Effect of Fat Content and Food Type on Heat Transfer during Microwave Heating

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ABSTRACT

Microwaves heat food rapidly and foods are prepared in less time. However, due to non-uniform heating nature of microwave cooking, there exists a serious concern over complete elimination of pathogens in the food. There has been an increase in interest to accurately understand the behavior of different food materials in a microwave field and microbial inactivation during microwave cooking.

Recent research showed that fat content in muscle food plays an important role in microbial inactivation by increasing the inactivation level with an increase in the fat level. It was also demonstrated that muscle food heats up differently than a vegetable food product. Cooking food in a microwave oven either by covering the food container or not results in significantly different temperature profiles. The current research attempts to use modeling techniques to analyze impact of these factors on microwave heating.

Mathematical modeling is faster, easier and economically better than actual experiments in determining heating behavior of a microwave-cooked food. Though modeling cannot completely replace actual experiments, it can be used as a tool to understand the effects of various factors influencing the microwave cooking.

A factor that is highly important during microwave processing is dielectric properties of the material. The interaction of microwave with the food is mainly based on its dielectric properties, which can change with temperature. Therefore, determination of dielectric properties of food with respect to temperature becomes critical.

The current research project has two parts. One to determine the dielectric properties of food being tested and another is to employ mathematical modeling techniques to analyze the effect of fat content, food type and the effect of cooking food by covering the bowl using the lid and not covering bowl.

Dielectric properties of ground beef patties at 4%, 9%, 20% fat levels and frozen broccoli were determined using an open-ended, 3.6 mm diameter, semi-rigid coaxial line with copper conductors, connected to a network analyzer. The properties were determined at various temperatures. Foods were measured in triplicate. Results showed that dielectric constant and dielectric loss factor of low fat ground beef were higher than that of high fat level ground beef. In addition, the dielectric properties of florets were lower than that of stem parts for frozen broccoli.

A 1,200W, household type microwave oven was used in this study to heat the food. Food was placed in a microwave-safe glass bowl and cooked for 120 seconds. One headspace and three internal temperature measurements were recorded for every 0.6 seconds. Five replications were performed. Finite element method was used as modeling technique and temperatures were predicted. Experimental and predicted temperature values were compared. Results showed that the model used in the study was more suitable for modeling the uncovered cooking than covered cooking process.

Modeling results also revealed that high fat ground beef patties reached higher temperature than low fat patties. In high fat meat products, fat content also contributed to increase in temperature during microwave heating. In vegetable products and low fat meat food, moisture content is mainly responsible for microwave heating.

A more extensive study on critical fat level above which fat content helps in increasing temperature is needed. In addition, inclusion of steam properties in the headspace for modeling the covered cooking is recommended.

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INTRODUCTION

Cooking using microwave is very common and it is widely adopted in developed countries. To an average consumer, the term "microwave" generally means a microwave oven, which is used in many households for heating food. The microwave oven has been an astonishing success, now about 95% of homes in America have at least one microwave oven. Microwave ovens are generally used as convenient method for reheating rather than cooking.

In microwave heating, the heat is generated due to the molecular friction between dipole molecules (example: water). Since water is easy to stimulate and most of the food products contains 40-80% water, microwave heating is highly suitable for cooking. Salts, fats and proteins also act as dipolar components and affect heating rates. Thus, microwave penetrates food easily and heats the food from inside out.

Drawbacks of microwave heating are its inability to brown food, non-uniform cooking, and excessive drying of foods such as breads. Another major problem in microwave cooking or reheating of the food is the chance for pathogen survival. Population groups such as pregnant women, immunocompromised, elderly, and young children are highly susceptible for food borne infections. As the cooking or reheating of the food is one of the last steps in food preparation, it should assure food safety. Therefore, food safety becomes important and cooking should ensure food safety.

Though the probability of pathogen survival in microwave-cooked food is higher than that for conventionally cooked food, consumers increasingly relay on microwave cooking. The reduction in process time, often as much as 10 to 1 compared to conventional methods, and higher food quality in terms of its appearance, flavor and taste, convenience, easy clean-up, decrease in cost of electricity, more retention of vitamins and minerals can be main reasons for consumer preference to microwave cooking. Therefore, elimination of pathogens during microwave cooking becomes very critical. Understanding the microwave cooking process, and the changes in the properties of food during cooking are important issues in developing specific recipes and heating instructions to assure food safety.

Mathematical models, simulating the microwave-cooking process, play an important role in designing and optimizing the cooking process. The modeling technique provides an insight into the microwave cooking process. Product developers will be able to test the effects of the changes in the food formulations without delay or with out the cost of having to work on product samples. Thus, the mathematical models are useful in improving the microwave cooking procedure.

The current research involves using mathematical modeling technique to understand the microwave cooking. In addition, an attempt had been made to determine the effect of fat, food type and evaporative cooling during microwave cooking.

Hypothesis

Using modeling technique, temperature profile in a microwave-heated food can be predicted. This could help in understanding the cooking process and studying various factors that affect the microwave cooking. This can lead to heating procedure, which will assure food safety. Outcome of this research could be helpful in investigating further in this area.

Objectives

The objectives of this study are to:

(1) Determine dielectric properties of food being studied.

(2) Develop and validate mathematical model for microwave heating process.

(3) Understand the role of fat in the food, steam, and evaporative cooling during microwave heating.

OUTLINE

This thesis consists of five chapters. Chapter 1, “Microwave Heating of Food – A Comprehensive Review”, is included in this thesis as a guide for the theoretical background and previous research work in the area of microwave heating. Chapter 2, “Effect of Fat Content and Temperature on Dielectric Properties of Ground Beef”, and Chapter 3, “Effect of Plant Parts and Temperature on Dielectric Properties of Broccoli” deals with the measurement of dielectric properties and determination of predictive equations for ground beef and broccoli to use in the mathematical modeling. Section 4, “Analysis of Microwave Cooking of Ground Beef Patties of Different Fat Levels and Broccoli using Finite Element Method”, provides the information about the mathematical modeling part of the thesis. Chapter 5, “Summary and conclusions”, is provided as the final chapter for summarizing the current research.

Chapter 1: Microwave Heating of Food – A Comprehensive Review[1]

N. Gunasekaran and P. Mallikarjunan

ABSTRACT

Microwave cooking is a widely adopted way of cooking. There has been considerable effort to improve the microwave cooking process and to increase safety of microwave cooked food. Facts behind the microwave and the factors affecting microwave heating are important. Mathematical modeling technique is commonly used to improve microwave heating. A review on microwave, microwave heating, affecting factors, safety of microwave cooked food and the relevant mathematical techniques were presented.

1. INTRODUCTION

An increase in temperature in a food or any material can be achieved in three possible ways, namely, conduction, convection and radiation. In conventional cooking methods, food is normally heated by conduction and convection where as heating through radiation uses radio frequency waves, microwave, and infrared radiation. While the radio frequency heating is still under development, infrared radiation is employed for surface heating, as the IR waves cannot penetrate below the surface (Knutson *et al.,* 1987). Microwave, on the other hand, penetrate food and produces heat from inside out (Mudgett, 1989).

Microwave oven is one of the most commonly used appliances for heating food. Almost every home in North America has at least one microwave oven (Schiffman, 1993). Most of the problems associated with microwave heating occur due to its uneven

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heating nature. Though there have been problems, consumers still use microwave oven for its fast and easy use. It is highly suitable for busy life style as it can heat food much faster than other conventional heating methods (Schiffman, 1993).

Understanding how the microwave heats the food and the science behind the microwave would be helpful in reducing the problems associated with microwave cooking. This article attempts to summarize information that is useful in understanding microwave cooking process. In addition, a general overview about mathematical modeling of microwave heating had been given.

2. LITERATURE REVIEW

2.1 Microwave Generation

Microwave is generated by magnetron. Magnetron is a circular symmetric tube like diode that consists of a cathode as the central axis of the tube and an anode around the circumference. The magnetron contains a space called resonant cavities. Resonant cavities act as tuned circuits and generate electric fields. These cavities also determine the output frequency of the microwave. The magnetron has an antenna connected to anode and it extends into resonant cavities. Antenna is used for transmitting the microwave from the magnetron to waveguide (Figure 1). The magnetic field is created by a magnet that surrounds the magnetron (Saltiel and Datta, 1999; Knutson, 1987).

When power is supplied, an electron-emitting material at the cathode becomes excited and emits electrons into the vacuum space between cathode and anode. The energy of the electrons is caught in the fields. The excess microwave energy travels as waves and extracted by the antenna. The antenna transmits the oscillating waves to the waveguide where they travel into oven cavity. The waveguide is a hollow metal tube.

Metallic walls of the waveguide are nearly perfect electric conductors and microwave propagates with low transmission losses. As the waves enter the cavity, they are dispersed by a stirrer (Figure 1). This action minimizes hot and cold spot in the oven cavity. Normally, the magnetron operates with efficiency around 60-65% (Saltiel and Datta, 1999).

