribution in foods which may result in insufficient lethality of microorganisms in some part. This non-uniformity can be due to a number of factors including composition and geometry of food. The objectives of this study were to develop a mathematical-model based on Maxwell's equations for predicting the temperature distribution in frozen oyster- meats undergoing microwave-heating and to solve the mathematical-model of the microwave heating process for frozen-oysters with finite-element-software.

Oyster meats were analyzed for proximate analysis. The thermal properties of oyster were determined by Choi and Okos's equation. The dielectric properties of oyster meat were measured by transmission line method. Oyster meats were frozen cryogenically at -20°C and weight, shape, and dimensions of the frozen-meats were measured. The frozen samples were placed in a laboratory Microwave-Workstation with a maximum power of 1200 W at the operational frequency of 2450MHz. Temperature sensors with fiber optic leads were used to minimize interactions with microwaves. The sensors were connected to a computer with a FISO commander direct acquisition system. Temperature profiles were plotted in real-time during microwave

heating. A model based on the Maxwell's equations was developed and used to model the heat generation during microwave-heating.

The model predicted hot spots and cold spots in the oysters. Fresh oysters were heated to 100°C within 12 sec with the microwave heating. Frozen oysters reached 100°C after 20 sec of microwave-heating. The temperatures of oysters immediately after microwave-cooking ranged from 85.9 to 100.3°C, which evidenced that microwave cooking creates non-uniform-heating. The root-mean-square-error of the predicted-temperature vs. actual experimental values at hot spots ranged from 0.23 to 5.47 °C. This is decent agreement, and thus provides confidence in the model's ability to predict temperature-profiles of frozen-oyster-meats during microwave-cooking. The models were also employed to predict the temperature distribution for oyster meat-contained microwavable instant meals.

CHAPTER 1 INTRODUCTION

As an alternative to conventional heating methods, microwave heating is widely used in the food industry and household to process foodstuff in past decades. The most important characteristic of microwave heating is volumetric heat generation, which means that materials can absorb microwave energy internally and convert it into heat rapidly (Yam and Lai, 2006). Therefore, microwave heating becomes a popular way to cook, thaw, bake and roast food conveniently for consumers. Nowadays, there are millions of microwave ovens all over the United States.

The main problem associated with microwave heating is non-uniform temperature distribution in microwave-heated foods. Both the electromagnetic fields and the properties of the food can affect the temperature distribution during microwave heating (Zhang and others, 2001). Due to non-uniform temperature distribution, some areas of the material get heated very rapidly, whereas the remaining regions get heated to a lesser extent, which will lead to hot spots and cold spots in food (Ryynanen and others, 1996). The hot spots can cause quality change or loss in food, but the more serious concern is the cold spots which can lead to the incomplete kill of microorganisms.

Due to the interference of measuring devices with the electromagnetic field, the experimental measurements of temperature in the microwave is limited (Salvi and others, 2011). Numerical methods can be used to understand the process of microwave heating. The distribution of the electric and magnetic fields in microwave ovens with

or without any load has been described by Maxwell's equations (Dibben and Metaxas, 1994; Verboven and others, 2003; Rattanadecho, 2006). Coupled mass and energy balances must be solved taking into account the absorption of electromagnetic energy. Solution of Maxwell's equations for electromagnetics coupled with heat transfer in the oven cavity can be obtained by using different numerical methods. Accurate modeling of the microwave heating process requires effective methods for solving both electromagnetic and thermodynamic problems (Kopyt and Celuch, 2006). The computer simulation is introduced into this field to solve the mathematic models and predict the temperature distribution during microwave heating.

Oysters are one of the most popular types of seafood in the USA. Louisiana leads the oyster production in the nation. Approximately 14.0 million pounds of eastern oysters (*Crassostrea virginica*) were harvested in Louisiana in 2009 (Louisiana Department of Wildlife and Fisheries, 2012). As a natural filter feeder, oysters can concentrate microbes from surrounding waters. The accumulation for pathogens in oyster tissue will cause serious health risk. The main concern associated with oyster consumption is *Vibrio* species (especially *V. parahaemolyticus* and *V. vulnificus*) (CDC, 2013; Richards and others, 2010). Rapid freezing is an efficient post-harvest technique to eliminate the health risk in the oyster industry (Muth and others, 2011; Parker and others, 1994; Mestey, 2003). The combination of rapid freezing and packaging technique can provide a better oyster product to consumers with longer shelf life and less health risk. In the LSU Food Engineering Lab, a novel microwavable instant meal

had been developed to provide consumers an oyster based, safe, frozen and ready-to-eat meal product and help oyster processors to expand their market. Therefore, a better understanding of the microwave heating of frozen oysters and the microwavable meal is necessary.

The overall goal of this study was to develop a mathematical model to predict the heating behavior of frozen oyster product and simulate the microwave heating processing using a computer-based model. The mathematical model was developed initially, and then employed to build a simulation of the microwave oven heating process in a commercial software. The temperature distribution was given by the model to locate hot spots and cold spots and heating time.

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CHAPTER 2 LITERATURE REVIEW

2.1 Microwave Heating
2.1.1 Microwave

Microwaves are electromagnetic waves. The frequency range of microwaves is from about 300 MHz to 300 GHz (Figure 2.1) and corresponding wavelengths from 1 to 0.001 m. Microwave heating refers to the use of electromagnetic waves of certain frequencies to generate heat in a material (Metaxas, 1996). The Federal Communications Commissions (FCC) regulated the frequencies of 2450 MHz or 915 MHz for microwave heating in food processing. Only 2450 MHz is commonly used for food processing in Europe and 896 MHz in the United Kingdom (Galema, 1997; Venkatesh and others, 2004).
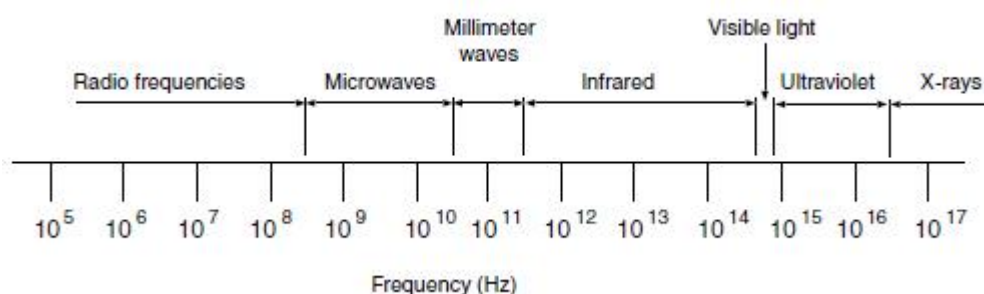
Figure 2.1 Electromagnetic spectrum (Dibben, 2001)

2.1.2 Mechanisms of dielectric heating

The volumetric heat generation is one of the most important characteristics of microwave heating. Conventional heating occurs by convection, followed by conduction, where heat must diffuse in from the surface of the material (Workneh and others, 2011). Volumetric heat generation means that materials can absorb microwave energy internally and convert it into heat. In microwave heating, heat is generated throughout the material, leading to faster heating rates (Workneh and others, 2011).

Microwave generates heat in two ways: dielectric and ionic (Yam and Lai, 2006). Dielectric heating by microwave involves dipole molecules, such as water, trying to align them in the electric field so that they oscillate to generate heat (Figure 1.2a). Ionic heating is due to the oscillatory migration of ions in the food driven by a high-frequency alternating electric field (Figure 1.2b). Rapid heating that requires less time to reach the desired temperature is the key advantage of microwave heating over conventional heating, resulting in less deterioration of organoleptic qualities.
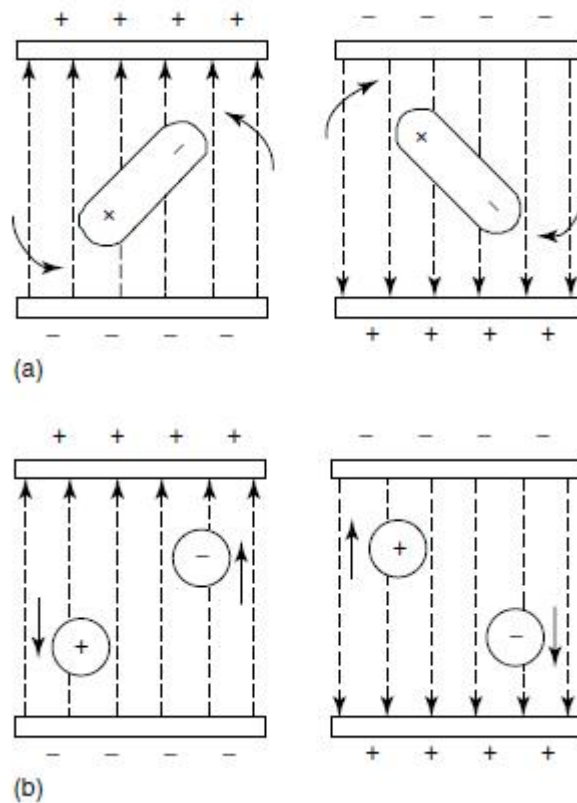
Figure 2.2 Microwave/heat conversion mechanisms (Yam and Lai, 2006).The dashed lines denote the alternating electric field at the frequency of microwaves. (a) A dipole rotates back and forth. (b) A positive ion and a negative ion oscillate in an alternating electric field.

2.1.3 Dielectric properties

The dielectric properties reflects how materials interact with an electromagnetic field. The relative complex permittivity (ε) is used to define the dielectric properties:

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$$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon|e^{-j\delta} \tag{2.1}$$

where ε' is the dielectric constant; ε'' is dielectric loss factor; j equals $\sqrt{-1}$ and δ is the loss angle of the dielectric, where $\tan \delta = \frac{\varepsilon''}{\varepsilon'}$ is defined as the loss tangent or dissipation factor (Nelson, 1999). The dielectric constant (ε') influences the material's capability to save the electromagnetic energy. The dielectric loss factor reflects the ability of the material to absorb electromagnetic energy and convert that energy into heat. The permittivity refers to the relative complex permittivity, which is the permittivity relative to free space, or the absolute permittivity divided by the permittivity of free space ($\varepsilon_0 = 8.854 \times 10 - 12$ F/m) (Nelson, 1999).

Microwaves can be reflected and transmitted by the food stuff. The fraction of microwave power reflected by the food material can be estimated by

$$P_{ref} = \left(\frac{\sqrt{\varepsilon'}-1}{\sqrt{\varepsilon'}+1}\right)^2 \tag{2.2}$$

The microwave power transmitted into the material can be calculated by Eq. 2.3.

$$P_{Tran} = 1 - P_{ref} \tag{2.3}$$

Engelder and Buffler reported ' ranges from 50 to 70 for most food materials, which results in approximately 20% of the energy transmitted into food items (Engelder and Buffler, 1991). Material can absorb the transmitted microwave power and convert it into thermal energy. The absorbed microwave power per unit volume of the food item is determined by Eq. 2.4.

$$P_{abs} = 5.56 \times 10^{-4} \times f \times \varepsilon'' \times E \tag{2.4}$$

where P is the absorbed microwave power (W/cm^3), f is the microwave frequency (GHz), ε'' is the dielectric loss factor of food material, E is the electric field intensity of given volume (V/m^3). The absorbed microwave power is associated with the microwave frequency, dielectric loss factor and the electric field intensity. The dielectric constant has an effect on heat generation by affecting the electric field intensity. On the other hand, the real heat generation also relied on thermal parameters, such as specific heat. However, the actual temperature increase caused by the microwave power also relies on thermal parameters, such as specific heat (Nelson, 1999).

Dielectric properties are related to many factors, including microwave frequency, temperature, density, moisture content, and salt content. There are three methods mostly used for the dielectric properties measurement: open-ended coaxial probe method, transmission line method, and resonant cavity method (Engelder and Buffler, 1991). These measurement methods have the same principle, including the generation of a radiation signal at a range of frequencies, the direction of the signal through the testing sample, the measurement of the changes in the signal caused by the material and the computation of from those detected changes by computer program. A microwave network analyzer is usually used to detect the signal changes (Engelder and Buffler, 1991).

As the fundamental effect on microwave heating, dielectric properties have gathered researchers' attention during recent decades. A number of studies have been

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completed to measure the dielectric properties of different food products. Nelson and Bartley (2001) measured dielectric properties for whey protein gel, ground whole wheat flour, and apple juice. Many fruits and vegetables were measured by Wang and others (2003) and Venkatesh and others (2004). Almonds and walnuts were determined by Wang and others (2003). Wang and others (2009) studied the effects of cooking on dielectric properties of liquid whole eggs and liquid egg whites in relation to radio frequency and microwave heating processes to prepare shelf-stable products. Lyng and others (2005) published a survey on the dielectric properties of meats (chicken, lamb, beef, pork and turkey). Wang and others (2008) measured the dielectric properties for anterior, middle, tail, and belly portions of Alaska pink salmon (Oncornynchus gorbuscha) fillets at frequencies between 27 and 1800 MHz from 20 to 120 °C. Dielectric properties of oysters were determined by Hu and Mallikarjunan (2005) between 300 MHz and 3 GHz to describe the temperature effects on thermal and dielectric properties of oysters. At microwave frequencies of 915 and 2450 MHz, the dielectric constant of oyster decreased (64.02-50.89 and 59.10-47.67, respectively), while the loss factor increased (13.84-20.14) at 915 MHz as temperature increased from 1 to 55 °C (Hu and Mallikarjunan, 2005).

2.1.4 Factors affecting microwaving heating

There are three aspects that can influence microwave heating significantly: microwave equipment, the properties of food, and operating conditions. Microwave equipment determined the generation of microwaves. The design of the microwave equipment, such as the size, the geometry of the cavity, and the direction of the

magnetron, can affect the magnitude and spatial variation of the power absorption in the product (Zhang and others, 2001). For food stuff, the geometry, mass, composition, thermal properties and dielectric properties are all critical parameters to determine the energy absorption and the energy spatial distribution (Zhang and others, 2001). They also have great effect on corner and edge overheating, focusing and resonance (Datta and Davidson, 2000). The operating conditions, including the input power, cycling pattern, operating frequency, air-circulation, location of the food in the cavity, and the heat equilibrium after microwave heating, can cause different heating rates and lead to uneven temperature distribution.

2.1.5 Non-uniform temperature distribution in microwave ovens

The main problem associated with microwave heating is the non-uniform temperature distribution in microwave-heated foods. Metal surfaces can reflect microwaves (Bih, 2003). In microwave ovens, microwaves continue bouncing around in the metal chamber until they are randomly absorbed by the product (Bloomfield, 2013). Thus, the distribution of electromagnetic field is uneven around different parts of the food. On the other hand, the geometry, composition, thermal properties and dielectric properties will affect both the absorption of microwave energy and heat transfer (Zhang and others, 2001; Manickavasagan and others, 2006; Ryynanen and others, 1996; Sosa-Morales and others, 2010; Vadivambal and others, 2010). Due to non-uniform temperature distribution, some areas of the material get heated very rapidly, whereas the remaining region gets heated to a lesser extent, which will lead to hot spots and cold spots in food (Ryynanen and others, 1996). The hot spots can cause

quality changes in food, including color, texture, and flavor or odor. The serious concern of the cold spots is the incomplete kill of microorganisms in cold spots.

Several studies have focused on the uneven temperature distribution in microwave heating (Fakhouri and others, 1993; Geedipalli and others, 2007; Manickavasagan and others, 2006; Ryynanen and others, 1996; Gunasekaran and Yang, 2007; Sosa-Morales and others, 2010; Vadivambal and Jayas, 2010; Liu and others, 2013 Fan and others, 2013). The solutions proposed to improve the non-uniform temperature distribution during microwave heating includes: combining conventional and microwave heating, controlling the food geometry, providing a shielding using metallic bands at suitable spacing and orientation, providing suitable microwave oven design, manipulating the heating cycle, and heating with reduced microwave power for a longer duration (Ryynanen and others, 1996; Vadivambal and Jayas, 2010).

2.1.6 Application of microwave heating

As an alternative to conventional heating methods, microwave heating has been widely applied in both the consumer and industrial areas during the past century.

The first commercial microwave oven, "Radarange[®]," was built in 1947 by Raytheon (Bih, 2003). The first home-use oven was introduced in 1955 by Tappan (Bih, 2003). However, the wide use of the household microwave oven in America did not appear until the late 1970s. Since then, manufacturers have improved the microwave ovens by employing more sensors to regulate temperature and automatic features. Nowadays, there are millions of microwave ovens all over the United States. The rapid microwave heating helps consumers to cook, thaw, bake and roast food conveniently.

As an alternative heating source, microwave heating can be applied in many food processing areas, such as drying, thawing, pasteurization and sterilization. Numerous studies were focused on the application of microwave drying for plants, such as wood, fruits, and vegetables (Safeena and Patil, 2013; Marcela and others, 2013; Arballo and others, 2012; Nair and others, 2011; Mahmoud and Taha, 2013; Chandrasekaran and others, 2013; Liu and others, 2012; Min and others, 2010). Microwave pasteurization was developed and employed in meat, eggs, juice, fruit, vegetables and packaged food (Koskiniemi and others, 2013; Dehghan and others, 2012; Cinquanta and others, 2010; Zhang and others, 2013; Huang and Sites, 2007). Many studies focused on using microwaves to inactivate food pathogens, including *Bacillus cereus*, *Bacillus subtilis, Clostridium perfringens*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Staphylococcus aureus* and *Salmonella* spp. in vegetables, beef, fish, pork, and eggs (Fouladkhah and others, 2013; Sheen and others, 2012; Ortega and Jyeyin, 2006; Rodriguez-Marval and others, 2009; Lianou and Koutsoumais, 2009). However, microorganisms treated by microwave heating still have greater chance to survive compared to conventional methods (Schiffmann, 1992).

2.2 Temperature measurement during microwave heating

Temperature is a critical factor for final product quality in microwave heating. It is important to know the temperature distribution for avoiding the survival of microorganisms during the food processing and storage. For reheating or cooking food, temperature can significantly affect the color, flavor, texture, and nutritional aspects of the food. In traditional heating methods, heat transfer is mostly limited by heat

conduction, and it is easy to identify the slowest heating location (Knoerzer and others, 2005). In microwave heating, as a volumetric heating method, the temperature distribution is uneven and hard to identify the over-heated area or insufficient heated area. Therefore, understanding the temperature distribution during microwave heating will be helpful for building a better heating pattern. There are several methods established for determining the temperature during microwave heating, such as thermocouples, fiber optic probes, infrared (IR) thermography, the use of model substances, and the use of magnetic resonance imaging (MRI) (Knoerzer and others, 2009).

2.2.1 Thermocouples

A thermocouple consists of two different electrical metallic conductors that contact each other at one or more spots. A voltage will be generated when the temperature of one of the spots differs from the reference temperature at other parts of the circuit (Wikipedia, 2013). Thermocouples are widely used in science and industry for temperature measurement. Unfortunately, thermocouples cannot be used in microwave devices because of the interaction between the electromagnetic fields and the metal components. Heat will generate to disturb the temperature probes, and the metallic components will cause a disturbance of the field, leading to overheating and possible arcing and destruction of the device, as well as damage to the product (Knoerzer and others, 2005).

2.2.2 Fiber Optic Probes

The fiber optic temperature probes consist of a gallium arsenide (GaAs) semiconductor crystal that is mounted on the end of an optical fiber (Wikipedia, 2013). The probe is complete non-metallic, so it is immune to microwave radiation. The GaAs crystal fixed on the tip of the fiber will be transparent at a wavelength above 850nm. The position of the band edge is temperature dependent and is shifted about 0.4nm/Kelvin. The light is directed via the optical fiber to the crystal, where it is absorbed and partially reflected back into the fiber. A miniature spectrometer provides a spectrum with the position of the band edge, from which the temperature is calculated (Wikipedia, 2013). Fiber optic probes have been used in microwave studies for analyzing the temperature distribution, assisting organic synthesis and validating the heating model (Cerón-Camacho and others, 2012; Pithcai and others, 2012; Nott and Hall, 2005; Salvi and others, 2009; Mochizuki and Wada 2011; Geedipalli and others, 2007).

2.2.3 Infrared Thermography

Since infrared radiation is emitted by all objects above absolute zero, it is possible to record the variations of temperature by a thermographic camera. The thermographic scanning system can measure and view temperature distribution based on IR radiations emitted from a heated surface of an object without physical contact between the measuring equipment and surface investigated, at the time of the test. As a result, a thermal two-dimensional image of the object is obtained, in different shades of colors or a gray scale (Ple u and others, 2012). Infrared thermography provides very good

local resolutions and is established for measuring surface temperatures. However, infrared sensors are metallic and cannot be placed inside the electromagnetic fields of a microwave heating assembly. Therefore, most measurements have to be done through a shield window because the sensitive electronics inside the infrared sensors require extensive electromagnetic shielding to allow accurate measurements in the presence of electromagnetic fields. Thus, the efficiency and accuracy of the temperature measurement, which in any case represents only the surface temperature of one part of the heated product, are reduced (Knoerzer and others, 2005).

2.2.4 Model Substance

A different approach to determine temperature distributions in microwave devices is the use of model substances that change their properties (e.g. color, pH value, and structure) after reaching a certain temperature (Knoerzer and others, 2005). Model substances with certain properties are used to represent certain foods. For microwave heating scenarios, it is sometimes sufficient that only the dielectric properties are representative for those of the food, in a certain temperature interval and at a frequency of 2.45 GHz (Risman and others, 1993). But often (especially at lower microwave powers or longer heating times) it is also indispensable that the thermal conductivity and the heat capacity of the model food also fit the values of real foodstuff. Model substances are widely used in microwave heating research. Pithchai and others (2012) used 1% gellan gel to study microwave heating in domestic ovens. Sakai and others (2005) conducted a study of model foods for use with microwave heating by using Agar gel as the base, and sucrose and sodium chloride to adjust the dielectric properties. Cong

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and others (2012) used whey protein and gellan gel to simulate sea cucumbers (*Stichopus japonicus*) in microwave heating. Different ratios of whey protein gels with d-ribose were used as a model food to study dielectric heating properties of salmon (*Oncorhynchus gorbuscha*) fillets by Wang and others (2009).

2.2.5 Magnetic Resonance Imaging (MRI)

Imaging methods based on the resonant absorption and emission of electromagnetic energy by hydrogen nuclei placed in strong magnetic fields (magnetic resonance imaging, MRI) are well known for their wide spread clinical applications. The fundamental relation of nuclear magnetic resonance (NMR) is the proportionality between the angular resonance frequency   and the magnetic-flux density B,   = − B, where   is the gyromagnetic ratio. Temperature mapping using MRI is possible, as a temperature shift leads to a very small shift in resonance frequency and angular velocity for hydrogen nuclei in water (Knoerzer and others, 2009). However, the high investment costs for equipment leads to limitations for employing this technique for microwave heating research.

2.3 Numerical Methods for Microwave Heating

Experimental measurement of temperature in the microwave is limited due to interference of measuring devices with the electromagnetic field (Salvi and others, 2011). Numerical methods have been used to understand and optimize the process of microwave heating. In order to characterize temperature distribution during food heating, coupled mass and energy balances must be solved taking into account the absorption of electromagnetic energy. The distribution of the electric and magnetic

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fields in microwave ovens with or without any load has been described by Maxwell's equations (Dibben and Metaxas, 1994; Verboven and others, 2003; Rattanadecho, 2006). Currently, two ways have been followed to solve the electromagnetic energy distribution inside the foods: to solve Maxwell's equations (Ayappa, 1997; Oliveira and Franca, 2002; Basak and Kumaran, 2005; Zhu and others, 2007; Hossan and others, 2010; Campañone and others, 2012) or to apply Lambert's approximate law which deals with an exponential energy decay inside the product (Tong and Lund, 1993; Lin and others. 1995; Chamchong and Datta, 1999; Liu and others, 2005).

2.3.1 Maxwell's Equations

James Clerk Maxwell (13 June 1831 – 5 November 1879) was a Scottish mathematical physicist, who published a set of equations to describe the interaction between electric and magnetic fields between 1861 and 1862. Those equations were named Maxwell's equations. The equations have two major variants, including the "microscopic" and the "macroscopic". The microscopic variant of Maxwell's equation expresses the electric field E and the magnetic field B in terms of the total charge and total current present. The macroscopic variant of Maxwell's equations defines two new auxiliary fields (magnetic field H and electric displacement D) that describe large-scale behavior, but requires parameters characterizing the electromagnetic properties of the relevant materials. The macroscopic variant of Maxwell's equations, which is widely used in microwave heating calculations (Dibben and Metaxas, 1994; Verboven and others, 2003; Rattanadecho, 2006; Zhu and others, 2007; Geedipalli and others, 2007; Hossan and others, 2010; Campañone and others, 2012), was given by:

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$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.5a}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2.5b}$$

$$\nabla \cdot B = 0 \tag{2.5c}$$

$$\nabla \cdot D = \rho_c \tag{2.5d}$$

where $\nabla \times$ is the curl operator, E is the electric field, $\nabla \cdot$ is the divergence operator, H is the magnetic field, B is magnetic induction field, D is electric displacement, J is the current density, and ρ_c is charge density. All of these properties depend on the frequency of radiation.

2.3.2 Lambert's law

Lambert's law, also known as the Beer-Lambert law, or Beer's law, relates the absorption of light to the properties of the material which the light travels through. The average temperature increases in a material during microwave heating time t depends on the total microwave energy absorbed by the material (Padua, 1993; Barringer and others, 1995; Yang and Gunasekaran, 2001). The energy balance is given by Eq. 2.6 (Yang and Gunasekaran, 2004):

$$\Delta T_{av} = \frac{t P_{abs}}{V \rho C_p} \tag{2.6}$$

where, ΔT_{av} is average temperature rise (°C), P_{abs} is total power absorbed (W), t is heating time (s) and V is sample volume (m³), ρ is sample density kg/m³, C_p is sample specific heat capacity (kJ kg^{-1} °C^{-1}).

Lambert's law predicts an exponentially decaying absorption of energy as a function of depth into the sample. When one-dimensional analysis is considered and the incident radiation is assumed to be normal to the surface, the power absorption can

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be given by the exponentially decaying of the incident power along that direction (Barringer and others, 1995; Yang and Gunasekaran, 2004). The power term (Eq. 2.7) was derived by Von Hippel (1954) and is often referred to as the Lambert's law:

$$P(x) = P_0 e^{-2\beta x} \tag{2.7}$$

where, x is the depth or distance from the surface along the radial axis (m), $P(x)$ is power dissipated at the depth x (Walts), P_0 is incident power or power at the surface (Walts), and β is the attenuation constant (m^{-1}) which is a function of frequency of radiation, f (Hz); velocity of radiation, c (m/s); dielectric constant, ε'; and loss tangent, $\tan \delta$. However, some studies reported that Lambert's law may cause errors by predicting small size material due to the assumption that all transmitted energy is absorbed (Barringer and others, 1995; Budd and Hill, 2011). Yang and Gunasekaran (2004) reported that the power formulation based on Maxwell's equations is more accurate than that based on Lambert's, especially at the outer boundary of the sample; and the temperature at 3-cm for the 3.5-cm radius (smaller) sample was overestimated due to ignoring the standing wave effect in Lambert's law's prediction.

2.3.3 Modeling for Microwave Heating

Due to the lack of computing ability to solve the necessary equations, there was little research focused on numerical modeling of microwave heating before the late 1980s (Dibben, 2001). With the growth of computing technology, as well as significant advances in simulation techniques, the modeling for microwave heating received more attention in the past decades. The finite element method (FEM) and finite different time domain method (FDTD) are two popular methods for simulating microwave heating

(Dibben, 2001; Liu and others, 2013; Oliveira and Silva, 2010; Romano and others, 2005; Dev and others, 2012; Pandit and others, 2003; George and others, 2005; Chen and others, 2008; Torres and Jecko, 1997). Modeling is a useful tool to study how food properties and oven parameters influence the microwave heating and to predict the temperature distribution during the heating process. Both electromagnetic and thermodynamic problems need to be taken into consideration for accurate modeling of the microwave heating process (Kopyt and Celuch, 2006). Accounting to the lack of understanding of non-uniform heating, complicated interactions of microwaves with food and heat and mass transfer, the microwave heating modeling has been performed by trial-and-error procedures (Knoerzer and others, 2006).

2.4 Oysters
2.4.1 Oyster Biology

Oysters are bivalve mollusks, which lives in marine or brackish habitats. Oysters are one of the most popular types of seafood in the USA. During last five years, the average oyster landing in the US was over 165 thousand metric tons and the value exceeded $1,185 million at total (National Marine Fisheries Service, 2013). There are two main species of oysters in the USA, which are pacific oyster (*Crassostrea gigas*) and eastern oyster (*Crassostrea virginica*). The eastern oyster occupies 75% of the total commercialized oyster market share in the USA (Prapaiwong, 2009). Louisiana leads the nation in the production of oysters. An average of 35% of the nation's oyster landings was produced in Louisiana over the 1999 – 2009 time period (Louisiana Department of Wildlife and Fisheries, 2012). Approximately 14.0 million pounds of

eastern oysters (*Crassostrea virginica*) were harvested in Louisiana in 2009 (Louisiana Department of Wildlife and Fisheries, 2012).

Oysters are natural marine filters. They can obtain nutrition by filtering surrounding waters. In ideal conditions, an oyster can pump 5 gallons of water within 1 h (Perkins, 1995). Therefore, both food particles and microorganisms can be concentrated in the oyster tissue, resulting in contaminated oysters if the water is not clean.

2.4.2 Properties of Oysters
2.4.2.1 Chemical composition of oyster meat

Depending on sex, maturity, harvest seasons, food supply, stress and other environmental parameters, 100 g of raw oyster meat contains 75-95 g moisture, 5-10 g protein, 2-5 g carbohydrate, 0.7-2.4 g total fat, 0.7-2.9 g ash, 35-60 mg cholesterol and about 75 calories (Sidwell and others 1974; Hu, 2004).

2.4.2.2 Thermal properties

Thermal properties of oyster meat, such as thermal conductivity and specific heat, are important for calculation and modeling in thermal processing of oysters. The thermal properties of the oysters may vary with the chemical composition, physical structure, state of the substance, and temperature.

Thermal conductivity (k) is the property of a material to conduct heat. Fourier's law (Eq. 2.8) is used to describe the heat conduction. It states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat is flowing.

$$q = -kA\frac{dT}{dx} \qquad\qquad (2.8)$$

where q is the heat (W), k is the thermal conductivity (W·m^{-1}·K^{-1}), A is area (m^2), and T is the temperature (K). The most commonly used method to measure thermal conductivity is line heat source method, which applies transient state heat transfer, which is to apply a steady heat flux through a sample and measure the temperature rise at some point resulting from an applied heat flux. A modification of this technique was the development of the thermal conductivity probe. The theory of the line heat source is to assume a line heat source of constant strength in an infinite homogeneous body at uniform temperatures. Under these conditions, the temperature at any point of the body will be a function of several variables including time and thermal conductivity (Hu, 2004). Thermal conductivity was closely related to the product's bulk density (Shrivastava and Datta, 1999). It is reported that thermal conductivity was reduced when the bulk density decreases, which is due to the air being a poor heat conductor. Thermal conductivity of unfrozen foods or biological materials having high moisture content has a value close to water, which is 0.597 W/m°C at 20 °C (Hu, 2004). Hu and Mallikarjunan (2005) reported the thermal conductivity of oyster meat increased from 0.578 W/m°C to 0.677 W/m°C as temperature increased from 0°C to 50°C.

Specific heat, also called heat capacity, or thermal capacity, is defined as the amount of heat energy required to change the temperature of an object or body by a given amount. The method of mixtures and the differential scanning calorimeter method are used to measure the specific heat. The method of mixtures is placing a specimen with known mass and temperature into a calorimeter of known specific heat and water of known mass and temperature (Rahman, 1993). The principle of the

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differential scanning calorimeter (DSC) is to heat a sample and a reference at a known rate in a controlled environment. The increase in sample and reference temperature will be about the same (depending on specific heat differences), unless a heat-related change takes place in the sample, where the sample either releases or absorbs heat (Hu, 2004). In DSC, the temperature difference between sample and reference from such a heat change is directly related to the differential heat flow (Hu, 2004). It was reported that the specific heat above freezing and below freezing was 3.77 and 1.93 kJ/ (kg °C), respectively, for oyster meat and 3.52 and 1.84 kJ/ (kg °C) for oysters in shells. The latent heat of fusion for both oyster products was reported as 290 and 267 J/g, respectively (Ashrae, 1977). A study reported the specific heat of oyster meat increased from 3.795 kJ/kg°C to 4.047 kJ/kg°C when the temperature increased from 10°C to 50°C (Hu and others, 2005).

2.4.3 Foodborne diseases related to oyster consumption
2.4.3.1 Foodborne diseases

Foodborne illness refers to any illness resulting from the consumption of pathogenic bacteria-, viruses-, or parasites-contaminated food. Foodborne diseases spread through food or beverages are a serious and worldwide problem for people. The Centers for Disease Control and Prevention (CDC) estimates that 31 identified pathogens cause 48 million episodes of foodborne illnesses, 128,000 hospitalizations, and 3,000 deaths each year (Scharff, 2012). During 2009–2010, a total of 1,527 foodborne disease outbreaks (675 in 2009 and 852 in 2010) were reported, resulting in 29,444 cases of illness, 1,184 hospitalizations, and 23 deaths (CDC, 2013). Foodborne

disease is extremely costly. Health experts estimate that the yearly cost of all foodborne

diseases in the United States is 5 to 6 billion dollars in direct medical expenses and lost

productivity (Nation Institute of Allergy and Infectious Diseases, 2012).

Seafood is a leading cause of foodborne disease with known etiology, responsible

for 10-20% of outbreaks (two or more cases caused by the same source) among all food

types and about 5% of all individual illnesses (Ralston and others, 2011). Many of the

detailed investigations of foodborne illnesses were focused on oysters, since they are

often prepared raw or mildly cooked (Iwamoto and others, 2010).

2.4.2.3 Health Risk Associated with Consumption of Oysters

Oysters are natural filter feeders that can filter and concentrate microbes from

their surroundings. The accumulation of pathogens in oyster causes serious health risks.

The main concern associated with the oyster is the *Vibrio* species, which are

characterized as Gram-negative, rod-shaped, or curved rod-shaped, halophilic bacteria.

The *Vibrio* spp. are widespread in marine and estuarine environments. According to the

Cholera and Other *Vibrio* Illness Surveillance (COVIS) system built by the CDC, 825

cases of vibriosis (excluding toxigenic *V. cholerae*) were reported in 42 states in 2009

(COVIS, 2011). Of these cases, 217 (26%) were from Pacific Coast states, 256 (31%)

from Atlantic Coast states, and 101 (12%) from non-coastal states (Figure 2.3). In Gulf

Coast states, the most frequently reported *Vibrio* species were *V. vulnificus* (27%) and

V. parahaemolyticus (21%), followed by *V. alginolyticus* (19%), and non-toxigenic *V.

cholera* (13%). In non-Gulf Coast States *V. parahaemolyticus* (58%) exceeded *V.

alginolyticus* (14%), *V. vulnificus* (7%), and non-toxigenic *V. cholerae* (7%).

Among the 825 vibriosis cases, nearly 60% (486 cases) were seafood-associated. In 236 cases reporting eating a single seafood item, 48% ate oysters (94% of whom consumed them raw), 9% ate clams (73% of whom consumed them raw), 10% ate shrimp, and 19% ate finfish. As a result, seafood, especially raw oyster, is the main health risk associated with the infection of the *Vibrio* spp.
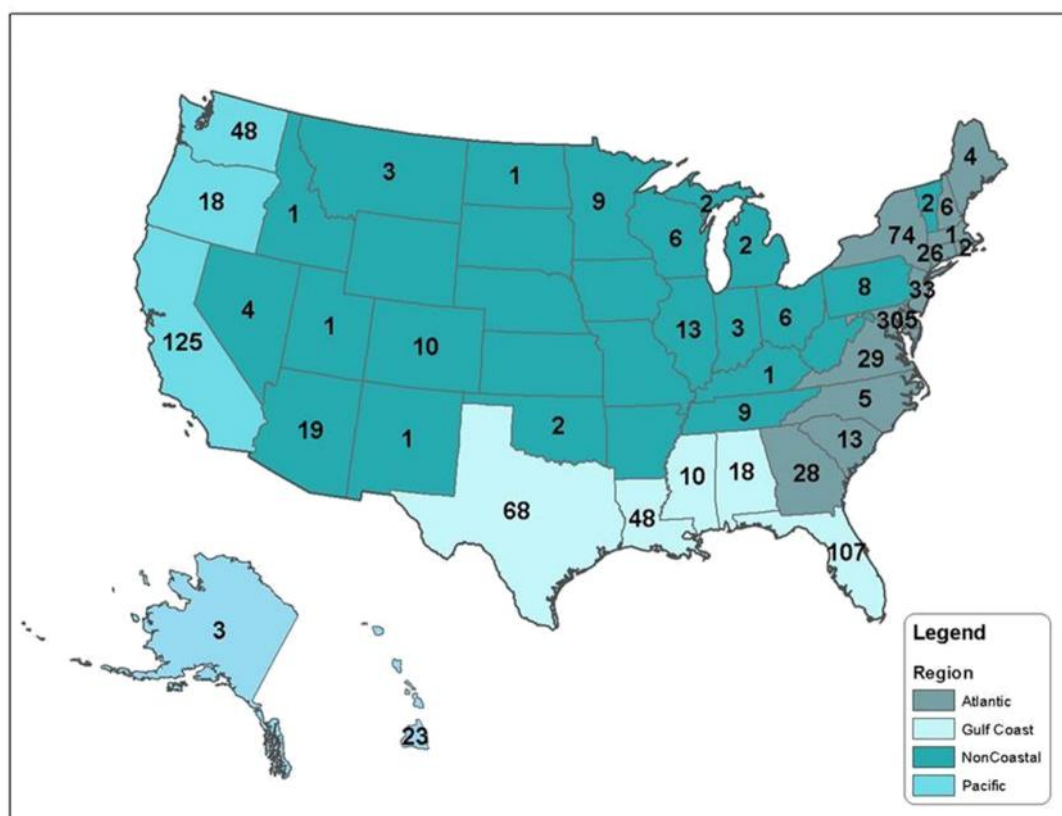
Figure 2.3 Number of cases of *Vibrio* infections (excluding toxigenic V. cholerae), by state, 2009 (n=825 in 42 states) (COVIS, 2011)

2.4.2.4 *Vibrio vulnificus* and *Vibrio parahaemolyticus*

The *Vibrio* family is a genus of gram-negative bacteria possessing a curved rod shape. They are motile and have polar flagellum with sheaths. *Vibrio* spp. are facultative anaerobes and do not form spores.

V. vulnificus has been recovered from fish, shellfish, water and sediments of a wide range of temperatures and salinities (Harwood and others, 2004). It often

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flourishes in warm water with a salinity of 5-25 ppt (Oliver, 2005). Optimal temperature for its growth is higher than 20 °C (Mahmud and others, 2008). It was reported that as the salinity increases, *V. vulnificus* is found only at higher temperatures (Randa and others, 2004). The growth of *V. vulnificus* was significantly suppressed when the temperature lower than 8.5 °C or above 35 °C (Kaspar and Tamplin, 1993). *V. vulnificus* has the highest mortality ratio of any foodborne pathogen, which is approximately 50% (FAO, 2005). It was reported *V. vulnificus* had a D value of 3.7 min at 47 °C and 1.15 min at 50 °C (Drake and others, 2003). *V. vulnificus* is particularly virulent. Persons at risk for severe *V. vulnificus* disease are those with preexisting liver disease, alcoholism, diabetes, hemochromatosis, or an immunocompromising condition (Vugia and others, 2013). Symptoms of *V. vulnificus* infections include vomiting, diarrhea, abdominal pain, and a blistering dermatitis. The infection exhibits two main clinical manifestations, including primary septicemia and primary wound infections, which can progress rapidly and become lethal even to an otherwise healthy person (Chien-Han and others, 2013). The case fatality rate is about 50% for bloodstream infections and 25% for wound infections (Iwamoto and others, 2010).