Once inside the microwave oven, waves can be reflected off the oven sides and floor, can be transmitted through containers and lids made of glass, paper, plastic, and can be absorbed by medium such as food. (Saltiel and Datta, 1999; Knutson, 1987).

2.2 Some Facts about Microwave

The electromagnetic waves, which includes microwave, travel at the speed of light (3×10^8 m/s) and possess energy in the form of high-energy packets known as quantum energy (Knutson, 1987). The quantum energy can break the chemical bond when the quantum energy exceeds the chemical energy. Gamma rays and X-rays, which have short wave lengths, high frequency and high energy, are capable of breaking the chemical bonds. Microwave and radio waves, which come under long wavelength, low frequency, low energy category, do not have enough energy to break chemical bonds (Knutson, 1987).

Microwave belongs to the group of non-ionizing form of radiations, since it does not have sufficient energy required for the ionization process. The quantum energy in the microwave is responsible for creation of heat as the microwave oscillates 2450×10^6 times per second and the dipole molecules align to the electric field of the microwave at the same rate. The alternating electric field stimulates the oscillation of the dipoles of the molecules (example: water) in the food. The heat is generated due to the molecular friction between dipole molecules. Breakage in the chemical bond might occur due to this heat generation, not due to microwave directly (Knutson, 1987).

Electric field component of microwave is responsible for heating. It causes the molecules of dielectric materials to rotate, and produces rise in temperature due to friction between molecules. Mechanism of heat generation is discussed in section 2.3. Magnetic field component of microwave does not take part in heating food. However, some susceptor materials in the food package may interact with magnetic field (Saltiel and Datta, 1999; Lorenson, C 1990).

Inside a microwave oven, when incident and reflected microwaves interact, standing wave patterns are formed. The standing waves patterns have maximum and minimum (when incident and reflected waves cancel each other) value at certain distances from the reflecting surface. It should also be noted that incident and reflected waves are always in continuous motion (Lorenson, C 1990). Inside a microwave oven, there are high possibilities for multiple reflections and hence there are number of standing wave patterns. Every possible pattern is referred as a mode and at least 20-30 different modes are possible in a typical microwave oven. Therefore, the microwave oven cavity can be termed as multimode cavity (Lorenson, C 1990). When a load (food) is placed inside a microwave oven, it changes the reflections and hence the standing wave patterns and the modes.

2.3 Sources of Heat Generation during Microwave Cooking

Microwaves inactivate microbes mainly by thermal effects (Heddleson and Doores 1994). The quantum energy level in microwave is very low and the chances for its lethal effect on microbes and production of toxic compounds in the food are very remote (Mudgett 1989). The microbial inactivation by microwave depends on the same time-temperature relationship as seen in conventional heating methods. The microwave heating occurs instantly through out the product compared to conductive heat transfer from surface to interior in a conventional oven. Therefore, microwave heating is much faster and the temperature necessary to kill microorganisms is reached quickly (Heddleson and Doores 1994).

The rotation of dipolar molecules accounts for the most of the heat generated during microwave processing. These dipolar molecules try to align with microwave field at a speed consistent with the microwave frequency. This rapid movement of polar molecules results in the development of heat, because of the friction between molecules. Another mechanism responsible for heat generation is ionic polarization. Ionic polarization occurs when ions in solution move in response to the applied electric field component of microwave. Ions are accelerated by this electric field. Displacement of ions causes collision with other ions, converting kinetic energy into heat (Schiffman, 1993; Decareau and Peterson, 1986). At microwave frequencies, numerous collisions occur, and much heat is generated. However, it is a less important mechanism than dipole rotation.

2.4 Influence of Food Characteristics in Microwave Heating

The important food characteristics are dielectric properties of the food, thermal conductivity of the food, size, shape, orientation of food in relation to oven, physical state of water in the product, the presence of bone in the food and its moisture content (Berk and Wickersheim, 1990).

2.4.1 Dielectric Properties and its Importance

Microwaves interact with materials based on their electrical properties. Metals are good electrical conductors and good reflectors of microwave. They are not heated by microwave. Materials such as dielectrics come under electrical insulators and are good absorber and transmitter of microwave. Heat is generated in the dielectric (or food) primarily through absorption of microwave and the absorption, and hence the dielectric properties, depends on microwave frequency, food composition, product temperature, physical state of water in the food, and product density. Absorption characteristics of a food can be changed significantly by altering the above factors, for example, addition of salt in the food increases absorption of microwave.

Microwave heating is mostly dielectric in nature and involves the rotation of dipolar molecules. The dielectric properties of a food are characteristics of the materials determining the interaction of electromagnetic energy with the materials. The dielectric properties such as dielectric constant and the dielectric loss factor play a major role in microwave heating. The capability of food to store electric-field energy is dielectric constant. The dielectric loss factor measures the ability of food material to dissipate electrical energy as heat (Nelson *et al.,* 2000). Therefore, the amount of dipolar molecules significantly affects the heating. When the dipolar food components are not evenly distributed in the food, uneven heating can be expected. Obviously, the difference in dielectric activity is a common problem in foods with more than one ingredient (Mudgett 1989). Dielectric properties for some of the common food materials are presented in figure 2 (Tanaka *et al.,* 1999).

Dielectric Properties Measurement

The measurement of dielectric properties in microwave frequencies can be done using waveguide and coaxial transmission line method, Open-ended Probe Method, and Cavity Perturbation Method. Generally, measurement techniques can be categorized into reflection or transmission measurements by resonant or non-resonant systems, with open or closed structures for measuring the dielectric property of the material (Kraszewski, 1980). Closed structures method can be divided into waveguide and coaxial line transmission measurements and short-circuited waveguide or coaxial line reflection measurements (Nelson, 1999). Open structure techniques include free space transmission measurements and open-ended coaxial line measurements. Resonant cavity structures can be closed resonant cavity or open resonant structures. In the case of open resonant structures, the measurements can be done as two-port device for transmission measurement or as one port device for reflection measurements (Nelson, 1999).

Dielectric properties of ground beef and broccoli were measured as part of the current research. Study on dielectric properties of ground beef and broccoli was limited in the literature. A study by Van Dyke (1969) analyzed the effect of fat content in ground beef on dielectric loss factor at 915 MHz. Dielectric properties for raw beef, cooked beef, and beef juice were reported (Ohlsson, 1974; Ohlsson, 1975; Tran, 1987; To, 1974; Bengtsson, 1971). Though there were studies on fruits and vegetables (Nelson, 1980; Nelson, 1983; Nelson, 1993; Seaman, 1991), dielectric properties of broccoli were not included.

2.4.2 Thermal Properties

The thermal conductivity of food plays important role in microwave heating. High thermal conductivity materials dissipate heat faster than low thermal conductivity materials during microwave heating. Food with high thermal conductivity will take lesser time to attain uniform temperature during holding period.

Specific heat of food determines how fast a food can be heated. Specific heat can be raised by increasing solid content by adding components like salt, protein (Schiffaman, 1993). Specific heat along with thermal conductivity constitutes thermal properties of the material.

A recent study by Pan and Paul Singh (2001) reveals that thermal conductivity of ground beef varies between 0.35 and 0.41 W/m °C in the temperature range of 5 to 70 °C. Another study on thermal and physical properties of ground beef by Rollin *et al.,* (1979) shows that the thermal conductivity of ground beef as 0.38 W/m °C. Specific heat of ground beef was reported as 3520 J/Kg °C (Rollin *et al.,* 1979). Thermal conductivity and specific heat of broccoli were reported as 0.42 W/m °C and 3473 J/Kg °C respectively (Jiang *et al.,* 1987).

2.4.3 Size and Shape of Food

The size of food product affects the depth of microwave penetration and affects the heating rate and uniformity (Heddleson and Doores, 1994). Irregular shape products are subjected to non-uniform heating due to the difference in product thickness (Mudgett 1989). A food of a spherical or cylindrical form with diameter of 20-60 mm will be heated evenly, as the heat is focused towards the center. The center will be heated more quickly than the surface (Hill, 1994). In rectangular or square products, the slab geometry determines the heating rates throughout the product (Decareau, 1985).

2.4.4 Orientation of Food in the Microwave Oven

The heating rate of the product is affected by orientation of product because of the variation in oven wave pattern. Metallic oven walls reflect microwave until all microwave are absorbed by the food. Therefore, the placements of food in the cavity affect how microwave hit, reflect and are absorbed into the product. Uneven distribution of microwave can be reduced by a wave stirrer, but may still present problem (Mudgett, 1989).

2.4.5 Physical State of Water

The physical state of water in a food affects microwave heating. The dielectric constant of water is higher than that of ice. When a frozen food product is heated in a microwave oven, initially thawed parts of the product gets heated up faster than the still frozen section of the product. Therefore, overcooking at thawed area and undercooking at frozen part can occur (Mudgett, 1989).