V. parahaemolyticus can be found in seafood, such as crabs, shrimps, prawns, scallops, oysters and clams (Far and others, 2013; Lim Mui and others, 2013; Parveen and others, 2008; Hayat Mahmud and others, 2006). The occurrence of *V.*

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parahaemolyticus in the marine environment is correlated with water temperature; with strains readily isolated when environmental temperatures exceed 15°C (Powell and others, 2013). It grows readily at temperatures from 22-42 °C but does not grow below 4 °C or above 45 °C. The D value at 50 °C varied from 2.95 min to 4.26 min depending on the location and time of the isolation (Wong and others, 2000). The *V. parahaemolyticus* infection will cause watery diarrhea, abdominal cramps, nausea, and vomiting. Wound infections and septicemia occur less commonly (Painter and others, 2013; Scallan and others, 2011). An estimated 35,000 cases of foodborne gastroenteritis are related the consumption of contaminated seafood with *V. parahaemolyticus* in the United States each year (Scallan and others, 2011), and most reported cases are caused by oysters. Although *V. parahaemolyticus* is recognized as a major cause of seafood-borne gastroenteritis, most strains of this species are not pathogenic to humans (Iwamoto and others, 2010).

During the summer months, oysters may concentrate *V.* spp. in warmer waters (Corcoran, 1998). Cases of vibriosis had a definite peak during the summer months (Figure 2.4). Most cases (78%) occurred from May to September, with the greatest number in August (COVIS, 2011).

Heating is an efficient way to eliminate *Vibrio* spp. A proper way to kill *Vibrio vulnificus* is to boil shucked oysters at least 3 minutes (CDC, 2009). By heating oyster meat at 50˚C for 5 min, 99.9% *V. vulnificus* and 100% *V. parahaemolyticus* were eliminated in the shell-stock oysters (Andrews and others, 2000).

The postharvest processing technologies have been proven to be an effective way to eliminate *V. vulnificus*. On April 14 2003, California enacted an emergency regulation, restricting the sale of raw oysters harvested from the Gulf of Mexico from April 1 through October 31, unless the oysters were treated with a scientifically validated process to reduce *V. vulnificus* to nondetectable levels (Vugia and others, 2013). After the implementation, *V. vulnificus* illnesses in California dropped to nearly zero (Vugia and others, 2013). As a result, the FDA has proposed a mandatory requirement to use post-harvest processing methods to treat oysters for eliminating the risk of foodborne illnesses.
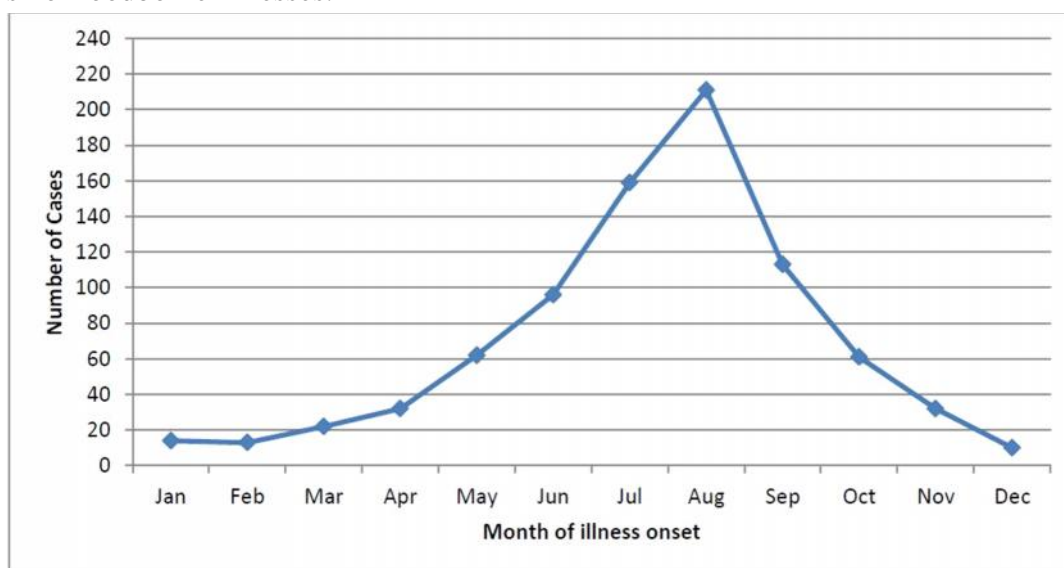
Figure 2.4 Number of cases of vibriosis by month of illness onset, 2009
(n=825 in 42 states) (COVIS, 2011)

2.4.3 Post-harvest Processing Techniques for Oysters

Post-harvest processing (PHP) techniques are widely used in the oyster industry to eliminate the potential health risk in oysters. The post-harvest processing techniques include depuration, heat-cool pasteurization (HCP), high hydrostatic pressure (HHP) processing, and cryogenic individual quick freezing (IQF) with extended frozen storage. Researchers also developed alternative PHP techniques including irradiation

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(electric beam irradtiation, X-ray and microwave technology) (Jakabi and others, 2003; Mahmoud, 2009) and high salinity treatment (Larsen and others, 2013). The Food and Drug Administration (FDA) required the applicable PHP methods should be able to reduce *Vibrio vulnificus* and *Vibrio parahaemolyticus*, by >3.52 log and by > 4 log respectively, to nondetectable levels (<30 MPN/gram) (FDA, 2009).

2.4.3.1 Depuration

Depuration is a process involving that immersion of oysters in tanks of clean seawater to allow sewage contaminants to be purged. The depuration is always associated with the ultraviolet irradiation to sterilize seawater. The temperature and salinity are two main factors which can affect the reduction of *Vibrios*. It is reported that depuration of oysters at 2 or 3 °C had no effect on reducing *V. parahaemolyticus*. Depuration at 7–15 °C for 5 days reduced *V. parahaemolyticus* populations in oysters by >3.0 log MPN/g (Phuvasate and others, 2012). Higher salinity will lead to greater reduction of *Vibrio*. Holding oysters in water with a salinity of 10 ppt for 5 days resulted in about 2 log MPN/g reductions of *V. parahaemolyticus*, which were significantly smaller than those (>3.0 log10 MPN/g) observed in water with higher salinities (20–30 ppt) (Phuvasate and Su, 2013). Using a salinity of 35 Practical Salinity Unit (PSU) it was possible to eliminate this *V. vulnificus* to non-detectable levels (Larsen and others, 2013).

2.4.3.2 Heat-Cool Pasteurization

The heat-cool pasteurization was developed and patented in 1995 by AmeriPure in Franklin, Louisiana (Horst and others, 2011). This process involves submerging the

raw product into warm water followed by immediate cold water immersion. The internal temperature of the oysters will be increased to high enough to reduce the loads of *Vibrio* spp. to non-detectable level without cooking the oyster meat during the exposure. In this process, oysters are washed, graded, sorted, and individually banded in order to avoid extreme loss of internal juices, arranged in racks, and then submerged in water at 52°C (127°F) for 24 minutes. Then the racks are lifted out and placed in 4°C water for 15 minutes. Temperature and time have been validated through several studies showing reduction of bacterial loads with minimal cooking of the meat and increasing of yields of higher moisture content compared to untreated oysters (Andrews and others, 2000; Muth and others, 2000). Chen and others (1996) found that the HCP process yielded oysters comparable in flavor, texture and smell to untreated oysters, but a slight lightening of color was observed.

2.4.3.3 High Hydrostatic Pressure

High pressure processing (HPP), also called pascalization, is a method to process food for preservation and sterilization by inactivating certain microorganisms and enzymes in the food under very high pressure. The operation pressure range can be 100 to 800 MPa, and the operation temperature can be below 0°C or over 100°C. In normal operation, food products are sealed and placed into a steel compartment, which contains liquid, often water, and pumps are used to create pressure.

The use of HPP on oysters was developed and patented by Motivatit Seafoods in Houma, LA in 1999. It has been suggested that susceptibility to high pressure (HP) of Gram-negative compared to Gram-positive bacteria is due to the complexity of Gram-

negative cell membranes (Shigehisa and others, 1991). As a typical Gram-negative bacteria, *Vibrio* spp. are more sensitive to pressure than other most of other bacteria. HP disrupts membrane function and causes leakage through the inner and outer membranes, lead to increased sensitivity to sodium chloride and bile salts, uptake of propidium iodide and ethidium bromide, and leakage of ATP (Murchie and others, 2005). Membrane perturbation is attributed to the promotion of phase transitions in the phospholipid bilayer from liquid to more tightly packed gel phases (Murchie and others, 2005). HP can also denature or displace membrane-bound enzymes. Berlin and others (1999) showed that pathogenic *Vibrio* spp. are susceptible to HPP treatment at pressure levels between 200 and 300 MPa. It was also reported that HPP can inactivate viruses accumulated in oysters (Black and others, 2010; Kingsley, 2009; Kingsley, 2007; Grove, 2009; Li, 2009; Grove, 2008). HPP starts with cleaning, washing, sorting and grading oysters. Then oysters are banded and containerized (placed in a stainless steel cylinder) in preparation for the high-hydrostatic pressure, which may last 4-6 minutes. After pressurization, the oysters are shucked for half shell or packaged as banded oysters. After the HPP treatment, the safe-to-eat oysters retain the appearance, flavor, texture and nutritional qualities similar to untreated fresh oysters (Murchie and others, 2005) with a shelf-life of almost 30 days (He and others, 2002) under refrigerated conditions. The adductor muscle of oyster is not removed from the shell in HPP, which can help oysters keep good shape and appearance, and also obtain a higher retention of moisture, providing shucking yields of 25–50% (Murchie and others, 2005).

2.4.3.4 Cryogenic Individual Quick Freezing

Individual quick freezing (IQF) involves cryogenically freezing of half shell oysters on trays, then adding a thin glaze of ice to seal in the natural juices before storing them frozen. Employing IQF to oysters for extending shelf life was first developed in 1989 and rapidly popularized in Australia, Canada, New Zealand, and the United States. IQF processing of oysters is applied by companies in California, Florida, Louisiana and Texas. It has the biggest market share of the post-harvest processed raw oyster market. In IQF processing, oysters are cleaned and shucked, then placed on specially designed trays and loaded into a tunnel freezer, where they are cryogenic frozen by liquid carbon dioxide or liquid nitrogen. After freezing, water is used to form a glaze of ice on the top of oysters on contact. Then oysters will be stored in wax-coated corrugated boxes and placed in a walk-in freezer for a period of time sufficient to achieve non-detectable levels of *Vibrio* spp. (Muth and others, 2011). The cryogenically quick freezing technique can give the frozen oysters longer shelf-life than any other post-harvest process technology and keep most of the flavor and appeal of non-processed oysters between six and twelve months under frozen storage (Songsaeng and others, 2010).

The formation of intracellular and extracellular ice crystals during freezing can affect microorganisms significantly, which will cause cellular damage, solute concentration in both intracellular and extracellular sides, and lead to death. The rapid decreasing of temperature can disrupt membrane transport mechanisms, which are intricate due to complexity of the membrane's structure, altering functional metabolic and enzymatic processes (Archer, 2004). Freezing is an efficient way to reduce the

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number of these pathogens in oyster and oyster meat. Parker and others (1994) reported significant reductions of three to four logs in *Vibrio vulnificus* in oysters injected with 10^6 CFU/g and then frozen at -20ºC in an air blast freezer. In the first seven days, most reductions occurred and continued with the time. Mestey (2003) and others observed there was a lower number of recoverable *V. vulnificus* when CO_2 was used for cryogenic freezing of half shell oysters. For whole oysters, bacterial levels were undetectable after 14 days for CO_2 (-67ºC) and after 21 days, in most cases, for liquid nitrogen (-91ºC). Muntada-Garriga and others (1995) reported that viable cells of *V. parahaemolyticus* (10^{5-7}CFU/g) in oyster homogenates were completely inactivated by freezing at -18 and -24°C for 15 to 28 weeks depending on initial populations of the microorganism and freezing temperatures. Liu and others (2009) investigated the effects of cryogenic freezing on *V. parahaemolyticus* by liquid nitrogen (-95.5ºC) in Pacific oysters. Half shell Oysters were frozen through a cryogenic tunnel with a retention time of 12 minutes. After the freezing process, the population of bacteria in the oysters declined by 0.22 log MPN/g. Followed by frozen storage studies, oysters stored at -10 had more rapid decrease of the *V. parahaemolyticus* population than at -23 or -30°C. There was greater than 3-log (MPN/g) *V. parahaemolyticus,* which started at 10^5 MPN/g in oysters, stored at -10°C for three months or at -23°C for four months.

However, studies also showed that both *V. vulnificus* and *V. parahaemolyticus* have tolerance to cold temperatures. *V. vulnificus* can have better tolerance to colder temperatures if it has been exposed at an intermediate temperature, such as being placed at 15°C before final storage at 6°C (Bryan and others, 1999; Johnston and others, 2002;

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Oliver, 2005). This tolerance may be due to formation of cold-adaptive protein during the freezing processing. *V. parahaemolyticus* has the same characteristic as *V. vulnificus*. The survival of *V. parahaemolyticus* would even be increased when stored at low temperatures (-18ºC) (Johnston and others, 2002; Lin and others, 2004). The reason for this increase may be the morphological changes of *V. parahaemolyticus* under cold and starvation stresses (Chen and others, 2009).

2.5 Microwavable packaging

The functions of food packages include protection for food integrity and quality, assisting the consumer in the use of the product and attracting consumers to purchase and use the product (Bohrer and Brown, 2001). If the package is used to hold the food during microwave heating, the interactions between microwaves and the package must also be considered. Since the package can transmit, reflect, or absorb microwaves, it can also greatly influence the microwave heating behavior. The microwavable package acts in two different ways: passive and active. The passive packages are made of materials that do not appreciably react to the microwave field of the oven or appreciably modify the power distribution in the oven (Guillard and others, 2010). The active packages are packages that can act in reflecting and absorbing microwaves in such a manner that the power distribution of the microwaves and the surface temperature of package are modified (Yam and Lai, 2006). Though there are numerous different microwave packaging formats used, round or oval shapes with vertical sides and round edges are the common characteristics of them. These shapes help to minimize corner and edge overheating during microwave heating, which is the major problem due to the

concentration of high intensity electromagnetic fields in these areas (Knoerzer and others, 2009; Risman and others, 1987; Zhang and others, 2001).

2.5.1 Passive packages

Passive packages do not interact with the electromagnetic fields, which means they are considered as microwave transparent. During cooking, they only act as the containers to keep the product, prevent spilling or leakage, and facilitate removal of the cooked product from the oven. The temperature stability required of a passive package for microwave use is dependent on the formulation of the food to be heated, as the temperature that the package reaches can be no higher than that reached by the hottest part of the food. In foods with high moisture contents, temperatures rise to the vicinity of 100°C, and then plateau in that range until substantial dehydration occurs (Yam and Lai, 2006). While dehydration will allow higher temperatures to be reached, continued microwave heating after that point will cause overheating of certain parts of the product, where are the hot spots existed, and lead to the quality loss.

The most common microwave transparent materials are plastic packages (mono- or multi-layer polymers), plastic-coated cardboard or fiber trays, and glass packages (Risch, 2009). Yam and Lai (2006) summarized several popular packages and materials. Plastic-coated paperboard trays are widely used for microwavable frozen meals due the low cost. The trays combine the rigidity of the paperboard and the chemical resistance of the plastic. The inside of the trays is either extrusion coated with a resin or adhesive laminated with a plastic film. Molded pulp trays are another common paper product and can carry more load than the paperboard containers. Thermoformed plastic trays

are also common heating containers for microwavable foods. Low-density polyethylene (LDPE) trays are suitable for light microwave heating because the trays tend to distort at temperatures as low as 75°C. Polypropylene (PP) trays have a distortion temperature of about 110°C. Polyethylene terephthalate (PET) trays can be used because of the high temperature stability (up to about 200°C). Crystallized polyethylene terephthalate (CPET) trays are the most widely used plastic trays for microwavable frozen meals. The CPET trays are functional in the temperature range from -40 to 220°C. Thus, the trays can be able to handle not only the low temperatures in distribution and handling end, but also the temperatures in cooking or thermal processing end. Bohrer and Brown (2001) summarized the performance characteristics of a selection of commonly used options for passive packages for microwave heating, which is shown in Table 2.1.

2.5.2 Active packages

Active packaging means that the package is designed to perform functions during the heating process. An active package augments the cooking process by either adding capability not normally present in microwave heating or by overcoming inherent deficiencies in the way microwaves interact with the food being heated. Two objectives of the active package design for improved microwave cooking include application of surface heating and power distribution modification (Bohrer and Brown, 2001). Materials used in active packages should balance three interactions with microwaves: reflection, absorption, and transmission. Aluminum foil, aluminum/plastic laminate, and aluminum/plastic/paperboard laminate are the most common microwave reflective materials (Yam and Lai, 2006). Since these materials do not allow the transmission of

microwaves, they are also known as microwave shielding materials. Aluminum is often used to selectively shield microwaves from certain areas of a food so that the entire food stuff or meal will be heated more evenly. However, precautions are necessary to prevent arcing for the use of aluminum in microwave heating. Microwave absorbent materials, which are also called susceptors, are used to generate surface heating to mimic the browning and crisping ability of the conventional oven. The only commercially available type is the metalized film susceptor (Yam and Lai, 2006). This type of susceptor consists of a metalized polyethylene terephthalate film laminated to a thin paperboard. The metal layer is a very thin (less than 100 angstroms), discontinuous layer of aluminum, which is responsible for generating localized resistance heating when exposed to microwaves. Heating can cause the susceptor to reach surface temperatures over 200°C within seconds. Susceptors are available in the forms of flat pads, sleeves, and pouches for different food types. However, due to the high temperature that will be reached in the susceptor, there is a public concern of migration of mobile compounds from the susceptor to the food. Bohrer and Brown (2001) summarized the commonly used active microwave packages (Table 2.2).

2.6 Microwavable instant meal

With the widespread use of microwave ovens, microwave instant meals have become more and more popular in recent decades (Mejia and others, 2011). Microwaveable meals are composed of raw and semi-cooked ingredients, which are frozen and packed in a microwavable container. The meal can be conveniently cooked in minutes by a microwave oven before serving. These products are developed by employing modified

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Table 2.1 Passive microwave packaging options (Bohrer and Brown, 2001)

Package style	Material(s)	Maximum service temperature, °C	Oxygen barrier	Moisture barrier	Grease resistance	Sealablility	Comments
Tray, sleeve, support board, or overwrap	LDPE coated paper or paperboard	95	Poor	Fair	Poor	Good	Light duty reheating only
Overwrap	Heat sealable oriented PET film	220	Poor	Good	Good	Good	Need venting during reheat, barrier improved by coatings
Overwrap	Heat sealable oriented PP film	110	Fair	Fair	Good	Good	Need venting during reheat, barrier improved by coatings
Tray	PP coated paperboard	125-135	Poor	Fair	Good	Good	Pressed or folded trays
Tray	PET coated paperboard	205	Poor	Fair	Good	Good	Pressed or folded trays
Thermoformed tray	LDPE	75	Poor	Good	Fair	Fair	Light duty reheating only
Thermoformed trays, clamshells	Polystyrene (PS) and foamed PS	80	Good	Fair	Good	Poor	Light duty reheating only
Thermoformed tray	PP	110	Poor	Good	Good	Good	Brittleness an issue at freezer temperatures
Thermoformed tray	CPET	220	Good	Fair	Good	Fair	Generally pigmented white or black

Table 2.2 Active microwave packaging options (Bohrer and Brown, 2001)

Package style	Material	Function	Examples of food application	Comments
Susceptor pad	Susceptor metalized film laminated to paperboard (board susceptor)	Bottom browning and crisping	Prebaked crust small pizza (< 125 mm)	Patterned susceptor more efficient for directing heating to crust shapes
Susceptor sleeve	Paper or board susceptor	Surface browning and crisping	Precooked pocket sandwich, enrobed dough snacks, waffles	May need side vents to assist in moisture transport; paper-based sleeves can be fully sealed and used as primary pack
Raised susceptor tray	Board susceptor	Bottom Browning and crisping	Prebaked crust larger pizza (100 – 225 mm)	Minimizes heat loss to oven floor
Susceptor tray	Press formed susceptor board	Surface browning and crisping	Small (< 500 gram) meat pies	Top crust can be browned using paper susceptor patched onto inside top panel of carton
Even heating tray	Patterned aluminum foil sandwiched between PET film and paperboard	Uniform temperature distribution after heating	Symmetrical food items of at least 350 gram weight	Even heating pattern can work with a broad range of products, but may need to be modified for specific food properties
Differential heating tray	Same as even heating tray	Desired temperature distribution after heating nonsymmetrical products	Multicomponent food products	A custom pattern will be required for each food combination
High-energy crisping	Patterned aluminum foil sandwiched between susceptor metalized PET film and paper or paperboard	Surface browning and crisping of difficult products and partial shielding	Raw dough and large meat and fruit pies, raw dough snacks, egg rolls	For pies, used in pressed tray and top panel carton patch. Can be used as sleeve for dough-enrobed products and rolls

atmosphere packaging to extend shelf life, and steam-venting technology to provide better final product quality.

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With the widespread use of microwave ovens, microwave instant meals have become more and more popular in recent decades (Mejia and others, 2011). Microwaveable meals are composed of raw and semi-cooked ingredients, which are frozen and packed in a microwavable container. The meal can be conveniently cooked in minutes by a microwave oven before serving. These products are developed by employing modified atmosphere packaging to extend shelf life, and steam-venting technology to provide better final product quality.

2.6.1 Modified atmosphere packaging

Modified atmosphere packaging (MAP) is any package that contains a gas composition deviant from atmospheric air. The modified atmosphere creates a controllable environment to inhibit the spoilage organisms or pathogens for extending the shelf life of food. Normally modified atmosphere is achieved by varying the amounts of oxygen, carbon dioxide, and nitrogen in the package (Yam and Lai, 2006). Most of the time a known concentration of gas mixtures is added to a high barrier plastic film in order to achieve a preservation effect. Another way to manipulate the atmosphere of a package is to employ the use of different types of plastics for packaging. After closing the packaging, the headspace composition may change during storage, since there is no additional manipulation of the internal environment. This is the critical difference when compared to controlled atmosphere (CA) systems, where continuous monitoring of the environment is necessary to maintain a stable gas atmosphere and other conditions (Del Nobile and others, 2012). MAP offers protection

to the product against deteriorative effects for food, including color change, off-flavor and off-odor development, nutrient loss, and texture change. However, the predominant concern is bacterial growth, which is most often the leading factor of shelf life.

The optimum MAP condition depends on different aspects, including product characteristics, respiring surface area, storage conditions, and package barrier properties (Rodriguez-Aguilera and others, 2011, 2009). Furthermore, different gas selections need to be used when working with respiring or non-respiring foods. Carbon dioxide is the predominant gas in the headspace composition in non-respiring food for antimicrobial purposes (Arvanitoyannis and others, 2012). Addition of nitrogen is commonly practiced to avoid package collapse due to the high solubility of carbon dioxide (Conte and others, 2013). Pure nitrogen is usually employed in food with low water activity and relatively high lipid content, in order to prevent the lipid oxidation. However, enzymatic and chemical reactions can still occur and results in deterioration in these products when the microbial spoilage is inhibited (Klensporf-Pawlik and others, 2009). Since the respiration of food will significantly affect the gas composition in the head space, the MAP for respiring food is complex. The applications of the usage of MAP in respiring foods are to develop the desired headspace associated with the product's respiration (passive MAP) (Costa and others, 2011; Kudachikar and others, 2011). Under passive MAP conditions, the respiration of the product and the gas permeability of the film are the two factors that influence the change in gas composition of the headspace in the product (Conte and others, 2013).

Conte and others (2013) concluded the advantages and disadvantages for consumers. The main advantages include increased shelf life allowing less frequent

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loading of retail display shelves; hygienic stackable pack, sealed and free from product drip and odor; reduction in production and storage costs due to better utilization of labor, space and equipment; increased distribution area and reduced transport costs due to less frequent deliveries; and little or no need of chemical preservatives. The disadvantages include capital cost of the packaging machine; cost of gases and packaging materials; cost of quality control equipment; increase of pack volume which will adversely affect transport costs and retail display space; and loss of the benefits of MAP once the pack is opened or leaks.

2.6.2 Applications of MAP on frozen seafood

Due to the higher moisture content and free amino acid content along with a lower amount of connective tissue, seafood has a more rapid spoilage rate compared to other foods; and spoilage in fish and shellfish depends on species and chemical components (Masniyom, 2011). MAP are widely used to extend shelf life of seafood products during refrigerated storage. There is significant extension of shelf life observed by employing MAP in seafood products. By employing CO_2 or the mixtures of oxygen, carbon dioxide, and nitrogen in headspace, the shelf life of seafood can be doubled or tripled (Hudecova and others, 2010; Lauzon and others, 2009; Hansen and others, 2009; Provincial and others, 2013; Yilmaz and others, 2009; Kamadia and others, 2013; Qian and others, 2013; Arvanitoyannis and others, 2011; Ulusoy and others, 2011).

The combination of MAP and freezing can provide conveniently packaged seafood products with longer shelf life and better quality (Bak and others, 1999; Bono and others, 2012). Bak and others (1999) reported overall better quality in relation to color stability, lipid oxidation and shrimp meat toughening was achieved in boiled

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shrimp packed in a nitrogen atmosphere and stored at -17ºC for 12 months. In MAP package, the effects of photooxidation in astaxanthin (red color in shrimp) and lipid oxidation were minimized. The exclusion of oxygen in the package helped eliminate chemical reactions for degradation of astaxanthin and fatty acid oxidation by photooxidation, which extended the shelf life by 50%. Combined MAP and freezing on deep-water rose shrimp (*Parapenaeus longirostris*) can completely inhibit lipid oxidation during storage and maintain natural color for up to six months (Bono and others, 2012).

2.6.3 Steam-venting technology

Steam meals are composed of raw and semi-cooked ingredients, and packed in a sealed plastic container in a gas mixture. Consumers cook the meals by microwave oven easily before consumption.

The main concern of steam meals is the content of raw and semi-cooked ingredient may cause food borne illness due to the cold spots caused by non-uniform temperature distribution during microwave heating (Ryynanen and others, 1996; Vadivambal and others, 2010; MacDougall and others, 2004; Smith and others, 2008). For consumers, microwave heating is the only protective step against pathogenic microorganisms in raw or semi-cooked ingredients, so microwave heating has a significant effect on food safety.

Self-venting technology uses specially designed package materials and containers in microwave heating for building up vapor pressure in the container until the self-venting happens. This technology utilizes the pressurized steam to cook inside sealed plastic pouches or containers, which have a self-venting release adaptation

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(Mast, 2000). The most common types of self-venting packages are pouches, flow packs and lidded trays (Fowle and others, 2005).

During microwave cooking, the rapid heat generation can turn the water in food into steam quickly. Vapor pressure is accumulated in the package resulting in reduced cooking time and evenly distributed heat. The package distends with the increase of the internal pressure and provides a visual indication that cooking is occurring while maintaining a temperature between 100ºC to about 105ºC (Mast, 2000). The general description of microwave cooking using steam-venting technology is shown in Figure 2.5 (Espinoza-Rodezno; 2013).

The functional ability of the system relies on one (or a combination of) partial or complete de-lamination, rupturing, peeling or a strategically placed hole or series of holes (Fowle and others, 2005). In each case there is a build-up of pressure inside the pack to start the process. Steam-venting occurs as the laminating adhesive dissolves when exposed to steam, preventing the pack from bursting while maintaining a constant pressure during cooking (Espinoza-Rodezno, 2013). This mechanism can be incorporated into roll-stock, lidding or pre-made pouches.

2.6.4 Product development of microwavable oyster meat-based meals

Food product development for the microwave oven is quite different from that for a conventional oven. Some characteristic features of microwave heating are unique, such as heating characteristics of food ingredients and food composites, volume and geometry of food, rapid rate of heating, and the electric field distribution on differential temperature profile within the food load. The composition of foods, in terms of microwave reactive and interactive components, limits the highest possible temperature

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attained within the food product (Shukla and others, 2001). An approach to product design with a good understanding of the basic principles of microwave heating, the nature of heat and mass transfer that occurs during microwave heating, and appropriate selection of ingredients and microwave reactive packaging can result in a superior microwaveable food product. In addition, investigations on placement, composition, geometry of the food, and properties of microwave oven can provide useful information for developing microwaveable food (Ryynanen and others, 1996).

a)
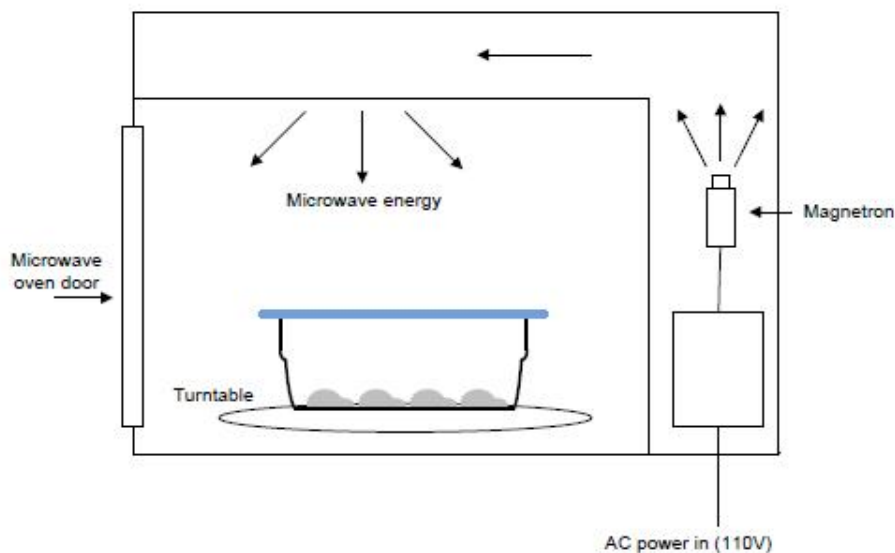
b)
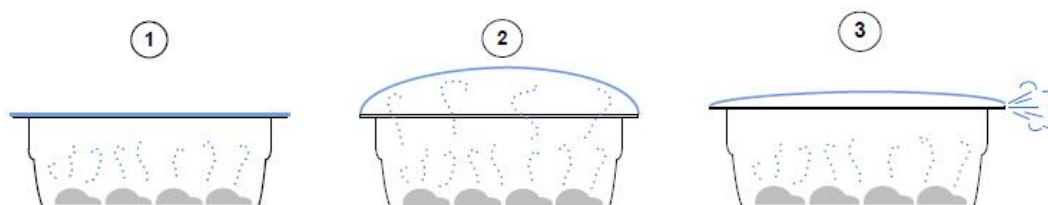
Figure 2.5 The general description of microwave cooking using steam-venting
a) Overall view of a household microwave oven, b) Microwave cooking schematic showing (1)the steam production, (2)built up, and (3)release at constant pressure
(Espinoza-Rodezno; 2013)

Combining microwave cooking and steam venting technology can provide a wonderful meal with better final product quality and less the health threat. During microwave cooking using steam-venting technology, the temperature is maintained between 100ºC and 105ºC throughout the entire cooking period (Mast, 2000). This can be considered to be enough to produce a safe product based on section 3-401.12 of the 2009 edition of the FDA Food Code which requires that raw animal foods, including seafood, heated via microwave energy must attain an internal temperature of at least 73.8ºC (165ºF) (USFDA, 2009).

Be employing steam-venting technology in microwave heating, a convenient microwavable oyster meat-based meal has been developed in the Food Engineering Laboratory, LSU (Espinoza-Rodezno, 2013). However, the information for microwave heating of this meal is insufficient. Uneven temperature distribution occurred during the heating process, and caused quality change and potential health risks. Therefore, development of a mathematical model to describe the heating behavior is necessary for further improvement of the meal.

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CHAPTER 3 DEVELOPMENT OF THE MATHEMATICAL AND COMPUTER-BASED MODELS FOR MICROWAVE HEATING

3.1 Introduction

For conventional heating by convection and radiation, heat only diffuses in the surface of the material at the beginning of heating, and then conducts into inside of the material. Since conduction is a diffusion process, the highest temperature during heating is always located on the surface. To avoid overheating, the temperature of the heating source cannot exceed the desired final temperature T_f, thus the overall heating rate is restricted by the heating source. The diffusion process can also affect the heating rate. Although the temperature distribution on surface can response to the heating source quickly, the bulk temperature of the material is mainly limited by the coefficient of thermal diffusivity a, which is defined as

$$a = \frac{k}{\rho_d C_p} \tag{3.1}$$

where ρ_d, C_p, and k are the density, specific heat, and thermal conductivity of the material, respectively (Wu, 2002). In conventional heating, it is easy to identify the slowest heating location (Knoerzer and others, 2005). If the diffusion time is infinite, the uniform final temperature T_f can be achieved.

For microwave heating, the internal heat is generated by the interaction between the material and electromagnetic field, so the maximum temperature is always inside the material rather than on the surface if the microwave is the only heating source. As a result, microwave heating will lead to non-uniform heating, which will cause overheating (hot spots) and insufficient heating (cold spots) in food stuff (Ryynanen and others, 1996). The hot spots can cause quality change or loss in food, including

color, texture, and flavor or odor. The more serious concern of the cold spots is the incomplete kill of microorganisms, which may cause food borne illness.

As the critical factor for the final product, the temperature profile of a product is important for microwave heating. Experimental measurement of temperature in the microwave is limited due to interference of measuring devices with the electromagnetic field (Salvi and others, 2011). So numerical methods have been used to understand and optimize the process of microwave heating. In order to characterize temperature distribution during food heating, coupled mass and energy balances must be solved taking into account the absorption of electromagnetic energy.

The earliest efforts in modeling microwave heating were primarily analytical (Shou-Zheng and Han-Kui, 1988; Watanabe and Ohkawa, 1978). However, with the availability of extensive computing facilities, solution of Maxwell's equations for electromagnetics coupled with heat transfer in the oven cavity can be obtained using different numerical methods. Maxwell's equations and Lambert's law are widely used to solve the electromagnetic energy distribution for microwave heating (Yang and Gunasekaran 2004; Ayappa, 1997; Hossan and others, 2010; Campañone and others, 2012; Chamchong and Datta 1999; Liu et al. 2005). However, the power formulation based on Maxwell's equations is more accurate than that based on Lambert's (Yang and Gunasekaran 2004). It is also reported that Lambert's law may cause errors in predicting small size material due to the assumption that all transmitted energy is absorbed (Barringer and others, 1995; Budd and Hill, 2011). With the availability of extensive computing facilities, solution of Maxwell's equations for electromagnetics coupled

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with heat transfer in the oven cavity can be obtained by different numerical methods such as finite difference time domain (FDTD) method (Dincov and others, 2004; George and others, 2005; Dibben, 2001; Chen and others, 2008; Torres and Jecko, 1997; Ma and others, 1995) and finite element method (FEM) (Romano and others, 2005; Liu and others, 2013; Dev and others, 2012; Zhang and Datta, 2000). However, the FDTD method is difficult to apply for complex geometry and can require long computational time (Geedipalli and others, 2007).

Due to the complexity of factors affecting microwave heating, it is hard to apply mathematic models to actual food stuff. The dielectric properties of food determine how materials interact with an electromagnetic field. The dielectric constant (ε') of food decides the level of a material to store electromagnetic energy, while the dielectric loss factor associates with the ability of the material to absorb the electromagnetic energy and convert that energy into thermal energy. The geometry, mass, composition, and thermal properties are also critical parameters to determine the energy absorption and the energy spatial distribution (Zhang and others, 2001). Therefore, computer-based modeling is introduced into the field to solve the mathematic models and used to simulate the microwave heating process. In this chapter, a mathematical model was developed to compute the energy absorption from microwaves, and a computer-based model was built to simulate the heating process and predict the temperature distribution.

3.2 Material and methods
3.2.1 Electromagnetic field equations

The microwave heating is governed by Maxwell's equations. Differential form for time harmonic electric fields and magnetic field flux were given as Eq. 3.1a and Eq.

3.1b. In order to completely specify the electric and magnetic fields, Gauss's laws were

employed as Eq. 3.1c and Eq. 3.1d.

$$\nabla \times E = -j\omega\mu H \tag{3.1a}$$

$$\nabla \times H = J_t = j\omega\varepsilon_0\varepsilon E \tag{3.1b}$$

$$\nabla \cdot E = 0 \tag{3.1c}$$

$$\nabla \cdot H = 0 \tag{3.1d}$$

where E and H represent 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;

$\nabla \cdot$ was 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 complex relative permittivity ε is defined as:

$$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta} \tag{3.2}$$

where ε' is the dielectric constant; ε'' is dielectric loss factor; and δ is the loss angle of

the dielectric material, where $\tan \delta = \varepsilon''/\varepsilon'$ is defined as the loss tangent or

dissipation factor (Nelson, 1999). The dielectric constant (ε') decides the level of a

material to store electromagnetic energy, while the dielectric loss factor is associated

with the ability of the material to absorb the electromagnetic energy and convert that

energy into thermal energy.

At the inner wall of the waveguide and cavity, a perfect conduction condition is

utilized. Therefore, normal components of the magnetic field (H_n) and tangential

components of the electric field (E_t) vanish at these walls, where the boundary condition is applied as:

$$H_n = 0 \qquad E_t = 0 \qquad (3.3)$$

3.2.2 Wave equations

The coupling between the electric field and the magnetic field produced by the displacement current (Eq. 3.1a) and magnetic induction (Eq. 3.1b) provides a complete description of the propagation of electromagnetic waves. By combining the two equations to eliminate the magnetic field strength H, the wave equation (Eq. 3.4) can be obtained (Dibben, 2001):

$$\nabla \times \frac{1}{\mu} \nabla \times E + \omega^2 \varepsilon E = 0 \qquad (3.4)$$

In a homogeneous source free medium we can use Eq. 3.1c to simplify the wave equation (Eq. 3.4):

$$\nabla^2 E + \omega^2 \varepsilon \mu E = 0 \qquad (3.5)$$

Restricting the situation to consider only a plane wave propagating in the z direction, Eq. 3.5 can be further simplified to:

$$\frac{d^2 E_x}{dz^2} = -\omega^2 \varepsilon \mu E_x \qquad (3.5)$$

Where E_x is the electric field parallel to the x axis. This equation has a solution:

$$E_x(z) = Ae^{+\gamma z} + Be^{-\gamma z} \qquad (3.6)$$

where the constants A and B correspond to the magnitude of the waves propagating in the +z and -z directions, respectively; $\gamma = \omega \sqrt{\varepsilon \mu}$ is known as the propagation constant. It can be given as:

$$\gamma = \alpha + j\beta \qquad (3.7)$$

where α is the attenuation coefficient and β is the phase constant. They are related to the material properties by the following equations:

$$\alpha = \omega \sqrt{\frac{\mu \varepsilon_0 \varepsilon'}{2}} [\sqrt{\sqrt{1 + (\frac{\varepsilon''}{\varepsilon'})^2} - 1}$$ (3.8)

$$\beta = \omega \sqrt{\frac{\mu \varepsilon_0 \varepsilon'}{2}} [\sqrt{\sqrt{1 + (\frac{\varepsilon''}{\varepsilon'})^2} + 1}$$ (3.9)

The linkage between the electric and magnetic fields implies that the electric field of the propagating wave will be accompanied by a normal magnetic field. When the medium in which the wave is traveling is "lossy", which means the medium will cause dissipation of electrical energy, the magnitude of the wave decays exponentially with distance.

3.2.3 Absorption of microwave energy

The microwave power absorbed in a food material is related to the dielectric conductivity and electric field strength (Decareau, 1992). An electromagnetic wave loses its energy when travelling through a lossy material. The electromagnetic energy is converted into thermal energy within the material. The amount of power that can be absorbed by a material or the conversion of microwave energy to heat is expressed by the following equation (Decareau, 1992):

$$P_{abs} = \sigma E^2$$ (3.10)

where P_{abs} is power absorbed (W/m^3), σ is dielectric conductivity and E is electric field strength (V/m). The dielectric conductivity σ is proportional to the permittivity of free space ε_0 (8.854×10^{-12} F/m), the relative dielectric loss factor of the material ε'', and the frequency of energy source f (Hz). The dielectric conductivity was calculated by:

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$$\sigma = 2\pi\varepsilon_0\varepsilon''f \tag{3.11}$$

So the equation of absorption power was converted into:

$$P_{abs} = 2\pi\varepsilon_0\varepsilon''fE^2 \tag{3.12}$$

3.2.4 Heat transfer equations

The temperature distributions in the particle and carrier liquid was obtained by the solution of the following energy equations (Eq. 3.13) with a source term which accounts for internal energy generation due to the absorption of the microwave energy.

$$\rho C_p\frac{\partial T}{\partial t} = \nabla \cdot (k\,\nabla T) + P_{abs} \tag{3.13}$$

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 heat transfer between the food surface and surrounding (other ingredients or surrounding air) was expressed as following convention equation (Geedipalli and others, 2007):

$$-k\frac{\partial T}{\partial z} = \mathrm{h}_c(T - T_a) \tag{3.14}$$

where z represents the direction towards the surface, h_c is the heat transfer coefficient (W/ (m^2 °C)), T is the surface temperature, and T_a is the surrounding temperature (° C). The heat transfer coefficient of value 10 W/ (m^2°C) was used in natural convective heat transfer in air to calculate the heat loss to the air from the load (Tong and Lund, 1993). The surfaces in front of the air will have higher heat transfer coefficient than the surfaces opposite to it when the air flow goes into the cavity (Verboven et al., 2003). To insure the natural convection was taking place at the air-material interface, the air flow inside the cavity was blocked in the simulation and the validation.