2.4.6 Moisture Content

The moisture content of the product significantly affects the dielectric properties of food and consequently, the penetration depth of microwave is affected (Hill, 1994). Uneven heating rate is observed in high moisture foods because of low microwave penetration depth. Low moisture foods have more uniform heating rate because of deeper microwave penetration (Mudgett, 1989). In addition, in high moisture foods, heat loss through surface cooling can occur as a result of evaporation (Berek and Wickersheim, 1990).

2.5 Microbial Safety of Microwave Cooking

Food safety of microwave cooked is critical in developing cooking instructions. The cooking instructions on the package must ensure that the pathogens are completely eliminated. Inoculation studies by researchers (Carter, 1994; Heddleson and Doores, 1994; Lund, 1994; Landgraf and Tassinari, 1997) showed that the food could sustain pathogen survival when the temperature is not closely monitored in the food product. A study by Flores (1994) on ground beef loaves concluded that fat content of food plays an important role in the pathogen survival. Higher fat content of ground beef helps in reduction of pathogen survival (Hix 2000). Microwave cooking of vegetable product has higher risk of pathogen survival than that of meat products (Hix 2000).

Post process contamination is contamination that occurs after cooking food due to contact with unsanitary or uncooked materials. Improper handling of food increases the chance of pathogen survival. Allowing holding time after microwaving could decrease the microbial population (Mallikarjunan, 1995). However, many consumers do not realize that proper holding time can considerably increase food safety.

Storage abuse is another factor to be addressed on microbial safety. Abuse in storage temperature whether it is in food industry, grocery store or consumer home would increase the pathogen survival. High storage temperature encourages growth of microorganisms (Jay, 1996). In addition, damage to the food or food packages during shipping and handling could be serious threat to food safety (Hotchkiss and Potter, 1995).

2.6 Reducing Non-Uniform Heating

Microwave heat food unevenly due to uneven distribution of power. Hot and cold spots exist in the food due to uneven wave distribution (Anatheswaran *et al.,* 1994). Developing instructions for cooking food is very challenging because of this uneven heating. Understanding the non-uniform heating with respect to oven, food, container shape and geometry, and the dielectric properties is very critical and mathematical modeling is a vital tool to do this (Lorenson, 1990; Anatheswaran *et al.,* 1994).

More uniform cooking results when food is positioned above the floor (for example, on a glass plate) than when food is placed on the floor. When the food is positioned above the floor, the microwave can then be reflected off the wall and floor of the oven, transmitted through the plate and be absorbed on the bottom of the food (Knutson *et al.*, 1987).

To increase the effect of uniform heating, microwave ovens are normally equipped with a mode stirrer. The mode stirrer is just a metallic fan blade, which is used to perturb the field distribution inside the oven. The food is also rotated with a motorized platter to increase the uniformity of heating by reducing concentration of power at certain places in the food (Pozar, 1998).

Providing sufficient holding time after the microwave heating gives time for heat conduction in the food and more uniform temperatures results (Gundevarapu *et al.,* 1995). Post-processing temperature rise (PPTR) is the increase in temperature after microwave heating as measured at the coolest point in the product. PPTR might depend on both the product and power level and help to reduce the differences in temperature with in the product (Knutson *et al.*, 1987). The provision of power settings in some of microwave ovens also helps in more uniform heating of food. When a microwave oven is operated at a power level other than full power, the food undergoes heat-hold-heat-hold cycle. The holding time in this case is determined by the power level chosen. Therefore, reduction in temperature differences in the food can be expected.

2.7 Modeling of Microwave Heating Process

Modeling represents a phenomena using set of mathematical equations. The solutions to these equations are supposed to simulate the natural behavior of the material. Modeling can be a design tool to develop food that will provide optimum heating results in the microwave oven. In the modeling work, the food system is represented as being made up of many small elements in the simulation process. These discrete elements are joined together to make up the product (Lorenson, 1990).

Modeling of microwave cooking process can involve two separate parts, one being modeling of heat and mass transfer in the food and another being modeling the electromagnetic field inside the microwave oven cavity for calculating heat generation term (Zhang and Datta, 2000). Modeling of electromagnetic field arises when Maxwell's equations are used for calculating the heat generation term. Maxwell's equations are the basic laws for the microwave propagation (Roa, 1994). If the model employs Lambert's law for calculating the heat generation term, electromagnetic field is not modeled and the simulation work becomes easier.

Modeling of heat and mass transfer equations uses standard heat transfer equation and the mass transfer terms are included in the boundary conditions of the governing heat transfer equation.

2.7.1 Governing Equation and Boundary Conditions for Heat and Mass Transfer

Prediction of temperature profile in the food exposed to microwave is done by solving the following energy balance equation:

$$\nabla.(K\nabla T) + Q = \rho C_p \frac{\partial T}{\partial t} \tag{2.1}$$

The above governing equation assumes that the heat is transported only by conduction in the food and the temperature is function of space and time. ρ, Cp and K are density, specific heat and thermal conductivity of the food respectively. The heat source term (Q) is function of space and temperature (Saltiel and Datta, 1999; Datta, 2001).

The surface of the food loses temperature to the surroundings by convection and radiative heat loss is not possible in a typical microwave-heating situation since the temperature do not reach high enough to radiate. Evaporative cooling on the surface of food also influences the temperature profile. Therefore, the boundary condition is (Mallikarjunan *et al.,* 1996):

$$KA\frac{\partial T}{\partial n} = h_t A(T_s - T_a) + \lambda_v \frac{\partial m}{\partial t} \tag{2.2}$$

where Ts is surface temperature of food, ht is the convective heat transfer coefficient, and $\lambda_v \frac{\partial m}{\partial t}$ represents the evaporative heat loss (λ_v is latent heat of vaporization and $\frac{\partial m}{\partial t}$ is rate of evaporation or moisture transport).

$\frac{\partial m}{\partial t}$ is calculated from the following governing equation (Datta, 2001):

$$\nabla.(D_m \nabla m) = \frac{\partial m}{\partial t} \tag{2.3}$$

with boundary conditions:

$$n(D_m grad(M)) = \frac{h_m}{\rho}(P_s - P_a) + \frac{SC_p}{\lambda_v}\left(\frac{\partial T}{\partial t}\right) \tag{2.4}$$

where, Dm is diffusivity, S is shape factor, λ_v is latent heat of vaporization, h_m is surface mass transfer coefficient, P_a and P_s are partial vapor pressure of air and partial vapor pressure at the product surface, respectively.

Mass transfer of the food material is temperature dependent and the energy balance equation depends on the mass transfer equations. In addition, food properties are temperature dependent. This condition leads to coupling phenomenon, where the equations must be solved simultaneously (Zhang and Datta, 2000).

2.7.2 Calculating Heat Generation (Q)

The heat source term in the energy balance equation can be calculated in two different ways. Lambert's law calculates power by simple expression assuming that the power decays in the food exponentially. On the other hand, Maxwell's equations models the electric field and magnetic field inside the microwave oven, and electric field is used for calculating the power generation term.

Lambert's law

Due to the complex nature of the Maxwell's equation, coupling the electromagnetic model with heat and mass transfer model requires high computational resources and interdisciplinary expertise in electrical and thermal engineering. Many models have used Lambert's law for heat generation, which simplifies the calculation of power absorption in a microwave field although Lambert's law does not represent the electromagnetic field completely (Datta, 2001). Many models are still using the Lambert's law for modeling microwave cooking process. In simplified way, Lambert's law is given by,

$$Q = Q_0 \exp\left(-\frac{(X - x)}{\delta_p} \right) \quad (2.5)$$

Lambert's law predicts the power absorption by the food materials based on magnitude and special distribution of power absorption. Let the x is the distance in to the material. The penetration depth δ_p, determines amount of heat generated at a particular location considering the exponential decay of power. The constant (Q_0) gives the heat generation at the surface of the product and is determined by experimental measurements (Datta, 2001).

Lambert's law assumes that the spatial distribution of absorption is an exponential decay and the rate of decay being determined by penetration depth (δ). This is possible only for plane wave penetrating a semi-infinite slab, which is not the case in the actual situation (Zhang and Datta, 2000). However, for foods with large amount of water and added salt, Lambert's law could give fair approximation (Datta, 2001).

Maxwell's Equations

The electric fields of microwave are primarily responsible for heating. Non-uniform heating nature of microwave creates temperature gradients and thus causes diffusion, heat transfer, flow, properties change (Ayappa, 1997). These changes can in turn, affect the microwave heating itself. Electromagnetic of microwave, heat and mass transfer in the food, kinetics of biochemical changes are all involved in the heating process. Therefore, modeling of microwave heating process is highly coupled phenomenon (Ayappa *et al.,* 1992).

Food material absorbs the electromagnetic energy and the air in the microwave oven absorb very little of microwave energy. Only the food material is heated by the microwave directly.

The electromagnetic field inside the microwave oven can be represented by Maxwell's equations (Roa, 1994):

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu B) \tag{2.6}$$

$$\nabla \times B = -\frac{\partial}{\partial t}(\varepsilon\varepsilon_0 E) + \varepsilon''\varepsilon_0\omega E \tag{2.7}$$

$$\nabla.(\varepsilon E) = 0 \tag{2.8}$$

$$\nabla.B = 0 \tag{2.9}$$

E - electric field vector.

B – magnetic field vector.

For food materials heating is done by electric field primarily through interaction with water and ions. The complex permittivity ε is given by

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{2.10}$$

ε' is dielectric constant

ε" is dielectric loss factor.

The Maxwell's equations can predict the electric field E as a function of position and time. Microwave heat generation term (Q) in the heat transfer equation is calculated using this electric field E by (Datta, 2001; Zhang and Datta, 2000):

$$\text{Q(position, time)} = \frac{1}{2}\omega\varepsilon_0\varepsilon'' E^2 \tag{2.11}$$

In the equation 2.11, the ε_0 is the permittivity of free space, which is equal to 8.86x 10^{-12} F/m and ω is angular frequency of the microwave.

Using Maxwell's equations and appropriate boundary conditions (discussed in the next section), electric field distribution inside a food can be calculated. Then the heat generation term (Q) is calculated from the electric field by equation (2.11). Since the Q varies with respect to position, non-uniform increase in the temperature is observed. This changes the dielectric properties and consecutively the electric field distribution.

The governing equation for electric field is:

$$\nabla^2 E + k^2 E = 0 \tag{2.12}$$

The wave number $k = \alpha + j\beta$ where,

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'(\sqrt{1+\tan^2\delta}+1)}{2}} \tag{2.13}$$

$$\beta = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon''(\sqrt{1+\tan^2\delta}-1)}{2}} \tag{2.14}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2.15}$$

β^{-1} is known as characteristic penetration depth and $2\pi\alpha^{-1}$ is wavelength.

Boundary Conditions for Maxwell's Equations

The behavior of microwave can be altered when it encounters boundary or interface. For example, the metallic walls in a microwave oven can impose a boundary condition on Maxwell's equation. As the metallic walls are good conductors and reflect the microwave, electric field parallel to wall is zero. In addition, food-air interface in the microwave oven and packaging material-food can impose boundary conditions (Jia and

Jolly, 1992). For example, the change in the microwave propagation at the food-air interface because of change in dielectric properties causes changes in the reflected (by the food surface) and transmitted waves through the food.

Boundary Condition on Walls

Since the walls of a typical microwave oven are metallic conductor, electric filed parallel to wall (or tangential) and hence the magnetic filed normal to wall disappears (Jia and Jolly, 1992; Ayappa, 1997; Datta, 2001).

$$B.n = 0 \tag{2.16}$$

$$E \times n = (\nabla \times B) \times n = 0 \text{ - this is Natural boundary condition.} \tag{2.17}$$

that is,

$E_{t,\ air} = 0$ t = tangential direction

$B_{n,\ air} = 0$ n = normal direction

Boundary Condition on Waveguide Ports

Dirichlet boundary condition is applied on the waveguide ports (Jia and Jolly, 1992):

$$B \times n = V_m \tag{2.18}$$

V_m- vector function described by the magnetic filed distribution on the waveguide port.

Boundary Condition on air-food Interface

Suppose the permittivity and permeability of food and air are ε_1, μ_1 and ε_2, μ_2 respectively, then the following condition has to be satisfied:

(2.19)

$$n \times (E_2 - E_1) = 0$$

$$n.(\varepsilon_2 E_2 - \varepsilon_1 E_1) = 0 \quad (2.20)$$

$$n \times (B_2 - B_1) = P \quad (2.21)$$

$$n.(\mu_2 B_2 - \mu_1 B_1) = 0 \quad (2.22)$$

where n is unit outward normal originating from food domain.

This set of equations implies that the magnetic field is chosen for computing the power distribution. This is valid when $\mu_1=\mu_2=\mu_0$ and P=0, i.e., the magnetic field is continuous across the interface and the electric field is discontinuous across the interface. In addition, tangential components of electric and magnetic field are continuous across the interface (Jia and Jolly, 1992; Ayappa, 1997).

However, Datta (2001) argues that the interior of the cavity is to be treated as a dielectric with appropriate dielectric properties of air and food. The food-air interface does not have to be taken into account in modeling the entire cavity. In that case, boundary condition at the food-air interface disappears.

2.8. Research in Modeling Microwave Heating

In the field of modeling the microwave energy distribution and heating, four modeling techniques, namely, Transmission-Line Matrix (TLM) method, Finite Difference Time Domain (FD-TD) method, Finite Element Method (FEM), and the method of moments are popularly used. Each method has its own advantages and disadvantages (Lorenson, 1990). However, FEM could be more flexible than other methods (Puri and Anantheswaran, 1993).

In some studies, Maxwell's equations were solved for calculating power density distribution inside a microwave oven (Ayappa *et al.,* 1991; Ayappa *et al.,* 1992; Fu and Metaxas 1994; Zhang and Datta 2000). Though the Maxwell's equations gives exact prediction of power distribution (Ayappa *et al.,* 1991), Lambert's law is commonly employed method (Decareau, 1985; Ayappa *et al.,* 1991). Modeling of microwave heating using Lambert's law (Mallikarjunan *et al.,* 1995; Mallikarjunan *et al.,* 1996; Chen *et al.,* 1993; Van Remmen *et al.,* 1996) produced reasonable accuracy of predicted values.

Heat transfer models (Ayappa *et al.,* 1991; Zhang and Datta, 2000; Chen *et al.,* 1993), and heat and mass transfer models (Mallikarjunan *et al.,* 1994; Mallikarjunan *et al.,* 1995; Mallikarjunan *et al.,* 1996) were reported in the literature. Analysis of effect of different shapes of the product on microwave heating had been reported (Ayappa *et al.,* 1992; Van Remmen *et al.,* 1996).

3. SUMMARY

Microwave heating has many advantages over conventional heating of food. However, there are number of challenges in understanding the complete microwave cooking process. Many factors affect the cooking process and food safety becomes important issue. Mathematical modeling is a vital tool for understanding and improving microwave heating. A general review about various issues in the microwave heating of food was presented.