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3.2.5 Assumptions

For simplicity, the microwaves were assumed to be transverse electromagnetic or uniform plane waves. Although a uniform plane waves could not be formed in a real system, the electric field distribution obtained from this simplified model could approximate the actual electric field in the system (Hossan and others, 2010). The other assumptions used to simplify the problem were:

1) Food systems obey linear material constitutive laws, which means the components in food system are linear constitutive.

2) Electroneutrality condition is satisfied within the system.

3) The magnetic permeability can be approximated by its value in free space.

4) Dielectric properties are temperature independent.

5) Material properties, such as thermal conductivity and specific heat, are temperature independent.

3.2.6 Simulation model development

In the differential form of the electromagnetic equations, the electric field (E) distribution equations inside the cavity with irregular objects and wave equations could not be solved merely by analytical methods. Therefore, numerical methods needed to be used to solve the dynamically varying electromagnetic fields inside the cavity. Several numerical techniques were used to solve the Maxwell's equations. The finite element method (FEM) and finite different time domain method (FDTD) are the two most popular methods for simulating microwave heating (Dibben, 2001; Liu and others, 2013; Oliveira and Silva, 2010; Romano and others, 2005; Dev and others, 2012; Pandit and others, 2003; George and others, 2005; Chen and others, 2008; Torres and Jecko,

1997). In this study, an FEM based commercial modeling software, COMSOL 4.3b (COMSOL, Burlington, MA) was used to solve the mathematic model and simulate the heating process. A simulation model was developed following these steps: 1) creating geometric model, 2) assigning material properties, 3) input governed equations, meshing, 4) selecting solver parameters, 5) computing and obtaining results. The modeling steps were shown in Figure 3.1.
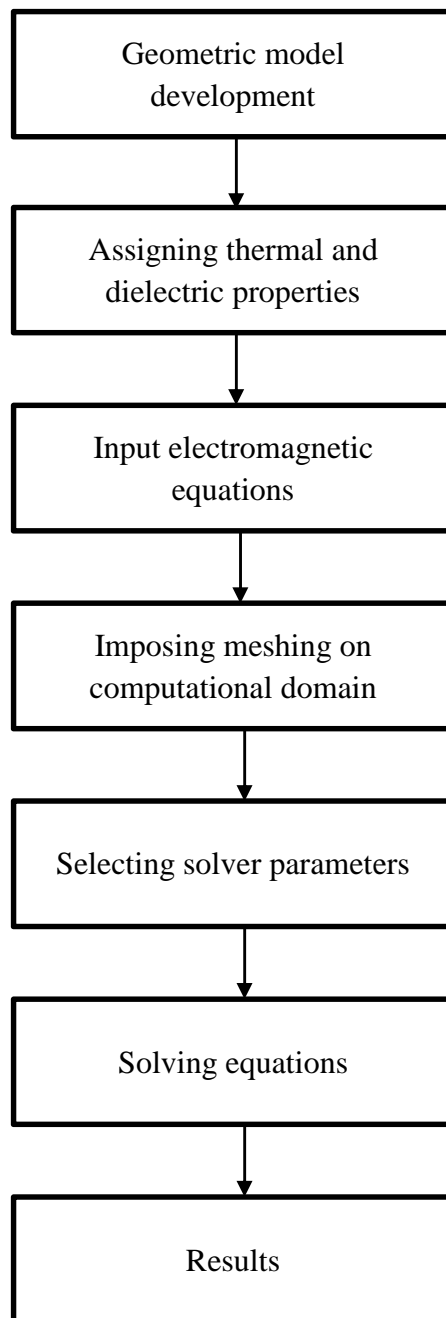
```
┌─────────────────────────┐
│     Geometric model     │
│       development       │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│   Assigning thermal and │
│   dielectric properties │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│   Input electromagnetic │
│        equations        │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│   Imposing meshing on   │
│   computational domain  │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Selecting solver parameters │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│    Solving equations    │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│         Results         │
└─────────────────────────┘
```

Figure 3.1 Flow chart of simulation model development

3.3 Results and Discussion
3.3.1 Model geometry

In COMSOL, the geometry of the microwave oven was built into the user interface. The creation of the microwave oven model can be customized to required size, waveguide, port, magnetron, and frequency. Figure 3.2 shows geometric model developed for 1200 W rated power microwave oven (Panasonic Canada Inc., Mississauga, Ontario, Canada) with an operating frequency of 2.45 GHz. The microwave oven included a cavity ($418 \times 470 \times 228$ mm), a turntable, and a magnetron. The port that provides microwave energy to the cavity was located in the middle of the right wall of the microwave oven cavity. The port was connected to a magnetron through a waveguide on the other side of the cavity.
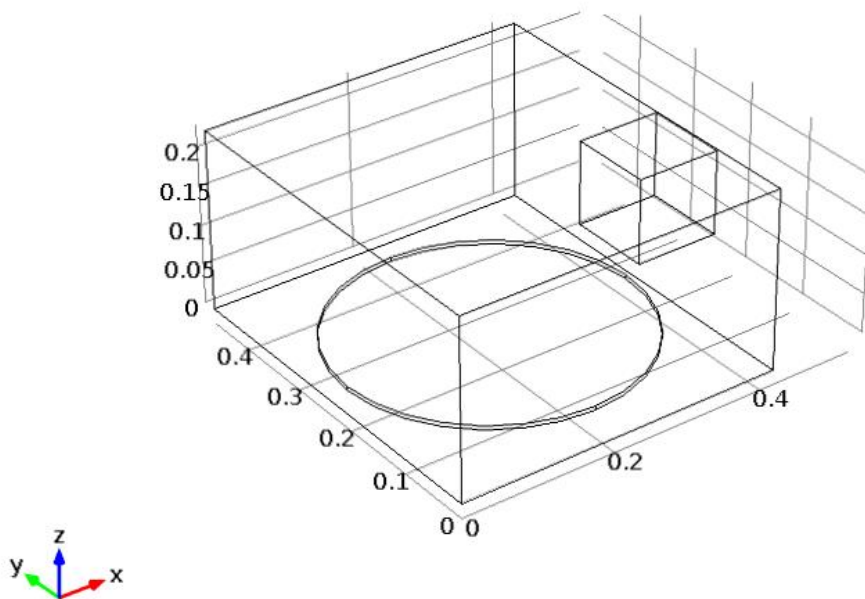

Figure 3.2 Geometry of microwave oven

3.3.2 Input properties and equations

Properties of materials were input into the software model easily in COMSOL. In COMSOL, the properties of materials were given in the material part. Each component in the computation domain was defined with electromagnetic and thermal properties.

Both independent variable and dependent function were used in the properties. Equations were input in COMSOL.

The real power output of microwave oven was measured by the protocol from The International Electrotechnical Commission (IEC). The protocol uses 1,000 g water load heated in the microwave oven to measure the temperature rise and then the microwave power output was determined. The water temperature was initially below ambient temperature and was raised to approximately ambient temperature by heating in the microwave oven. This procedure ensured that the heat losses and the heat capacity of the container have a minimum effect. A cylindrical container of borosilicate glass was used for the test. At the start of the test, the oven and the empty container were at ambient temperature. Water having an initial temperature of 10 °C ± 1 ° C was used for the test. The water temperature was measured immediately before it is poured into the container. The oven was operated and the time for the water temperature to attain 20 °C ± 2 ° C was measured. The oven was then switched off and the final water temperature was measured within 60 s. The microwave power output was calculated from the following formula (IEC 2006):

$$P = \frac{4.187 \, m_w \, (T_2 - T_1) + 0.55 \, m_c \, (T_2 - T_0)}{t} \tag{3.15}$$

where P is the power output (W), 4.187 is the specific heat of water (J/g °C), m_w is the mass of water (g), 0.55 is the specific heat of the glass container (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 heating time (s). The microwave power output was rounded off to the nearest 50 W.

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Solving dominated equations for electromagnetic and heat transfer requires iterative computational techniques to perform the simulation. Maxwell's equations were used to calculate each grid of the computation domain for electric field strength based on properties assigned for that grid and adjacent grids. The solution of electromagnetic equations required a large number of iterations to reach a steady state at each time step. The calculated electric field strength (E) was applied as an input to determine the dissipated power density (W/m^3). Heat transfer equations were applied on the materials placed inside the cavity. The heat change of the small grid was obtained by adding the new absorbed power into the old enthalpy field. The temperature was given by the result of the heat change in each grid. For temperature dependent functions, thermal properties of the medium were updated with the change of the temperature field at each time stop. As a sequence, new dielectric properties were calculated based on the new temperature field and used to calculate new electromagnetic fields and microwave power source term.

3.3.3 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 (Pitchai, 2011). 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. The relationship of electromagnetic periods (T_p) to the number of iterations (N$_p$) was described in the following relation (Pitchai, 2011):

$$N_p \times T_p = N \times dt \tag{3.16}$$

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where N is the number of iterations needed for reaching a steady state, and dt is the electromagnetic time step (ns).

3.3.4 Meshing

Mesh generation is one of the most critical aspects of simulation. The mesh settings determine the resolution of the finite element mesh used to discretize the model. The finite element method divides the model into small elements of geometrically simple shapes, in this case tetrahedrons. In each tetrahedron, a set of polynomial functions was used to approximate the structural displacement field: how much the object deforms in each of the three coordinate directions. In this study, the mesh was created in COMSOL itself.

3.3.5 Validation of the model

After the development of the model and simulation of the model in the software, the simulated temperature profile was compared with the experimental profiles. Model parameters were input into the simulation model, and computed for the result. The fresh and frozen oyster meats were used to valid the model. The validation of the model will be discussed in Chapter 4.

3.4 Conclusions

In this chapter, mathematical and computer-based models were built to simulate microwave heating. Maxwell's equations were used to solve the electromagnetic energy distribution. The microwave energy absorption equation was used to calculate the power absorption. The temperature distributions in the food stuff can be obtained by the solution of the heat transfer equations with a source term which accounts for internal energy generation due to the absorption of the microwave energy. An FEM based commercial software COMSOL was used to solve differential equations and simulate

the microwave heating. A microwave cavity was built in the software, and parameters

and dominated equations were input for the simulation.

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CHAPTER 4 APPLICATION OF MATHEMATICAL AND COMPUTER-BASED MODELS TO OYSTER MEAT

4.1 Introduction

As one of the most popular types of seafood in the US, oysters have become a leading cause of foodborne disease. The pathogens most associated with oyster consumption are *Vibrio* specie, especially *Vibrio parahaemolyticus* (*Vp*) and *V. vulnificus* (*Vv*) (CDC, 2013). *Vibrio* spp. are widespread and naturally present in marine and estuarine environments. As a natural filter feeder, oysters may concentrate microorganisms from the environment, which will lead to accumulation of pathogens. During the summer months, oysters may concentrate *V.* spp. in warmer waters (Corcoran, 1998). *V. vulnificus* has the highest mortality ratio of any foodborne pathogen, which is approximately 50% (FAO, 2005). The case fatality rate caused by *V. vulnificus* is about 50% for bloodstream infections and 25% for wound infections (Iwamoto and others, 2010). The *V. parahaemolyticus* infection causes watery diarrhea, abdominal cramps, nausea, and vomiting (Painter and others, 2013). An estimated 35,000 cases of foodborne gastroenteritis are related to the consumption of contaminated seafood with *V. parahaemolyticus* in the United States each year (Scallan and others, 2011) and most reported cases are caused by oysters.

Thermal processing can be used to kill the *Vibrio* spp. The CDC (2009) recommends boiling shucked oysters at least 3 minutes to kill *Vibrio vulnificus*. By heating oyster meat at 50˚C for 5 min, 99.9% *V. vulnificus* and 100% *V. parahaemolyticus* were eliminated in the shell-stock oysters (Andrews and others, 2000). Cryogenic individual quick freezing has been proven to be an effective post-

harvest processing technique for eliminating the pathogen in oysters (Muth and others, 2011).

Volumetric heat generated by microwave can heat food quickly. Food absorbs microwave energy internally and then it is converted into heat. The main problem associated with microwave heating is the non-uniform temperature distribution in microwave-heated foods. The non-uniform temperature distribution causes hot spots and cold spots on food during microwave heating and lead to quality issues and health risks (Ryynanen and others, 1996). Some pathogenic microorganisms may survive in cold spots after microwave heating. In oyster products, pathogen survival in cold spots can cause serious health risk to consumer.

Temperature is a critical factor for final product quality in microwave heating. However, the characteristic of microwave heating limits the experimental measurement of temperature. The interference of measuring devices with the electromagnetic field can disturb microwave heating in heating devices (Salvi and others, 2011), so numerical methods can be introduced into the determination of temperature distribution in microwave heating. The distribution of the electric and magnetic fields in microwave heating can be described by Maxwell's equations (Rattanadecho, 2006). The dielectric properties determine how materials interact with an electromagnetic field. Coupled mass and energy balances need to be solved taking into account the absorption of electromagnetic energy to determine the temperature distribution. Accurate modeling of the microwave heating process requires effective methods for solving both electromagnetic and thermodynamic problems (Kopyt and Celuch, 2006). Computer

technology and simulation technology can be employed in solving microwave heating problems. The finite element method (FEM) is widely used for simulating of the microwave heating (Liu and others, 2013; Oliveira and Silva, 2010). Due to the variation in properties of foods, modeling consists of solving specific and limited problems in microwave heating.

This study was conducted to employ a mathematical model to predict the temperature distribution during microwave heating for oysters, and used simulation software to solve the mathematical model and simulate the microwave heating. Evaluation of the non-uniform temperature distribution of oysters during microwave heating will help to locate the hot spots and cold spots during heating, and provide information to predict the temperature change in oyster.

4.2 Materials and methods
4.2.1 Shucked oysters

Fresh gulf oysters (*Crassostrea virginica*) were purchased from a local seafood market in Baton Rouge, Louisiana. The oyster meat was cryogenically frozen by a cabinet-type cryogenic freezer (Air Liquide, Houston, Texas), which employed liquid nitrogen with an operation temperature of -123.3ºC Freezing was carried out until the geometrical center reached -20ºC. The temperature was monitored at one second interval and recorded using a temperature data logger and type K thermocouples (Comark®, Comark Limited, Stevenage, Herts, UK). After freezing, oyster meat samples were stored in a walk-in freezer at -20ºC.

4.2.2 Proximate analysis of oyster meat

Moisture, protein, lipid, and ash were analyzed for the fresh shucked oyster meat. The oyster meat was analyzed for moisture and ash contents by using the AOAC

standard methods 930.15 and 942.05, respectively (AOAC International, 2005) in triplicate. Three batches of oyster meat obtained from 15 oysters were collected and homogenized separately in a Waring® commercial laboratory blender for 60 s at high speed. Approximately 5 g samples were dried at 105°C for 24 h in a draft oven for moisture content determination. The weight loss was used to calculate the moisture content of samples. About 1 g of freeze dried sample was incinerated at 550°C for 24 h for determining ash content. The lipid content was measured in triplicate using AOAC standard methods 948.15 (AOAC International, 2005). About 5 g freeze dried oyster meat was placed in a sohxlet extractor to extract the fat content at 60°C for 3 hours. Petroleum ether was used as extraction solvent. To measure protein, the nitrogen content was first determined in triplicate by the Dumas combustion method using a Leco TruSpec® Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). The protein content was then calculated as percent nitrogen times 6.25.

4.2.3 Thermal properties of oyster meat

The thermal conductivity of oyster meat was estimated by Choi and Okos's equation (1986).

The thermal conductivity (K) for oyster meat with *n* components was estimated using equation 4.1.

$$K = \sum_{i=1}^{n} V_i K_i \tag{4.1}$$

where V_i is the volume fraction of the *i*th component, which was calculated by equation 4.2.

$$V_i = \frac{\frac{m_i}{\rho_i}}{\sum_{i=1}^{n} \frac{m_i}{\rho_i}} \tag{4.2}$$

where m_i is the mass fraction of the *i*th component, and ρ_i is the density of the *i*th component.

The specific heat (C$_p$) of oyster meat was estimated by equation 4.3.

$$Cp = \sum_{i=1}^{n} m_i Cp_i \qquad (4.3)$$

where C$_{pi}$ is the specific heat of the *i*th component.

Similarly, the thermal diffusivity α of oyster meat was estimated by equation 4.4.

$$\alpha = \sum_{i=1}^{n} m_i \alpha_i \qquad (4.4)$$

where α_i is the specific heat of the *i*th component.

The thermal properties are functions related to temperature. But to simplify the calculation and simulation, values at room temperature (20°C) were used to development the simulation model.

Latent heat (*L*) was calculated as:

$$L = x_i L' \qquad (4.5)$$

where *L'* was the latent heat of fusion of water (333.6 kJ/ kg) and x_i was the weight fraction of ice, which was given by $x_i = (x_{wu} - Bx_s)(\frac{T_{if} - T_f}{T_0 - T_f})$, where x_{wu} equaled the weight fraction of water, x_s equaled the weight fraction of solute, B was bound water/kg solute, which was calculated by $b - \frac{M_w}{M_s}$, where M_w and M_s were the molecular weight of water and solutes, and *b* was the constant. The constant $b = 0.32$ was reported for fish (de Reinick, 1996). The molecular weight of solutes was calculated as $M_s = 18.02(\frac{X_w (1 - x_{wu})}{x_{wu}(1 - x_w)})$, and X_{wu} was the mole fraction of water of the oyster meat. X_w was calculated by $ln(X_w) = -18.02(\frac{L'(T_0 - T_{if})}{RT_0^2})$, where *R* was the ideal gas constant = 8.314 J/ mol K and temperature was expressed in K. The latent heat for cryogenically frozen

oyster meat was measured and calculated in the Food Engineering Lab, LSU Ag Center.

The latent heat of oyster meat during cryogenically freezing was 224.93 ± 2.05 kJ/kg

K (Espinoza-Rodezno, 2013).

4.2.4 Dielectric properties of oyster meat

The permittivity of the shucked oysters was measured by two open-ended, 1 mm

diameter coaxial probes, connected to a Network Analyzer (Model N5230A, Agilent,

Santa Clara, CA). Two probes were connected by a 9 cm transmission line. An

aluminum pan was used to hold oyster samples. Care was taken to insert the

transmission line into the oyster meat, and avoid any contact between the transmission

line and the container (Figure 4.1). The time of the signal travelled through the

transmission line was recorded using the network analyzer, and then converted into the
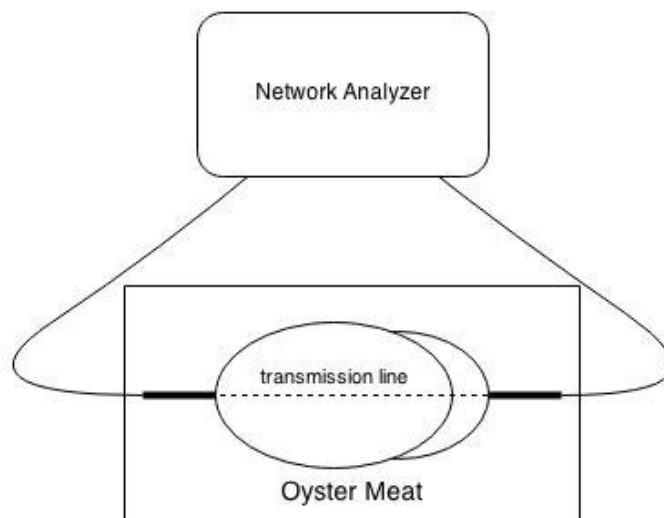
permittivity of the oyster meat.