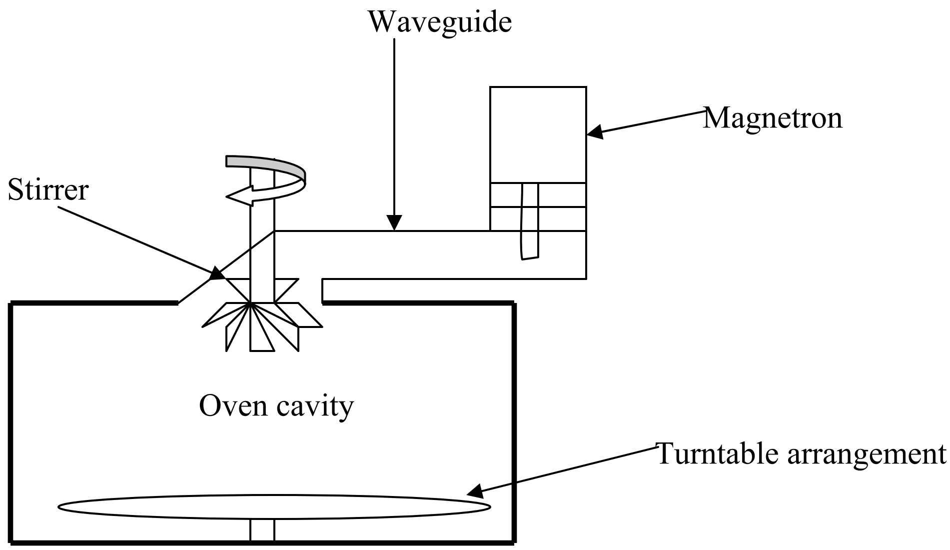

Fig 1: Major components of typical microwave oven

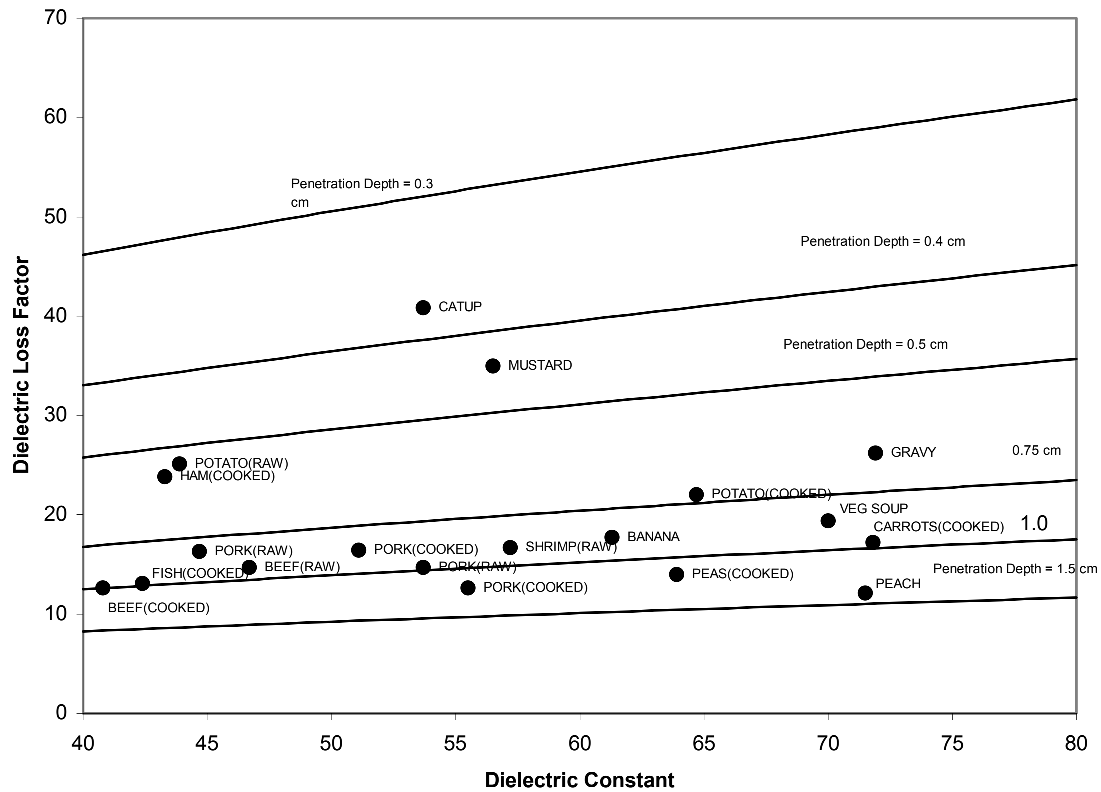

Fig 2: Food map for dielectric properties

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Chapter 2: Effect of Fat Content and Temperature on Dielectric Properties of Ground Beef [2]

N. Gunasekaran, P. Mallikarjunan, J. Eifert, and S. Sumner

ABSTRACT. *Microwave heating depends on dielectric properties, microwave frequencies, food composition, product temperature, physical state of water in the food, and product density. Proper microwave cooking or thawing procedure for ground beef products is needed to ensure food safety. Recent studies showed that the fat content significantly affected the survival of pathogens. The objective of this study is to determine the effect of fat content and temperatures on dielectric properties of ground beef.*

The dielectric properties were determined by measurements on an open-ended, coaxial line with copper conductors, connected to a Network analyzer. The relationship among dielectric properties, fat level, and temperature was obtained for 915 MHz and 2450 MHz. Results of the experiment showed that dielectric loss factor and dielectric constant increases with increase in temperature at both frequencies at temperature below freezing point . Above freezing point, dielectric constant decreases with increase in temperature. Dielectric loss factor increases with temperature at 915 MHz. At 2450 MHz, it remains almost constant with varying temperature.

Dielectric constant and dielectric loss factor of low fat ground beef were higher than that of high fat level ground beef. Based on comparison with literature data, raw beef has higher dielectric properties than that of ground beef. Results of this research will be helpful in developing microwave-heating procedures that will increase microbial safety,

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and in developing proper thawing procedure. Regressive equations were developed for predicting dielectric properties at different temperatures and fat levels.

Keywords. *Microwave heating, Dielectric properties, Ground beef, Measurements, Temperature dependence, Dielectric constant, Dielectric loss factor.*

INTRODUCTION

Food application of microwave technology is widely adopted in North America. Microwave technology makes cooking and thawing faster and easier than conventional methods. Microwaves fall under the category of electromagnetic radiation. Microwave frequency generally implies electromagnetic waves of frequency between 0.3 GHz and 3 GHz (Decareau, 1985).

The dielectric properties describe the behavior of the material when subjected to electromagnetic fields for dielectric heating applications. These properties are important in determining the penetration depth of microwave power and power absorption rate by the food in a microwave oven.

Dielectric properties of interest are dielectric constant (ε') and dielectric loss factor (ε''). Dielectric constant is a measure of ability to store electrical energy. Dielectric loss factor is a measure of ability to convert electrical energy to heat. Dielectric constant and dielectric loss factor can also be defined in terms of relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon|\, e^{-j\delta}$, where $\tan \delta = \varepsilon''/\varepsilon'$ is termed as the loss tangent or dissipation factor. The magnitude of these parameters determines the interaction of the microwave field with the material (Nelson, 1973).

Dielectric properties of food and agricultural materials are important in developing microwave heating procedures and in the design of electrical and electronics equipments that interact with the food. They can be related to the composition, which is useful in quality control and assurance. Dielectric properties can also be used to analyze the biophysical properties of the composition as the temperature changes. They will be helpful in determining proper microwave heating time in automatic smart kitchens.

Consumption of ground beef in the US was 3.2 billion Kg in 1995 (Morrison et al., 1997). Per capita consumption of beef increased from 29 Kg to 30 Kg between 1990 and 1998 (ERS, 2001). It is important to have well – developed microwave heating process for cooking ground beef. A study by Hix (2000) showed that fat level in ground beef has direct effect on pathogen survival in microwave cooking process. Measurement of dielectric properties at various temperatures and at various fat levels will help to achieve well-developed microwave-heating procedures and also help in understanding behavior of the ground beef during microwave heating.

Objective

The objective of this study is to determine the dielectric properties of the ground beef at three different fat levels (4%, 9%, and 20%) in the frequency range of 0.3 GHz to 3 GHz and at temperatures from -25º C to 75º C.

MATERIALS AND METHODS

Sample preparation

Ground beef with different fat levels (4%, 9%, and 20%) was obtained from local grocery store (Blacksburg, VA) and stored at -18ºC. In order to prepare samples for dielectric measurements, the ground beef was thawed in a refrigerator for 24 h and 30 g of ground beef was weighed. It was then placed into Aluminum weighing dish. The dishes were already modified to fit well in the sample holder of the heater/cooler unit (Figure 1). The ground beef was pressed by hand gently and repeatedly so that it was well packed and had flat surface on top in order to facilitate measurement by the dielectric probes. Three samples were used in the experiment for each temperature setting.

Little shake was done to distribute beef uniformly in the end of sample preparation. Care was taken to maintain uniform density of the samples. Density of the samples was in the range of 1018.5 Kg/m^3 to 1160 Kg/m^3.

Experimental Setup and Procedure

The test sample was first placed in the sample holder, which was cooled or heated by constant temperature circulator (Type: 000-7069 Haake A82, Germany). The sample was kept in the sample holder until the top center of the product reached the designated testing temperature. The temperature of ground beef was measured during the experiment with a T-type thermocouple connected to a data logger (21X Micrologger, Campbell Scientific Inc., Logan, UT). Ethylene glycol was used in the constant temperature bath as the medium to maintain temperatures of –25, -15, -8, -1, 1, 5, 10, 20, 30, 45, 60, and 75º C.

Figure 1 shows a schematic diagram of experimental apparatus. The dielectric properties determinations were made by measurements on an open-ended, 3.6 mm diameter, semi-rigid coaxial line with copper conductors, connected to a network analyzer (Model 85107A, Hewlett-Packard, Santa Clara, CA). The coaxial probe was fixed in a place well by a stand arrangement. The sample holder was placed on a vertical movable table.

Experimental Measurement

The heater/cooler unit was switched on and desired temperature was set. After the designated temperature was reached, the table was moved up slowly and the sample was brought in contact with the probe tip. Care was taken to avoid any air gap between sample and the probe tip without applying much pressure on the sample. Measurement was triggered and the network analyzer recorded the reflection coefficient at the probe-sample interface. Dielectric probe kit software (Model 85070A, Hewlett-Packard, Santa Clara, CA) was used to calculate the dielectric properties of the ground beef.

Calibration of the system was done by triggering measurement while the probe tip was in air, with metallic short-circuit and with water at 25º C. The frequency range was fixed from 0.3 GHz to 3 GHz and the instrument obtained data for every 5 MHz in that range.

Moisture Content Determination

Moisture content of randomly selected samples was determined by AOAC method 950.46 (AOAC, 1995). The moisture content of 4% fat ground beef was 73% (wb), of 9% fat ground beef was 71% (wb), and of 20% fat ground beef, it was 62% (wb). It can be said that low fat ground beef has higher moisture content.

RESULTS AND DISCUSSIONS

Effect of Temperature

The effect of dielectric constant and dielectric loss factor with respect to temperature of the sample is shown in figures from 2 to 5 at 915 MHz and 2450 MHz at different fat levels.