Figure 4.1 Measurement of dielectric properties of oyster meat

4.2.5 Geometry of oyster meat

The cryogenically frozen oyster meats were used to measure the geometry. After

cryogenically freezing, frozen oysters were moved to a food processing room, and

vernier calipers were used to measure the length, width, and height. One hundred

oysters from different batches were used to determine the average length, width, and

height of oysters.

4.2.6 Model development
4.2.6.1 Mathematical equations

The main equations of mathematical models include:

The Maxwell's equations:

$$\nabla \times E = -j\omega\mu H \tag{3.1a}$$

$$\nabla \times H = J_t = j\omega\varepsilon_0\varepsilon E \tag{3.1b}$$

$$\nabla \cdot E = 0 \tag{3.1c}$$

$$\nabla \cdot H = 0 \tag{3.1d}$$

Absorption of microwave energy equations:

$$P_{abs} = 2\pi\varepsilon_0\varepsilon''fE^2 \tag{3.12}$$

Heat transfer equations:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + P_{abs} \tag{3.13}$$

The energy balance and mass balance were estimated by following equations:

$$P_{input} = P_{abs} + +P_{unabs} + P_{loss} \tag{4.5}$$

$$m = m_{heated} + m_{loss} \tag{4.6}$$

where P_{input} is the energy input, P_{abs} is the absorbed energy, P_{unabs} is unabsorbed

energy, P_{loss} is the energy loss from the heated material; m is the mass of food,

m_{heated} is the mass of heated food, m_{loss} is the mass loss of the heated food. During

microwave heating, moisture content in the oyster meat was evaporated and left the

food. The evaporation of moisture takes away some absorbed energy and causes energy

loss. This dynamic process is difficult to predict, and affects the temperature

distribution. Therefore, the following assumptions were made to simplify the modeling process:

1) Food systems obey linear material constitutive laws.

2) Electroneutrality condition is satisfied within the system.

3) Dielectric properties are temperature independent.

4) Material properties, such as thermal conductivity and specific heat are temperature independent.

5) No mass change during heating.

4.2.6.2 Simulation model development

A finite element method (FEM) based commercial modeling software, COMSOL 4.3b (COMSOL, Burlington, MA) was used to simulate the microwave heating process. The cavity (418 × 470 × 228 mm), a turntable, and a magnetron were built in the software. In the middle of the turntable, two ellipses composed the simulation of oyster meat geometry. Due to the symmetry of the simulation, the cavity was cut into half to simplifying the computing. The geometry of the simulation model was shown in Figure 4.1.

The operation frequency of the microwave oven was set to 2450 MHz. The temperature of the cavity was set to 20 °C. The initial temperature of frozen oyster meat was set to - 4°C. The power output was evaluated by adjusting the International Electrotechnical Commission (IEC) protocol: heating of 200 g water load for 30 s, then calculating the microwave power output by the following equation:

$$P = \frac{4.187 \, m_w \, (T_2 - T_1) + 0.55 \, m_c \, (T_2 - T_0)}{t} \tag{3.15}$$
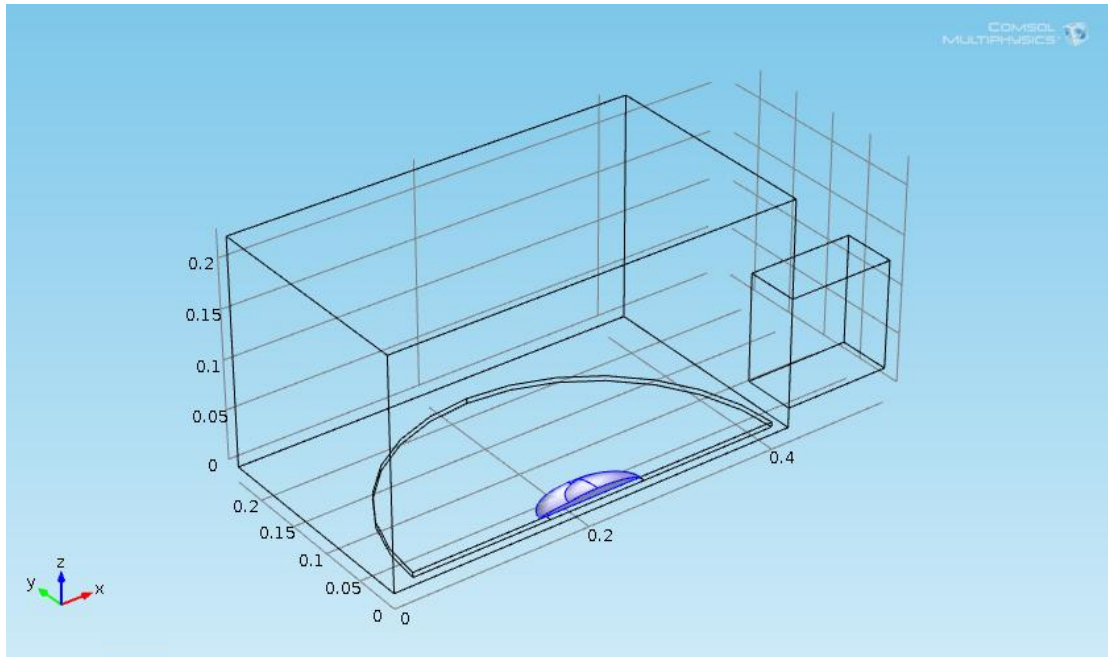
Figure 4.2 Geometry of the simulation model

where P is the microwave power output (W), 4.187 is the specific heat of water (J/g °C), m_w is the mass of water (g), 0.55 is the specific heat of glass container (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 heating time (s). The microwave power output was stated in watts, rounded off to the nearest 50 W. The heat transfer inside the oyster meat was set up for better simulation.

4.2.6.3 Validation of the simulation models

The model was validated by measuring the temperature change during microwave heating. Data collection of temperature during microwaving was performed in a Microwave Workstation (MW) (FISO Technologies Inc., Quebec, Canada) which included a 1200 watts, 2450 MHz microwave oven. Data were collected through the (MW) commander control. Fiber optic temperature sensors (FOT-L-SD-C1, FISO Tech. Inc. Canada) were used in the current study. The microwave oven power output was

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calculated by measuring the temperature difference of 200 g water for 25 s before heating and after the heating. The output energy can be calculated by using the thermal properties of water and the temperature increasing in water and. Temperature sensors were used for measuring the internal temperature in oyster meat. The sensor was inserted into the oyster meat during microwave heating to collect the temperature data.

The hot spot was picked to monitor the temperature change. The hot spot was identified by running the simulation model. The location of potential hot spot of oyster meat was found and used to measure the temperature change. For frozen oyster meat, it was carefully perforated with a 2 mm stainless steel drill before placing the sample into the microwave oven. For internal temperature measurement, the tip of the sensors was introduced into the drilled holes of the frozen oyster meat. The collected data were compared to the temperature result from the simulation model. The simulated temperature profile (T_p) was compared with the experimental temperature profile (T_e) and the root mean square error was calculated by $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_p - T_e)^2}$ (Pitchai and others, 2012).

Due to the property difference between ice and water, the simulated temperature for frozen oyster meat was divided into two parts: below the freezing point and beyond freezing point. When the temperature was below freezing point, the thermal properties calculated from the properties of ice were used, and the latent heat needed to be taken into account.

4.2.9 Statistical analysis

The collected data were analyzed using SAS version 9.2 (SAS, Version 92, SAS Institute Inc., Cary, NC., USA). One-way analysis of variance (ANOVA) was used to

detect statistical differences (P 0.05). Means values from three measurements and/ or triplicate analysis were reported.

4.3 Results and discussion
4.3.1 Proximate analysis of oyster meat

The moisture, protein, fat and ash content of fresh oyster meat were 90.28 ± 0.22 %, 4.51 ± 0.03%, 1.51 ± 0.44% and 0.77 ± 0.01 %, respectively. The carbohydrate was calculated by subtracting of moisture, protein, fat and ash content from total weight of oyster meat. The proximate composition of oyster meat was shown in Table 4.1.

Table 4.1 Proximate composition of oyster meat

Composition (wet basis)	
Moisture %	90.28 ± 0.22
Protein %	4.51 ± 0.03
Fat %	1.51 ± 0.44
Ash %	0.77 ± 0.01
Carbohydrate % (calculated)	2.9 ± 0.49

Due to the harvest season, environment, growth and reproductive cycles and metabolic condition, the composition of oysters has variance (Lira and others, 2013). During a warmer season, oyster meat has lower protein content, but higher ash content; but during winter, oyster meat tends to obtain higher moister content and protein (Cruz-Romero and others, 2008; Lira and others, 2013).

4.3.2 Thermal properties of oyster meat

Based on proximate analysis, the thermal properties of oyster meat can be calculated based the thermal properties of food ingredients (Appendix A). The thermal properties of oyster meat were showed in Table 4.2.

Table 4.2 Thermal properties of oyster meat

Thermal Property	Fresh oyster meat	Frozen oyster meat (-4°C)
Thermal conductivity k (W/m·°C)	0.571 ± 0.002	2.105 ± 0.006
The thermal diffusivity (mm^2/s)	0.141 ± 0.001	0.112 ± 0.004
Density (kg/m^3)	1028.617 ± 4.748	953.428 ± 5.346
The specific heat C$_p$ (kJ/kg·°C)	4.019 ± 0.097	2.024 ± 0.001

During freezing, weight loss occurs in the oyster meat. The weight loss was relatively low for cryogenically freezing for oyster meat (less than 1%). The weight loss was not included in the calculation.

The results in this study were close to other researcher's. Hu and Mallikarjunan reported the thermal properties for oyster meat at 20 °C were 0.604 W/m°C for thermal conductivity, 3.740 kJ/kg °C for specific heat, 1037 kg/m^3 for density, and 0.156 mm^2/s for thermal diffusivity (Hu and Mallikarjunan, 2005). The difference of composition of oyster meat affected calculated result and caused slightly difference.

4.3.3 Dielectric properties of oyster meat

The relative complex permittivity (ε) of oyster meat was found to be 68.66 at 20 °C with the frequency of 2450 MHz. The dielectric constant was found to be 55.65, and the loss factor was 15.06. Dielectric properties of oysters were determined by Hu and Mallikarjunan (2005) between 300 MHz and 3 GHz to describe the temperature effects on thermal and dielectric properties of oysters. At 2450 MHz, the dielectric constant of oyster decreased from 59.10 to 47.67, while the loss factor varied from 12.94 to 16.08 at 2450 MHz as temperature increased from 1 to 55 °C. The result from the measurement in this study was within the range of reported values.

4.3.4 Geometry of oyster meat

Due to the growth condition, nutrition condition, and harvest season, the size of oyster meats varied. After the measurement of 100 cryogenically frozen oyster meats, the average length, width, and height (thickness) were given in Table 4.3.

Table 4.3 Geometry of oyster meat

Geometry	Result
Length (mm)	66 ± 14
Width (mm)	33 ± 5
Height (mm)	13 ± 3

4.3.5 Validation of the simulation models
4.3.5.1 Power output of microwave oven

The result of microwave oven power output was showed in Table 4.4.

Table 4.4 Power output of microwave oven

Trial 1	Trial 2	Trial 3	Average
815.25	671.66	734.48	741.83 ± 58.67

Therefore the real power output of the microwave oven was set to 750 W based on the International Electrotechnical Commission (IEC) protocol. The real power output was input into the simulation model.

4.3.5.2 Temperature profile of the heated oyster meat

The temperature profile of oyster meat was obtained from the simulation model. The temperature profile of the oyster meat after 12s microwave heating was shown in Figure 4.3. The lighter color in the figure meant the higher temperature, and the darker area represented the lower temperature.

The hot spots and cold spot were identified from the temperature profile from the model. The hot spot and cold spot were showed in Figure 4.4. The locations for hot spot and cold spot were found in the simulation model (Table 4.5). The zero point in Figure

4.4 was left apex of the simulated oyster meat. The existence of hot spot and cold spot proved the non-uniform temperature distribution of oyster during microwave heating.
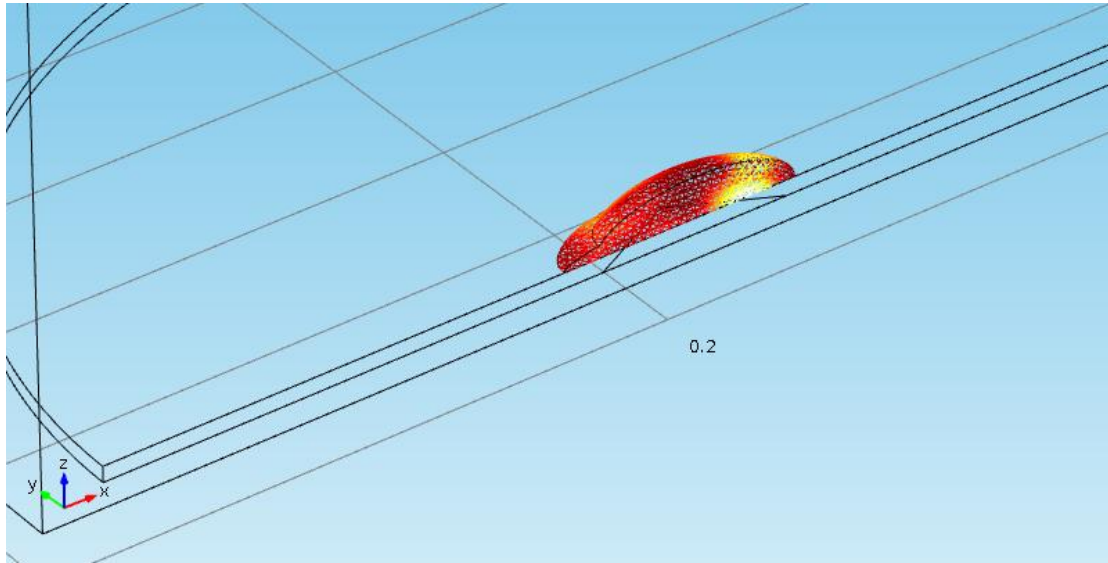

Figure 4.3 Temperature of oyster meat after microwave heating

Table 4.5 Hot spot and cold spot in heated oyster meat

	X-axis	Y-axis	Z-axis	Temperature ˚C
Hot Spot	6.00 ± 0.13 cm	0 ± 0.04 cm	0.13 ± 0.03 cm	100.36
Cold Spot	4.20 ± 0.07cm	0.25 ± 0.09 cm	2.00 ± 0.02 cm	85.90

However, in the real world, the oyster meat shrank and lost a lot of water after heating. So the temperature of the oyster may be varied and much higher than the predicted cold spot temperature, due to the mass loss and heat conduction. In this case, the temperature change in the hot spot was easier to monitor.

4.3.5.3 Temperature change of the hot spot

The hot spot was picked to monitor the temperature change. The hot spot was shown in the temperature profile of the heated oyster at Figure 4.4a. The result was shown in Figure 4.5. The root mean square error of the simulated temperature and the measured value at the hot spots ranged from 0.23 to 5.47 ˚C. Compared to the experimental data, the simulated temperature had a lower rate of increase. That might
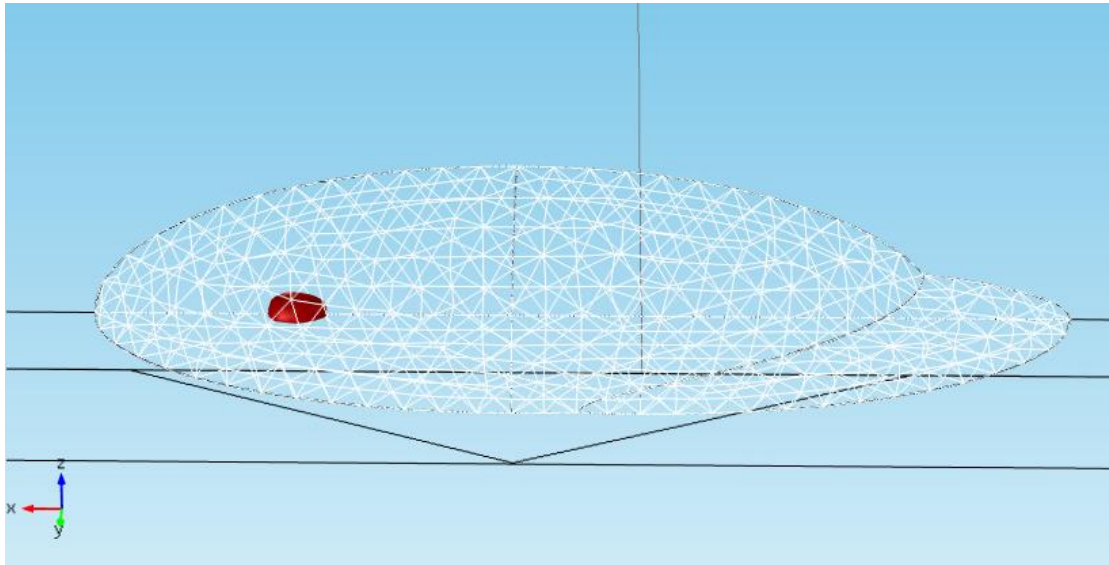
Figure 4.4 (a) Hot spot (red area) in heated oyster meat
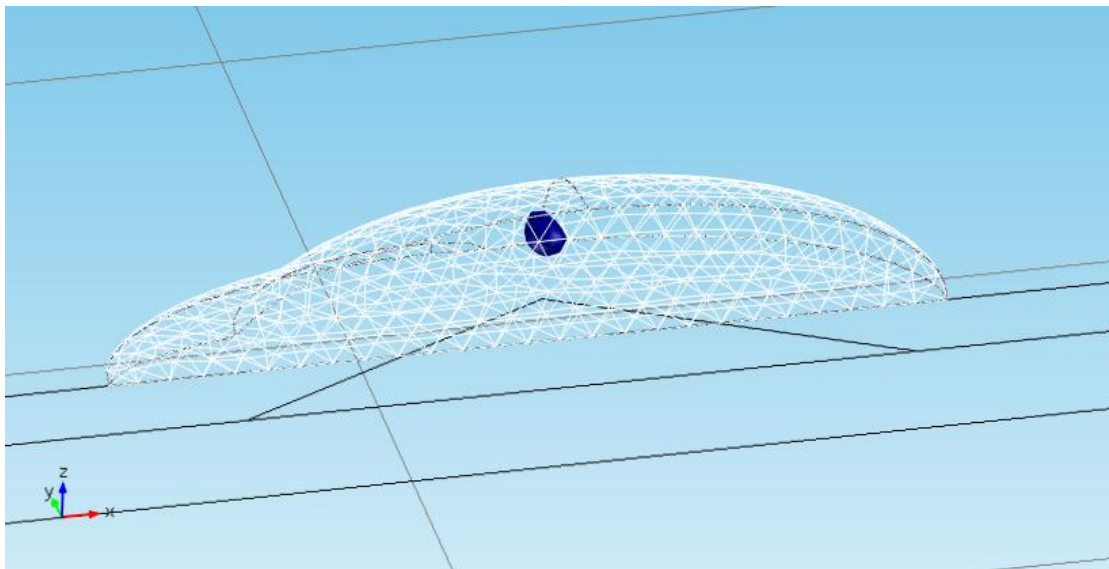

Figure 4.4 (b) Cold spot (blue area) in heated oyster meat
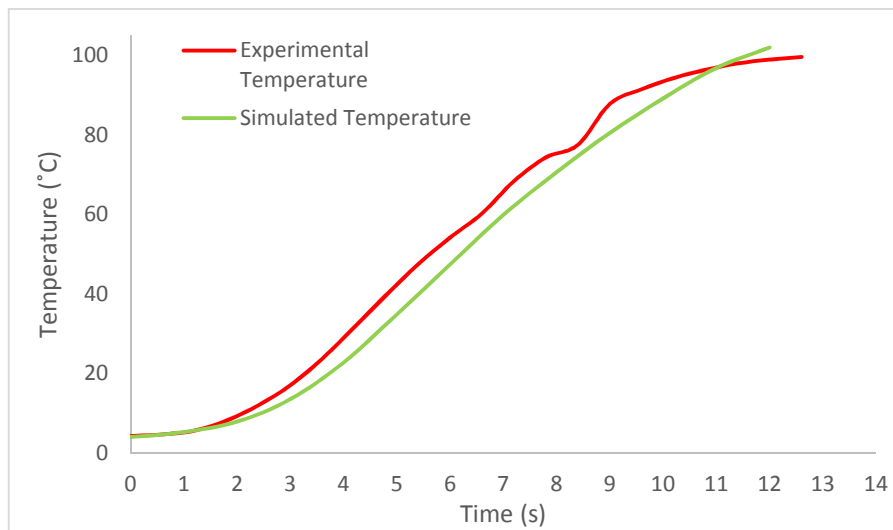

Figure 4.5 The temperature change of hot spot in fresh oyster meat

be due to the constant thermal properties and dielectric properties from the assumption. At the same time, the mass loss of the oyster meat during heating may also have an effect on the temperature change.