At both 915 MHz and 2450 MHz, above 0°C, dielectric constant decreases with increase in temperature and below 0°C, dielectric constant increases with increase in temperature. Sudden increase in the dielectric constant at the temperature range -1°C to +1°C was observed. The decrease in dielectric constant with increase in temperature above 0°C is reasonable for food materials that have high moisture content (70%) and the decreasing trend occurs due to relaxation of water molecules with increase in temperature (Nelson and Bartlay 2001a; Ohlsson *et al.,* 1974).

At both 915 MHz and 2450 MHz, below 0°C, dielectric loss factor increases with increase in temperature. At 915 MHz, above 0°C, dielectric loss factor increases with increase in temperature. This can be attributed to increase in ionic conduction in the product as temperature increases (Bengtsson and Risman, 1971). This also indicates that the increase in energy absorption could occur with increase in temperature at 915 MHz (Nelson and Bartlay 2001b). At 2450 MHz, above 0°C, dielectric loss factor decreases with increase in temperature till 45°C and then starts increasing with increase in temperature till 75°C. Increase in dielectric loss factor was observed with increase in temperature at 915 MHz. Increase in dielectric properties with increase in temperature at both frequencies, below 0°C, may be due to the increase in fraction of water as temperature increases (Ohlsson *et al.,* 1974). Dielectric loss factor at 915 MHz is less than that in 2450 MHz at any particular temperature.

At any particular temperature, dielectric properties at 915 MHz are greater than dielectric properties at 2450 MHz. This could be due to the decrease in wavelength of 2450 MHz waves compared to 915 MHz waves. The wavelength and hence the microwave frequency, affects the dielectric properties (Tanaka *et al.,* 1999).

Small variation of dielectric properties among replications was observed. This might be due to variation in the product density and difference in the applied pressure by the probe on the food surface. The open ended coaxial probe was at room temperature and this could have influenced the measurements at temperatures below freezing point.

Differences in temperatures of food and probe could be the contributor for variations in observed dielectric properties especially at frozen state of the ground beef patties.

Effect of Fat Content

The effect of dielectric constant and dielectric loss factor with respect to fat level of the sample is figures from 8 to 11 for 915 MHz and 2450 MHz. Decrease in dielectric constant and dielectric loss factor was observed with increase in fat content at temperatures above 0°C. The decreasing trend of dielectric loss factor with increase in temperature was also reported in the literature (Van Dyke *et al.,* 1969). In addition, the values of loss factor were in close agreement. Since the low fat ground beef has high moisture content comparing to high fat ground beef, the decreasing trend is reasonable. It also implies that moisture content of the product is more important than fat content.

At all temperatures below 0°C except -1°C, the dielectric constant and dielectric loss factor remains almost constant irrespective of fat content. This might be due to the frozen state of water. At -1°C, sharp increase in dielectric constant and loss factor was observed from 4% fat to 9% fat. This could be due to increase in ionic activities at temperature close to melting point of ice. The increasing trend in properties after 9% fat to 20% fat was lesser than that between 4% and 9% fat.

Raw Beef Vs Ground Beef

Dielectric properties of raw beef were obtained from literature values. Dielectric properties of ground beef from the present study were compared with literature values (Ohlsson *et al.,* 1974, To *et al.,* 1974, and Ohlsson and Bengtsson, 1975, Tran and Stuchly, 1987 and Van Dyke *et al.,* 1969) of raw beef to get of the effect of grounding.

Based on the comparison, it can be concluded that the raw beef has higher dielectric properties than that of ground beef. This could be due to the grounding operation, which increases pore space with air in the meat compared to intact raw muscle. The presence of air in the voids space could be attributed for lower values for dielectric properties of ground beef than that for raw muscle.

Penetration Depth and Dielectric Properties

As expected, the penetration depth at 915 MHz was greater than that at 2450 MHz. Higher penetration depth of 915 MHz was reported by researchers (Decareau, 1985; and Tanaka *et al.,* 1999). Above 0°C, at both frequencies, high fat ground beef had higher penetration depth than low fat ground beef. At 915 MHz, penetration depth increases till 10°C and then starts decreasing. At 2450 MHz, penetration depth increases till 20°C and then decreases slightly with increase in temperature. Below 0°C, penetration depth increased with decrease in temperature, that is, microwave power absorption decreased with decrease in temperature at both 915 MHz and 2450 MHz frequencies.

Regression Analysis

Stepwise regression procedure was used to develop predictive equations for dielectric properties at 915 MHz and 2450 MHz by Statistical Analysis Software (SAS Institute Inc., Cary, NC). R^2 value between predicted and observed values was greater than 0.82 in all cases. Predictive equations were of the form:

$$\varepsilon' = a_0 + a_1T + a_2T^2 + a_3(F \times T) + a_4F + a_5F^2 + a_6(1/T) \quad (1)$$

$$\varepsilon'' = a_0 + a_1T + a_2T^2 + a_3(F \times T) + a_4F + a_5F^2 + a_6(1/T) \quad (2)$$

where, T is temperature in °C and F is fat content in %. The values of the constants are given in the table 1 and table 2. Dielectric constant and dielectric loss factor can be determined for varying fat levels at different temperature using these predictive equations.

CONCLUSION

The dielectric properties of the ground beef were measured at 4%, 9%, and 20% fat levels, in the frequency range of 0.3 GHz to 3 GHz and at temperatures from -25º C to 75º C. The following conclusions can be derived:

1. Fat content and temperature influenced dielectric constant and dielectric loss factor.
2. Dielectric constant and dielectric loss factor of low fat ground beef were higher than that of high fat level ground beef.
3. Dielectric constant was increasing with increase in temperature below 0°C and decreasing with increase in temperature above 0°C. Dielectric loss factor was increasing with increase in temperature at 915 MHz. Dielectric loss factor was increasing with increase in temperature below 0°C and remained almost constant above 0°C at 2450 MHz. The temperatures between –1 and +1°C were critical for dielectric properties.
4. Regression equations for predicting dielectric constant and dielectric loss factor at various temperature and fat levels were determined. The predictions of dielectric properties by the regression equations were in good agreement with experimental results.

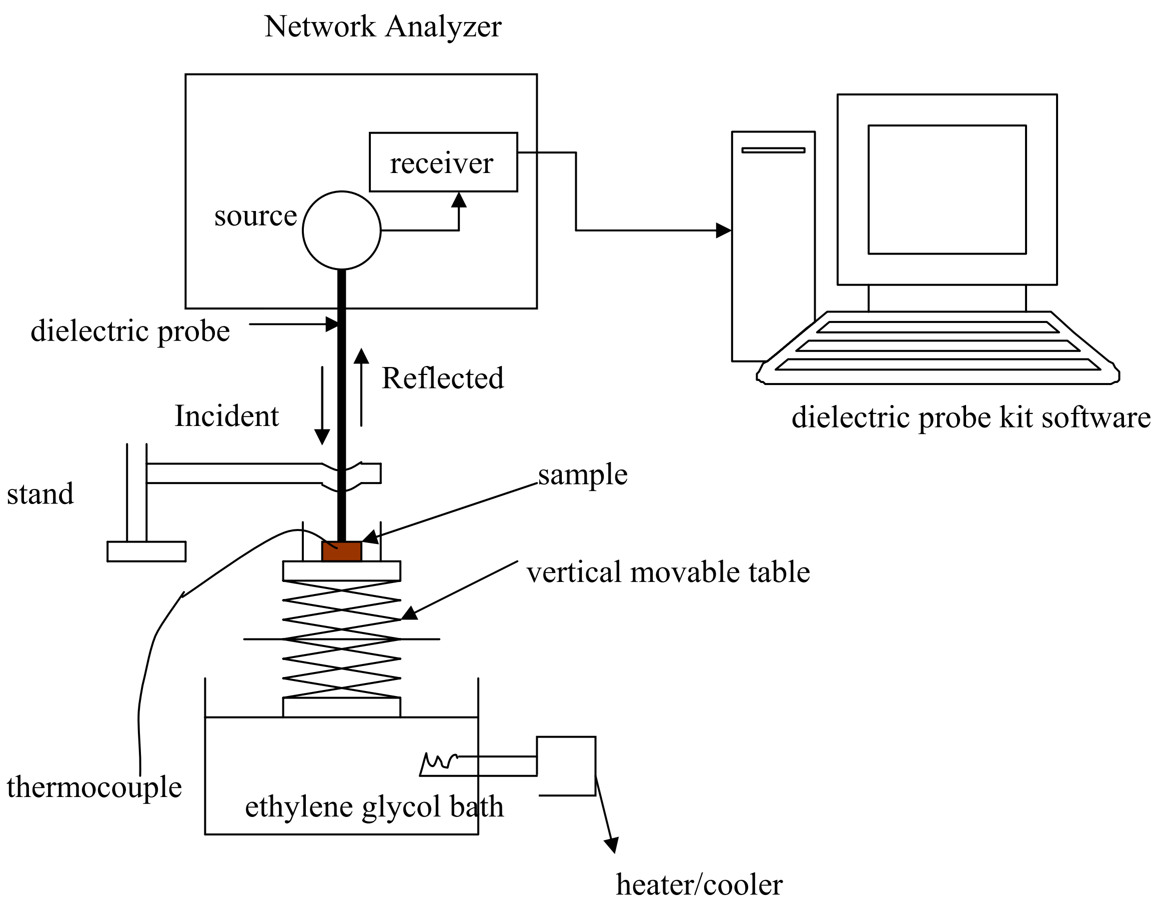

Fig. 1: Schematic diagram of experimental apparatus

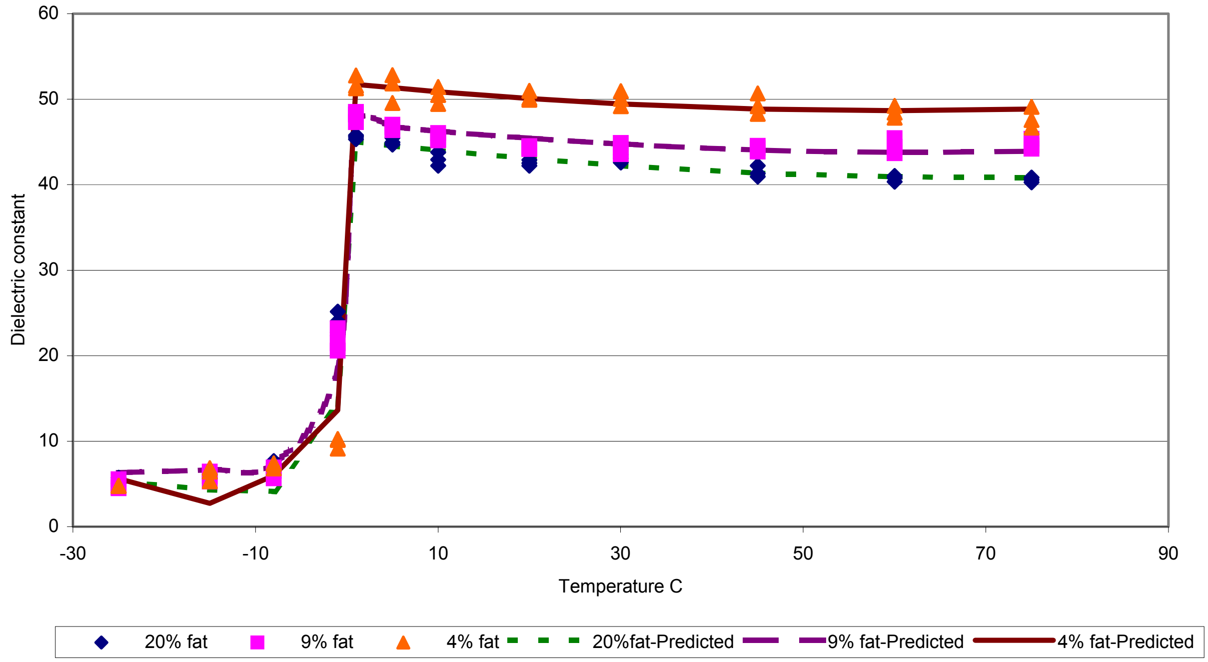

Fig. 2: Dielectric constant at different fat levels, at 915 MHz

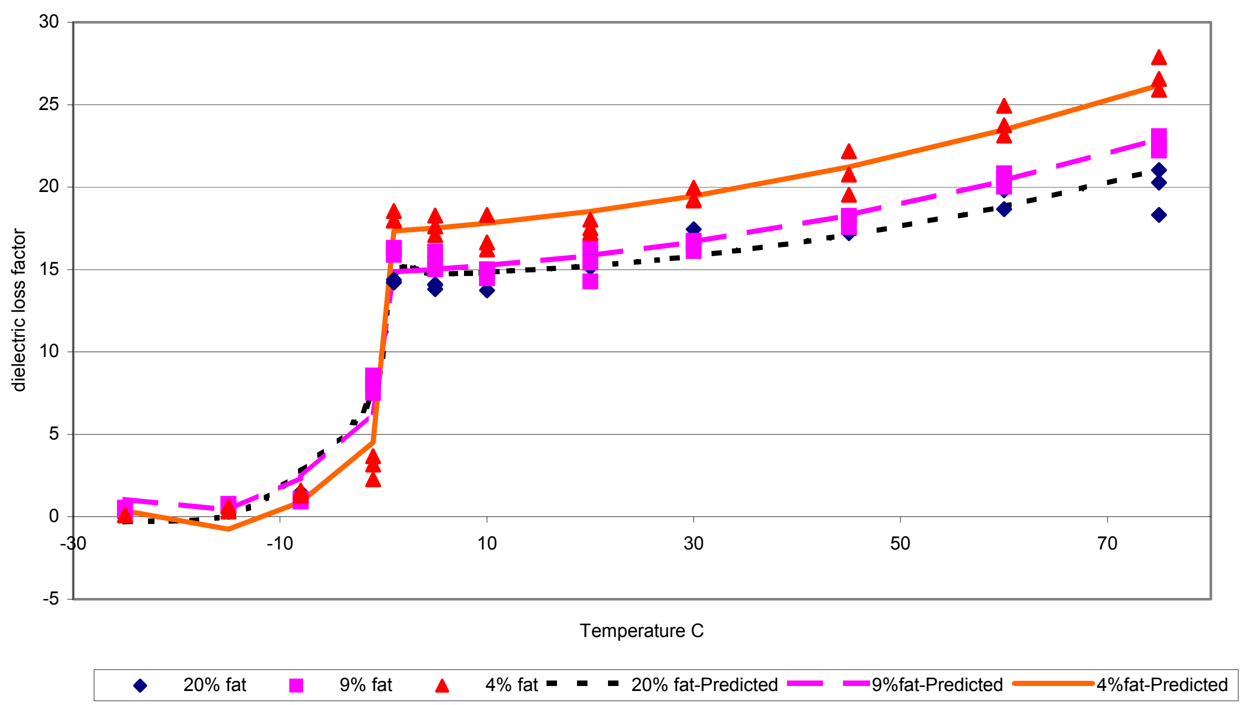

Fig. 3: Dielectric loss factor at different fat levels, at 915 MHz

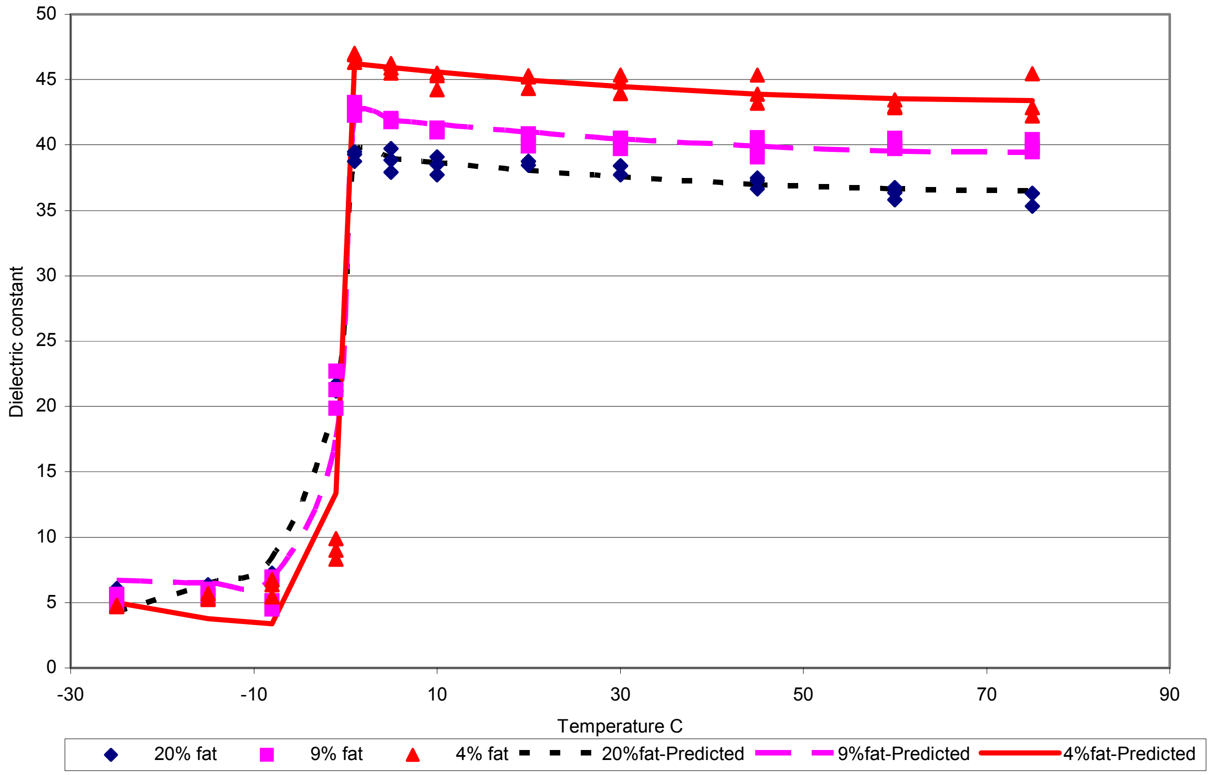