After running the simulation model, temperature data were combined into one figure to be compared with the experimental data, which was shown in Figure 4.6:
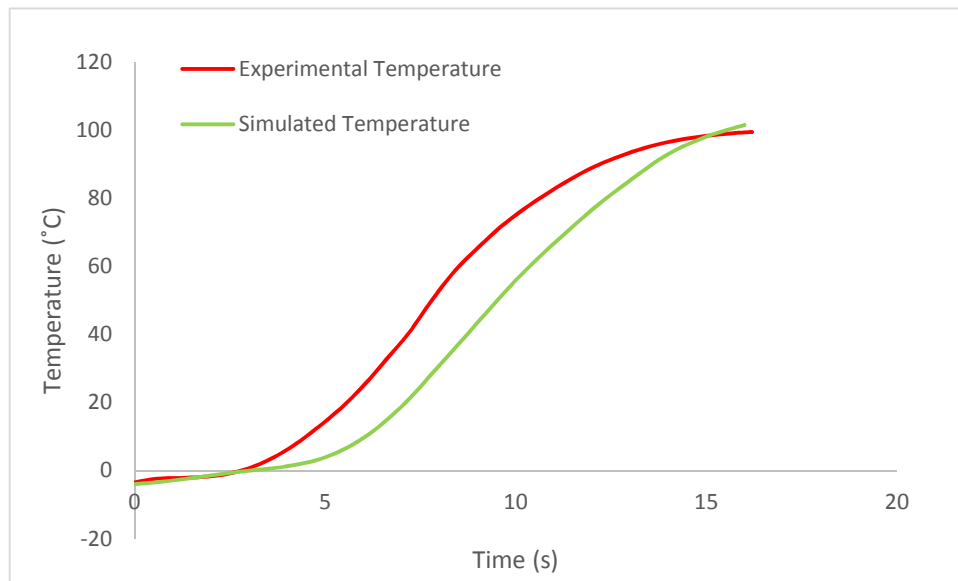

Figure 4.6 The temperature change of hot spot in frozen oyster meat

Due to the properties difference between water and ice, the heating rate of frozen oyster meat was slower when the temperature was below 0 ˚C. The ice has much lower dielectric properties compared to water. The ice molecules cannot act as water's in the microwave field due to the fixed structure. In addition, the phase change of the material during melting in microwave heating absorbed energy, so that the temperature increased slowly below 0 ˚C. Since the data were combined from two simulations, the temperature curve did not fit the experimental temperature well, but both curves had a similar tendency. When the frozen oyster was thawed, the microwave heating rose the temperature from 0 to 100°C in 15s, which was close to the predicted heating time for fresh oyster meat.

4.4 Conclusion

A simulation model using coupled electromagnetic and heat transfer equations was used to predict the temperature profile of oyster in this study. The FEM based commercial software was used to solve the electromagnetic Maxwell's equations and Fourier heat transfer equations and simulate the microwave heating processing.

Oyster meat was used for approximate analysis. The oyster meat contained 90.28% moisture, 4.51% protein, 1.51% fat, 0.77% ash, and 2.9% carbohydrate. Based on the composition of oyster meat, the Choi and Okos's equation was used to calculate the thermal properties of oyster meat. The dielectric properties of oyster meat were measured by the transmission line method. The geometry of oyster meat was determined by measuring 100 frozen oysters.

In this simulation model, the geometry of microwave oven and oyster were built into the simulation model. The temperature profile of oyster after heating was obtained by the model. Hot spot and cold spot were identified. The model predicted temperature change in hot spot agreed well with the experimental one; the fresh oyster can be heated from 4°C to about 100°C in 12s. The root mean square error of the simulated temperature and the experimental value at the hot spots ranged from 0.23 to 5.47 ˚C. The frozen oyster cannot be heated quickly below the freezing point. But when the temperature rose beyond the freezing point, the temperature increased quickly.

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CHAPTER 5 APPLICATION OF MATHEMATICAL AND COMPUTER-BASED MODELS TO OYSTER MEAT-BASED MEAL

5.1 Introduction

Microwavable meals are a group of prepackaged, frozen, and ready-to-cook convenient instant products. Consumers can cook these meals in minutes in a microwave oven before serving. Microwaveable meals are composed of raw and semi-cooked ingredients, which are frozen and packed in a microwavable container. Therefore, the temperature is a critical factor for heating microwavable meals. The non-uniform heat distribution during microwave heating is the main concern related to microbiological risk and quality in food. In the food industry, food safety is often achieved by heating foodstuff to eliminate microbiological threats and thus if the food product is not adequately heated pathogenic microorganisms may survive. At the same time, microwave heating may cause texture damage, due to over-heating, poor yield due to moisture loss, and poor appearance (Mizrahi, 2012).

Self-venting technology has rapidly spread in food industry for microwave cooking. The steam builds up with time during the cooking process due to the special designed package. During microwave cooking, the rapid heat generation can turn the water content in food into steam quickly. Vapor pressure is accumulated in the package and resulting in reduced cooking time and evenly distributed heat. The package distends with the increase of the internal pressure and provides a visual indication that cooking is occurring while maintaining a temperature between 100ºC to about 105ºC (Mast, 2000). The pressurized steam inside sealed plastic pouches or containers will have a self-venting release adaptation (Mast, 2000). Steam-venting technology for microwave

cooking has been engineered to improve the final product quality through controlled package expansion in conjunction with proprietary self-venting mechanisms (Fowle and others, 2005). Steaming is a gentle, fat-free cooking method that retains the natural moisture of foods. This feature makes it an excellent choice for preparing seafood meals, which contains high moisture content ingredients.

Combining the microwave cooking and steam venting technology can provide a wonderful meal with better final product quality and less health threat. However, the information for microwave heating of this meal is insufficient. The uneven temperature distribution occurred during the heating process, and might result in quality change and potential health risk. So the employment of mathematic and simulation models to describe the heating behavior for this meal during microwave heating is necessary.

5.2 Materials and methods
5.2.1 Ingredients

Fresh shucked gulf oysters (*Crassostrea virginica*) were purchased from a local seafood market in Baton Rouge, Louisiana, and processed in the Food Processing Pilot Plant, Louisiana State University Agricultural Center. The oyster meat was drained and placed on aluminum trays that were previously covered in aluminum foil. Freezing paper then was used to cover the oyster meat. To cryogenically freeze the oyster meat, a cabinet-type cryogenic freezer (Air Liquide, Houston, Texas) employing liquid nitrogen with an operation temperature of -123.3ºC was used. Freezing was carried out until the geometrical center reached -20ºC. The temperature was monitored at one second intervals and recorded using a temperature data logger and type K thermocouples (Comark®, Comark Limited, Stevenage, Herts, UK). After freezing,

oyster meat samples were stored in a walk-in freezer at -20ºC. Spaghetti (Great Value) was purchased from a local supermarket. Spaghetti was cooked in boiling water for 10 minutes, then the water was drained and the pasta was cooled right before further processing. Great Value Traditional Pasta Sauce was purchased from a local supermarket.

5.2.2 Preparation of microwavable meals

Based on former work conducted in the Food Engineering Lab, Louisiana State University Agricultural Center, one microwavable meal (PS) contained about 40g frozen oyster meat (2 average oysters), 43g Traditional Pasta Sauce and 157g cooked spaghetti.

Due to the difficulty to simulate the geometry of the meal and the measurement of the temperature change during heating, pasta sauce and spaghetti were ground by a Waring® commercial laboratory blender for 60 s at high speed. After the blending, paste was collected for further processing. PS paste then were transferred into plastic trays, and made into an $18cm \times 13cm \times 0.5cm$ (L$\times$W$\times$H) rectangular mass. All prepared trays were cryogenically frozen by a cabinet-type cryogenic freezer (Air Liquide, Houston, Texas) employing liquid nitrogen with an operation temperature of -123.3ºC. Freezing was carried out until the geometrical center reached -20ºC. Two frozen oysters were placed on the top of the paste. The trays then sealed in a Multivac T-200 tray sealer (Multivac Inc, Kansas, MO) using nitrogen as headspace gas. The trays were stored at -20ºC.

5.2.3 Proximate analysis of ingredients

Moisture, protein, lipid, and ash were analyzed for the paste of the instant meal. The paste were analyzed for moisture and ash contents by using the AOAC standard methods 930.15 and 942.05, respectively (AOAC International, 2005) in triplicate. Approximately 5 g samples were dried at 105°C for 24 h in a draft oven for moisture content determination. The weight loss was used to calculate the moisture content of the sample. About 1 g of freeze dried sample was incinerated at 550°C for 24 h for the ash content determination. The lipid content was measured in triplicate using AOAC standard methods 945.16 (AOAC International, 2005). About 5 g freeze dried paste was placed in a sohxlet extractor to extract the fat content at 60°C for 3 hours. Petroleum ether was used as extraction solvent. To measure protein, the nitrogen content was first determined in triplicate by the Dumas combustion method using a Leco TruSpec® Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). The protein content was then calculated as percent nitrogen times 6.25.

5.2.4 Thermal properties of oyster meat

The thermal conductivity, specific heat and thermal diffusivity of each principle component with respect to the changes of temperature can be estimated using Choi and Okos's equation (1986).

The thermal conductivity (K) for meal paste with n components was estimated using equation 4.1.

$$K = \sum_{i=1}^{n} V_i K_i \tag{4.1}$$

where V_i is the volume fraction of the ith component.

The specific heat (Cp) of meal paste was estimated by equation 4.3.

$$Cp = \sum_{i=1}^{n} m_i Cp_i \tag{4.3}$$

where Cp_i is the specific heat of the ith component.

Similarly, the thermal diffusivity α of meal paste was estimated by equation 4.4.

$$\alpha = \sum_{i=1}^{n} m_i \alpha_i \tag{4.4}$$

where α_i is the specific heat of the ith component.

The thermal properties are functions related to temperature. But to simplify the calculation and simulation, values at room temperature (20°C) were used to development the simulation model.

5.2.5 Dielectric properties of oyster meat

The permittivity of the meal paste was measured by two open-ended, 1 mm diameter coaxial probes, connected to a Network Analyzer (Model N5230A, Agilent, Santa Clara, CA). Two probes were connected by a 9 cm transmission line. An aluminum pan was used to hold the sample. Care was taken to insert the transmission line into the sample, and avoid any contact between the transmission line and the container (Figure 5.1). The time that the signal travelled through the transmission line was recorded by the network analyzer, and then converted into the permittivity.
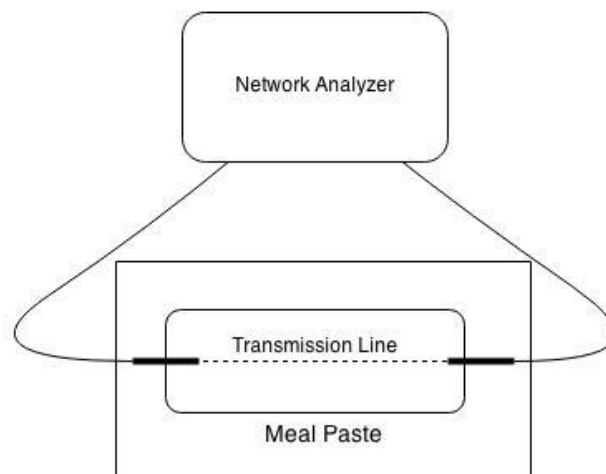

Figure 5.1 Measurement of dielectric properties of meal paste

5.2.6 Geometry of the meal

The size of the rectangular area was built into the simulation model. The paste was placed in the middle bottom of the cavity. Two frozen oysters were placed on the top middle of the paste, and ± 4cm to the center. The geometry of oyster meat used in this model was the same as Chapter 4.

5.2.7 Model development

The basic principles had been discussed in Chapter 3. The Maxwell's equations, microwave energy absorption equation, heat transfer equations and energy balance and mass balance equations were used. The assumptions were made to simplify the modeling:

1) Food systems obey linear material constitutive laws.

2) Electroneutrality condition is satisfied within the system.

3) Dielectric properties are temperature independent.

4) Material properties, such as thermal conductivity and specific heat are temperature independent.

5) No mass change during the heating.

6) No heat transfer between the package and the food.

The same procedures were used to build a simulation model in COMSOL. The heat transfer inside the foodstuff was set up for better simulation. The heat transfer between the paste and oyster was enabled, which means the surface between the paste and oyster would have the heat conduction.

5.2.8 Running of the simulation models

Both sealed trays and unsealed trays were prepared for microwave heating. Data collection of temperature during microwaving was performed in a Microwave

Workstation (MW) (FISO Technologies Inc., Quebec, Canada). Fiber optic temperature

sensors (FOT-L-SD-C1, FISO Tech. Inc. Canada) were used to insert into the frozen

oyster meat and meal paste during microwave heating to collect the temperature data.

For frozen oyster meat and paste, it was carefully perforated with a 2 mm stainless steel

drill after being removed from the cabinet cryogenic freezer. For sealed meal, the tip of

the sensors were introduced in the center of the frozen oyster meat passing through the

film and secured by special heat resistant septa to maintain the integrity of the film

(Figure 5.2). The sensors were placed on the center of both oyster meats and the paste.

The collected data were compared to the temperature result from the simulation model.

The simulated temperature profile (T_p) was compared with the experimental

temperature profile (T_e) and the root mean square error was calculated

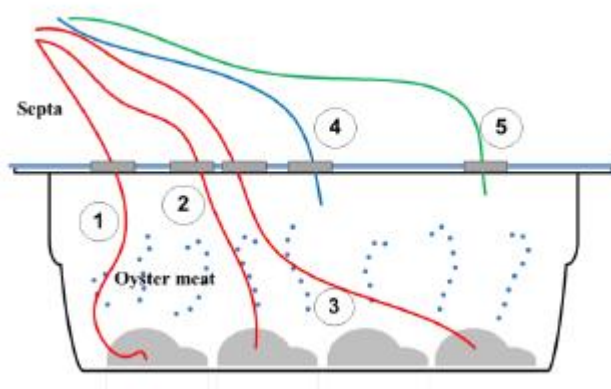by $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_p - T_e)^2}$ (Pitchai and others, 2012).

Figure 5.2 Distribution of the internal temperature sensors inside the package
(Espinoza-Rodezno, 2013)

5.2.9 Statistical analysis

The collected data were analyzed using SAS version 9.2 (SAS Institute Inc., Cary,

NC, USA). One-way analysis of variance (ANOVA) was used to detect statistical

differences (P 0.05). Means were from three measurements and/ or triplicate analysis.

5.3 Results and discussion
5.3.1 Proximate analysis

The proximate composition of ingredients was shown in Table 5.1.

Table 5.1 Proximate composition of meal paste

	Meal Paste (wet basis)
Moisture %	67.2 ± 0.48
Protein %	5.81 ± 0.03
Fat %	18.00 ± 0.99
Ash %	3.30 ± 0.26
Carbohydrate % (calculated)	6.69 ± 1.13

The meal paste contained less moisture content and higher fat content compared

to oyster meat.

5.3.2 Thermal properties of ingredients

The thermal properties of meal paste were shown in Table 5.2.

Table 5.2 Thermal properties of meal paste at 20 °C

Thermal Property	Meal Paste (wet basis)
Thermal conductivity k (W/m·°C)	0.468 ± 0.003
The thermal diffusivity (mm^2/s)	0.130 ± 0.001
Density (kg/m^3)	1050.05 ± 10.33
The specific heat C_p (kJ/kg·°C)	3.497 ± 0.021

The thermal properties were related to components of the meal paste. The paste

had lower thermal conductivity, thermal diffusivity than oyster meat. But it had higher

density and the specific heat compared to the oyster meat.

5.3.3 Dielectric properties of oyster meat

The relative complex permittivity (ε) of pasta sauce and spaghetti paste was found

to be 26.02 at 20 °C with the frequency of 2450 MHz. The dielectric constant and loss

factor were 31.43 and 12.33, respectively. Due to the difference of composition of the

meal and measuring frequency, the relative complex permittivity of the meal can be

varied. Wang and others (2003) reported the cooked macaroni noodles had a dielectric constant of 27.60 of the and a loss factor of 6.05 at 1,800 MHz, and show a tendency for the dielectric properties of the cooked macaroni noodles to decrease with a frequency increase.

5.3.4 Geometry

The geometry of the simulation model was shown in Figure 5.3.The meal was placed in the center of the turntable; two oysters were placed on the top of the paste symmetrically. The distance of the center of each oyster to the middle line of the width was 4 cm.
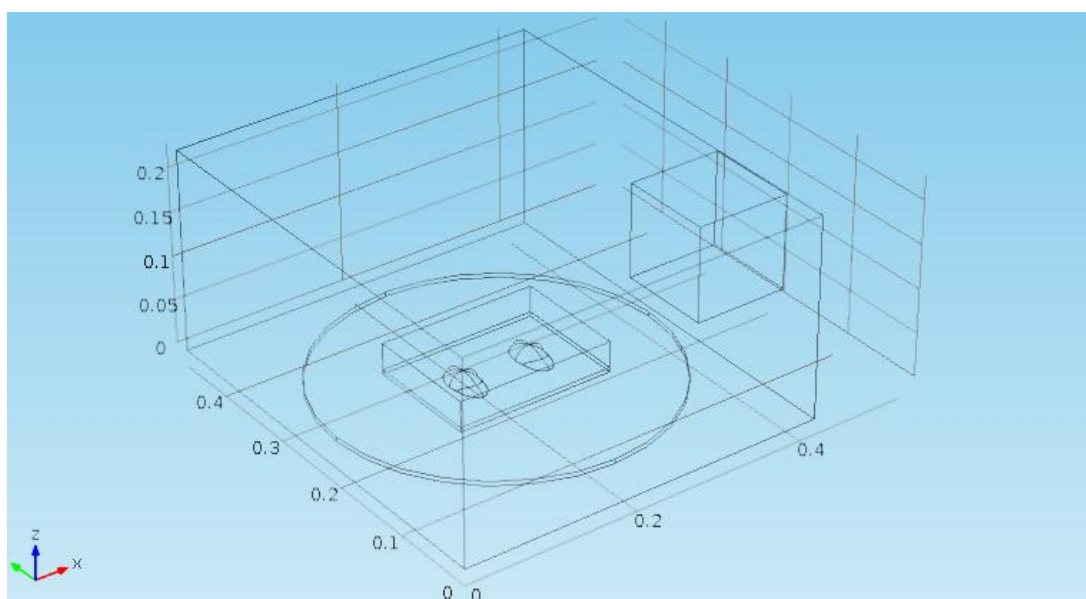
Figure 5.3 Geometry of the simulation microwavable meal

5.3.5 Results from the simulation models
5.3.5.1 Temperature profile of unsealed meal

The temperature profile of the unsealed pasta sauce and spaghetti meal was obtained by running the simulation model. The temperature profile of the oyster meat after 60s microwave heating was shown in Figure 5.4. The hot spots and cold spots in the meal after microwave heating were showed in Figure 5.5. Hot spots were spread all over the meal randomly (Figure 5.5a). On the other hand, cold spots concentrated on

oyster meats (Figure 5.5b). The temperatures of the hot spot and cold spot were 16.5°C and 105.7°C, respectively. Therefore there has a high possibility that when the paste was heated, the frozen oyster meat may remain cold. The reason may be the different composition of the meal paste and the oyster meat. The difference of composition of the meal paste and the oyster meat led to the variances of thermal and dielectric properties, which meant they cannot be heated at same heating rate. The other reason might be the location of these two components in the microwave. The meal paste was spread on the bottom of the tray; so it might have more volume to absorb the microwave energy. The electric field might have more interaction area with the paste due to the larger bulk volume compared to oyster meats.
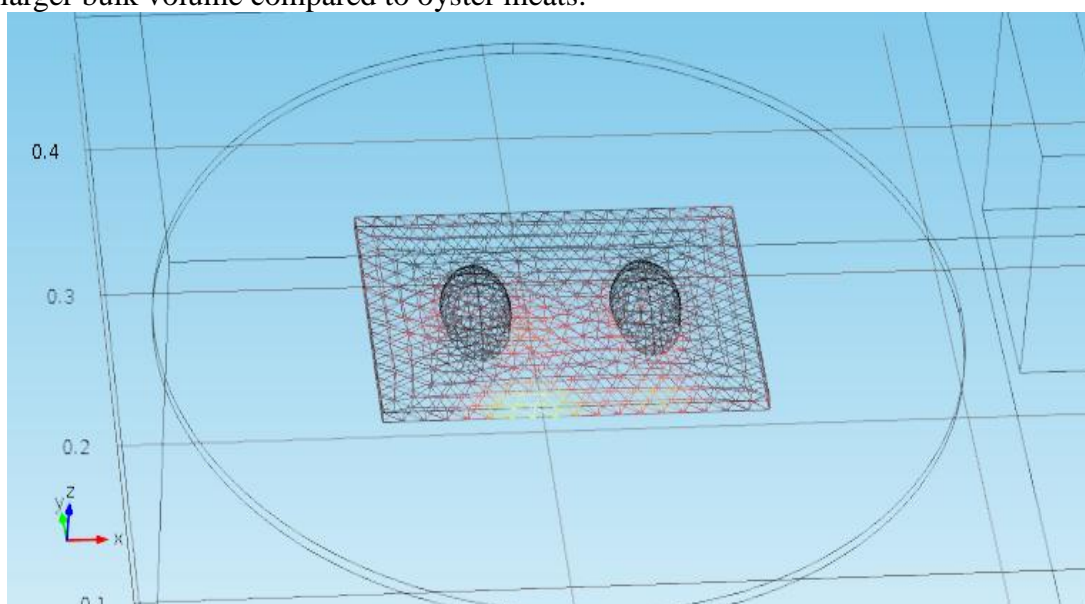

Figure 5.4 Surface temperature profile of the unsealed meal paste and oyster meat after microwave heating

Figure 5.6 showed the simulated temperature and the experimental temperature change in the center of the paste after 60s microwave heating. Figure 5.7 showed the temperature change at the geometry central of the frozen oyster.
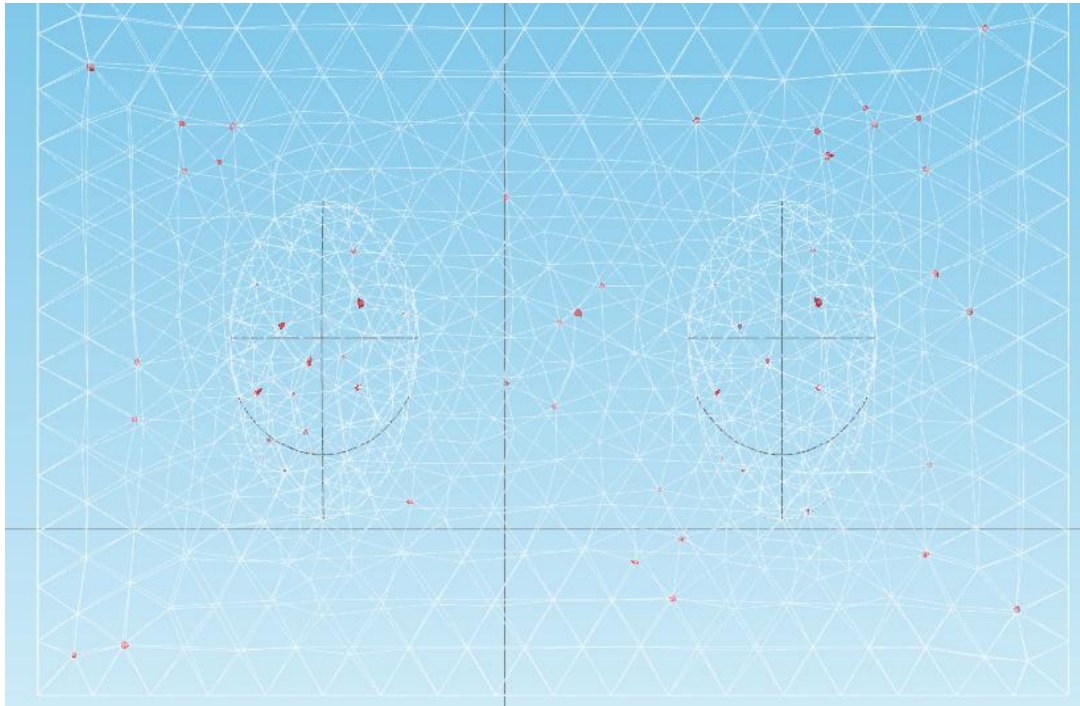
Figure 5.5 (a) Hot spots (red area) in the unsealed meal paste and oyster meat after microwave heating

Figure 5.5 (b) Cold spots (blue area) in the unsealed meal paste and oyster meat after heating
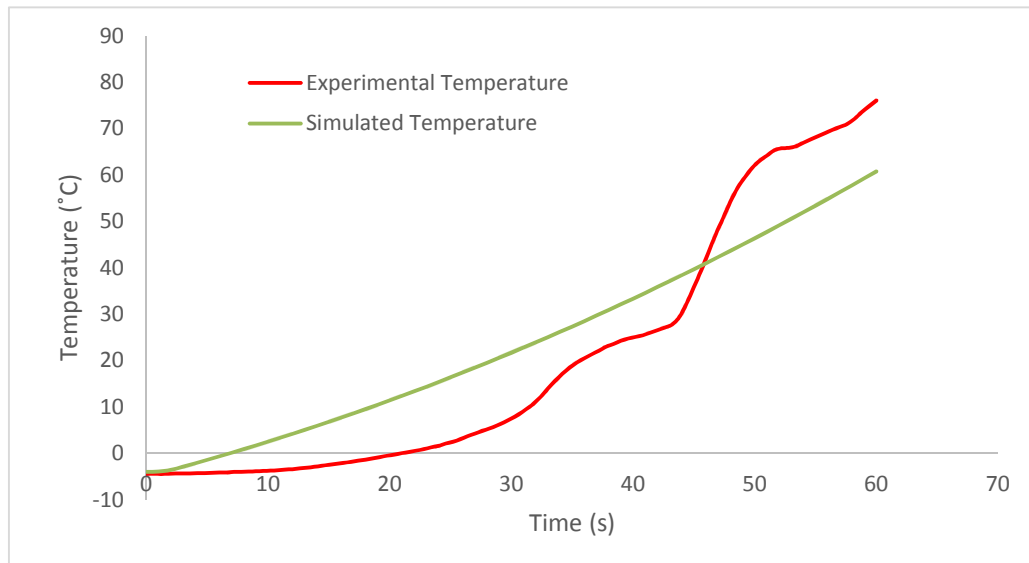
Figure 5.6 Temperature change of the central point of paste in the unsealed meal

The simulated temperature from both paste and oyster differed from the experimental temperature. The root mean square errors for these two predictions were more than 15 °C, which meant the predicted value was not closer to the experimental temperature. That could be caused by simplified model factors. In this simulation model, the thermal properties and dielectric properties were chosen at 20°C. However, the heating behavior of frozen food was different from the food with room temperature. The thermal and dielectric properties are functions of temperature. At the same time, the latent heat was ignored in this simulation, which has an obvious effect on the temperature related to phase change.

5.3.5.2 Temperature profile of sealed meal

For a sealed meal, the heating was totally different from the open one. The sealed meal produced a lot of vapors during heating, so the built-up pressure and gas circulation inside the package changed the heat transfer inside the package. The pressure cooker effect could change the thermal properties of food in the package; on the other hand, the massive vapor could affect the microwave distribution inside the package.
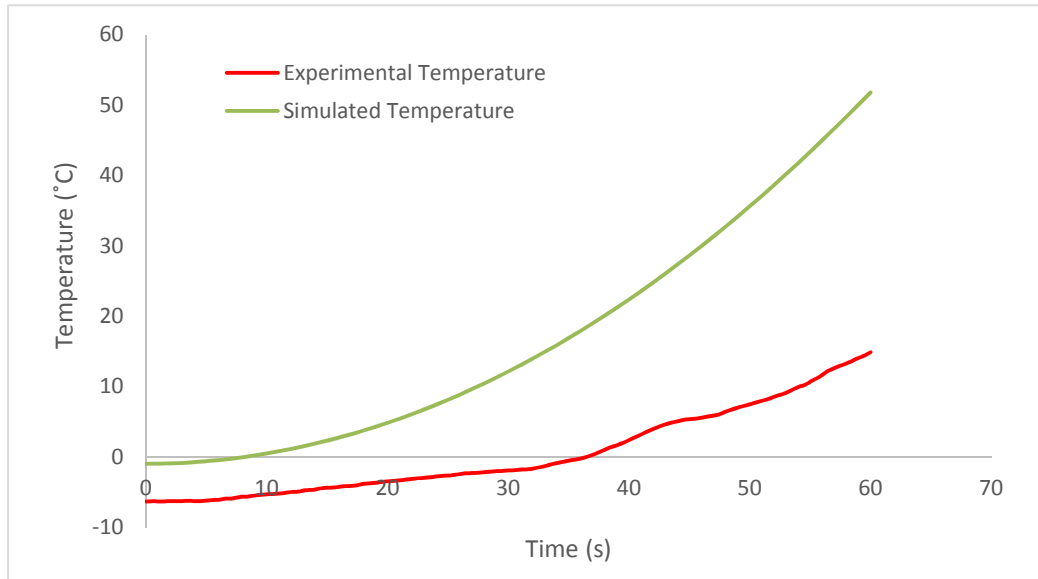
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Figure 5.7 Temperature change of the central point of the frozen oyster in the unsealed meal

Due to the complexity of the problem and lack of necessary modules to simulate the moisture evaporation during microwave heating for the vapor venting package, the thawing of the meal and heating stage before the massive vapor produced was not simulated by the model.

Figure 5.8 showed the temperature profile for heating the sealed meal for 30 sec. The lighter color represented the higher temperature and the darker color represented the lower temperature. The hot spots and cold spots were obtained by the simulation model, which were shown in Figure 5.9.

The temperature for hot spots and cold spots was 24.82 °C and 8.43 °C, respectively. The temperature change at the central point of oyster meat was showed in Figure 5.10 and compared to simulated temperature. The simulated temperature in the central point of the frozen oyster of sealed meal was composed of two simulation data. The data below the freezing point was calculated from the thermal properties of frozen oyster meat. This result had very good agreement with the experimental temperature.

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The root mean square error was 1.02°C in this area. However, when the temperature

increased, steam started appearing. The temperature in the central point of the frozen

oyster was affected by the steam. Compared to the predicted value, which reached

25.33°C at 21 sec, the experimental temperature rose slowly and arrived at 5.95°C at

21 s. That data proved the steam-venting technology was a good gentle cook method to

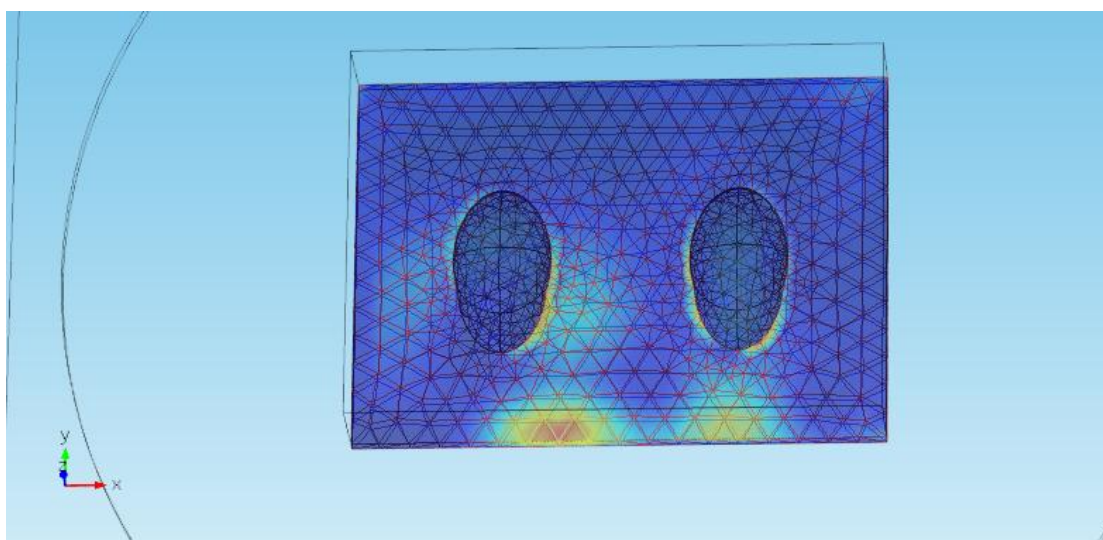prepare an oyster meat-contained microwavable meal.

Figure 5.8 Surface temperature profile of the sealed meal after 30s heating

5.4 Conclusion

In this study, the mathematical and computer-based simulation model was used

on the oyster-contained microwavable meals. The approximate analysis for ingredients

of the meal was conducted, and thermal properties were calculated. The dielectric

properties were measured. Hot spots and cold spots were given by the model, and the

temperature profile was achieved. The difference of temperature in both meals was

found during heating.

However, the heating behavior for the microwavable meal was complicated.

Several assumptions were made to simplify the simulation, but that affected the

predicted results dramatically. The simulated temperature differed from the

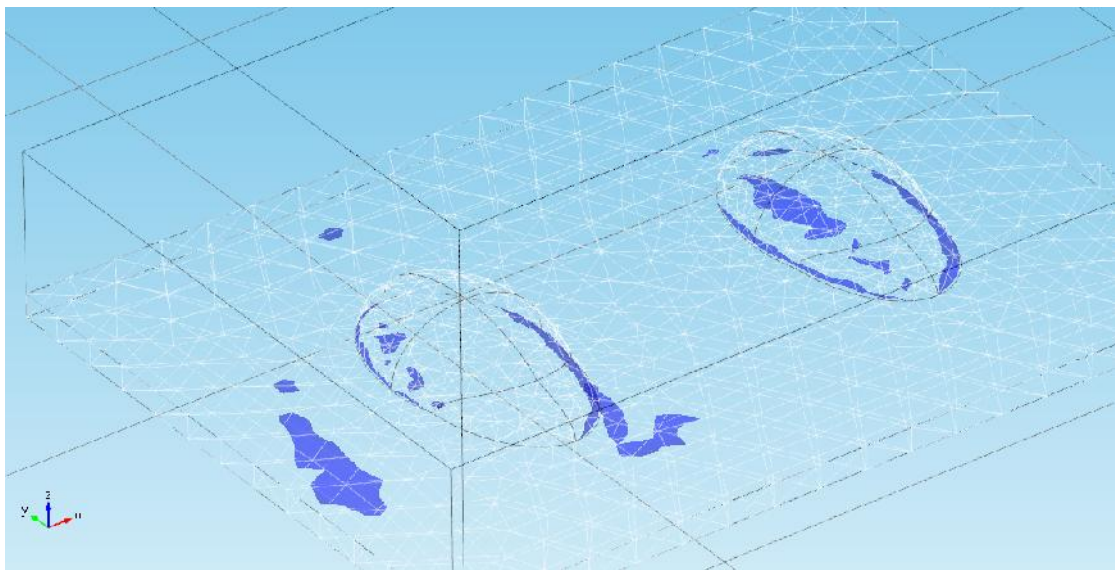Figure 5.9 (a) Hot spots (red area) in the sealed meal after 30s heating

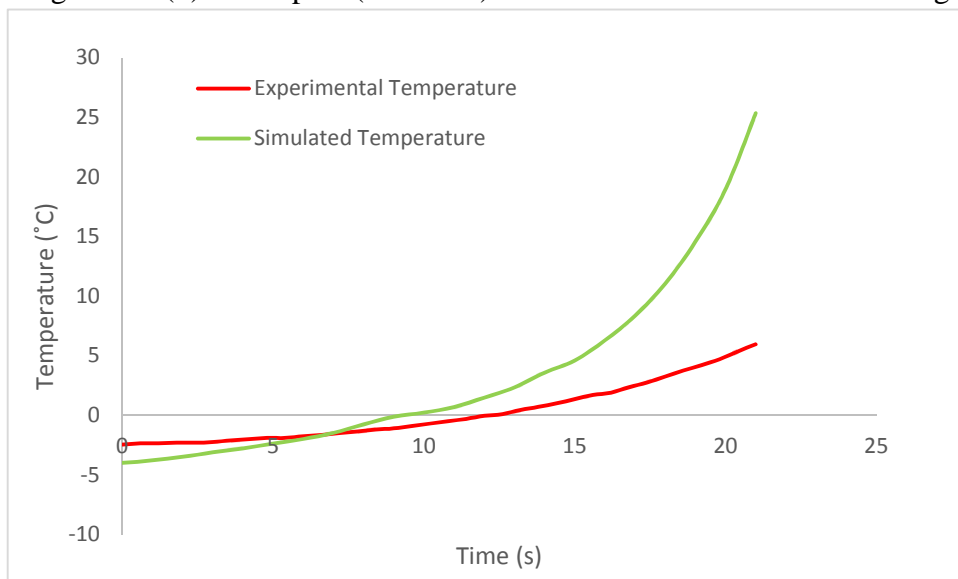Figure 5.9 (b) Cold spots (blue area) in the sealed meal after 30s heating

Figure 5.10 Temperature change of the central point of the frozen oyster in the sealed meal

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experimental temperature in both meal heating studies. Comparing the simulated data

to the experimental data demonstrated the steam-venting technology could help to

improve the heating of microwavable meal and improve the final product quality.

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CHAPTER 6 SUMMARY AND CONCLUSIONS

In this study, coupled electromagnetic and heat transfer equations were employed to develop a mathematical model to predict the temperature distribution. A finite element method based on commercial software was used to develop a simulation model for a microwave oven and microwave heating. The simulation result can be used to profile the temperature distribution during microwave heating.

As one of the most popular types of seafood in the USA, oysters are gathering people's attention not only because of their flavor, but also the potential health risks associated with them. Freezing is an efficient way to eliminate the pathogen in the oyster. A combination of freezing and microwave heating can provide consumers with a novel oyster product with better quality and more safety.

The main concern for microwave heating is non-uniform heating. Due to the unique characteristics of microwave heating, common methods cannot be used to obtain the temperature information during microwave heating. The numerical method can be a good tool to understanding the temperature distribution during the heating process.

This study developed a numerical method and computer-based simulation model to help obtain a better understanding of the heating behavior of oysters and oyster products in a microwave oven. By employing models, hot spots, cold spots and temperature distribution of oysters and oyster products can be known easily, and it can also be used to develop better microwavable products.

APPENDIX
THERMAL PROPERTIES FOR MAJOR COMPONENT OF FOOD INGREDIENTS

Thermal Property	Major Component	Result at 20 °C
Thermal conductivity k(W/m·°C)	Protein	0.202
	Fat	0.125
	Carbohydrate	0.227
	Ash	0.356
	Water	0.598
	Ice (-4°C)	2.246
Thermal diffusivity (mm^2/s)	Protein	0.078
	Fat	0.095
	Carbohydrate	0.091
	Ash	0.131
	Water	0.145
	Ice (-4°C)	1.201
Density (kg/m^3)	Protein	1319.532
	Fat	917.239
	Carbohydrate	1592.891
	Ash	2418.187
	Water	998.21
	Ice (-4°C)	917.412
The specific heat C_p(kJ/kg·°C)	Protein	2.032
	Fat	2.012
	Carbohydrate	1.586
	Ash	1.129
	Water	4.182
	Ice (-4°C)	2.038

VITA

Jie Zhang graduated from Sichuan University in Chengdu, China, with a Bachelor of Science degree in Food Science and Technology in June 2006. He earned his Master of Science in Food Engineering from Sichuan University, Chengdu, China, in June 2009. He joined the Department of Food Science at Louisiana State University as a Ph.D. student under the direction of Dr. Subramaniam Sathivel in August 2010. He will receive his degree in Food Science in May, 2014. Jie published three refereed articles and 3 abstracts. Jie was awarded second place and $750 at the 2013 IFT-Refrigerated and Frozen Foods division graduate student paper competition for presenting a paper entitled "Mathematical and Computer-based Models for Optimizing Microwave Heating Process of Frozen Oysters". Jie won the IFT Gulf Coast Section scholarship for presenting a paper entitled "Sonication-assisted Fish Oil Extraction with Application to Fish Processing Byproducts" on the IFT Gulf Coast Section meeting in April 2012.