Fig. 4: Dielectric constant at different fat levels, at 2450 MHz

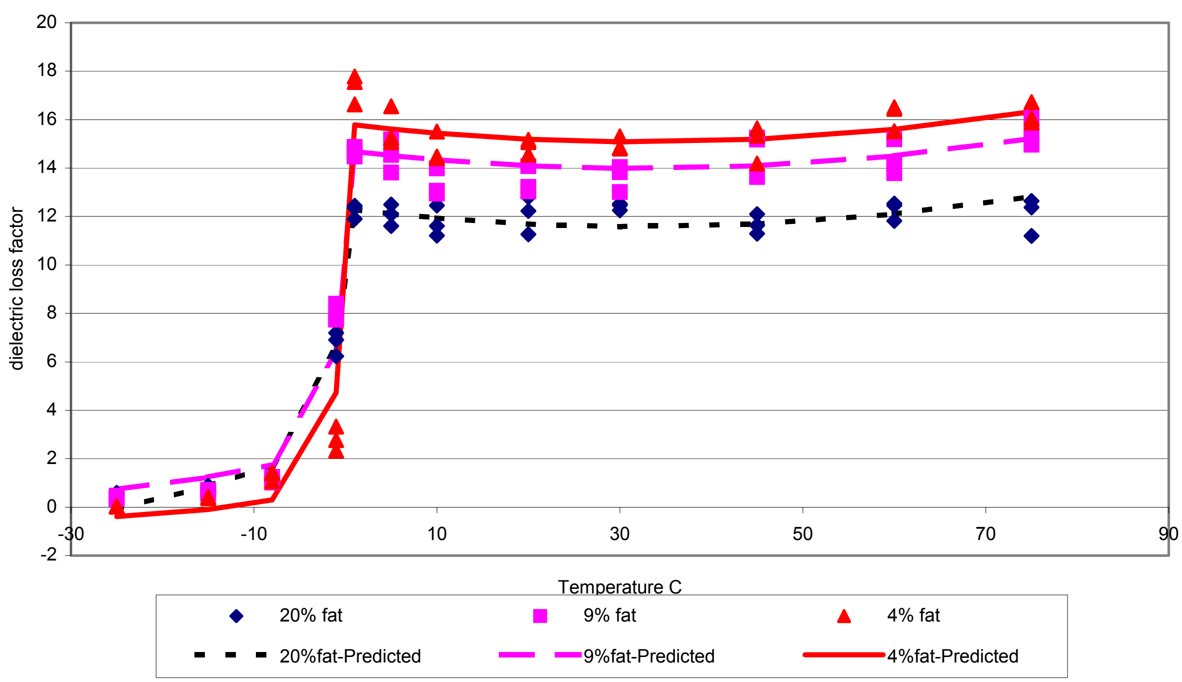

Fig. 5: Dielectric loss factor at different fat levels, at 2450 MHz

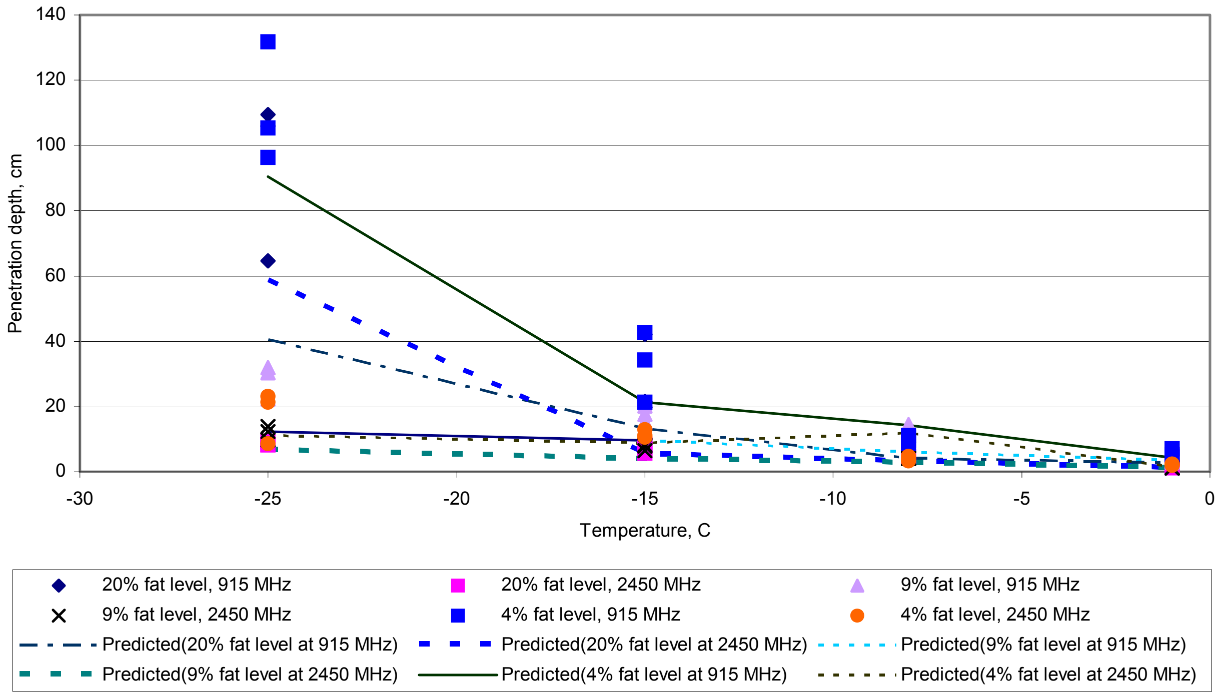

Fig. 6: Penetration depth at temperatures below 0 °C

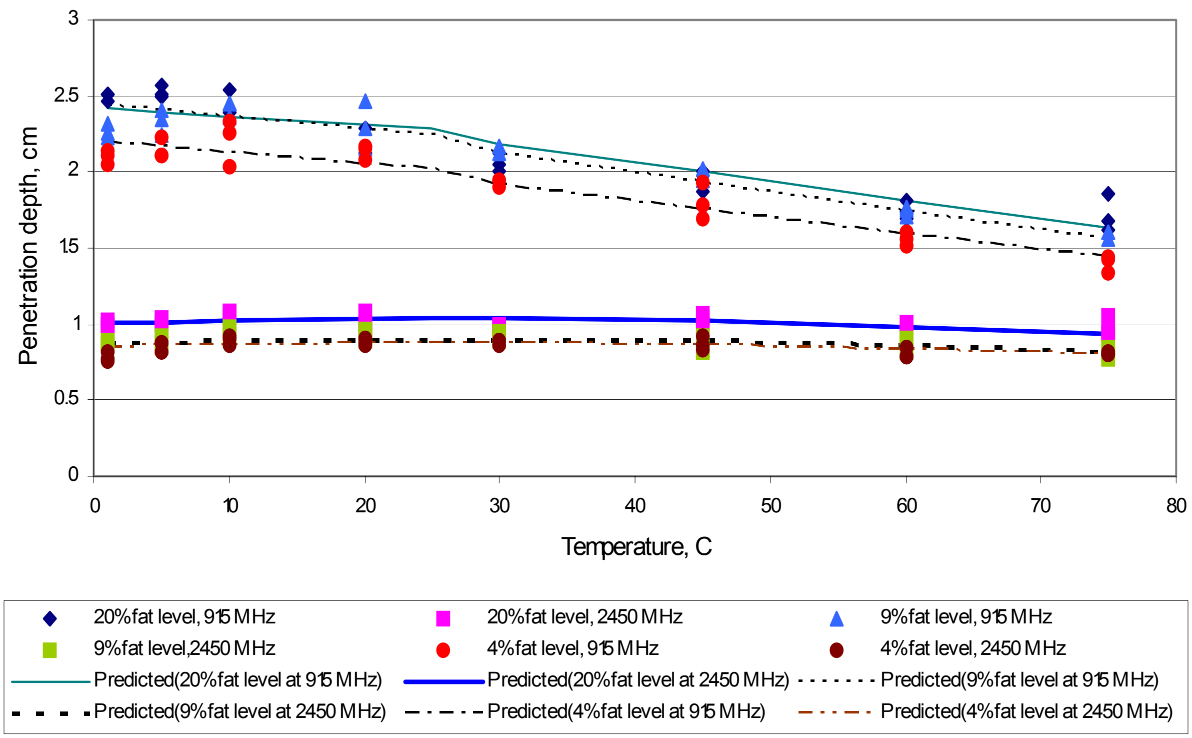

Fig. 7: Penetration depth at temperatures above 0 °C

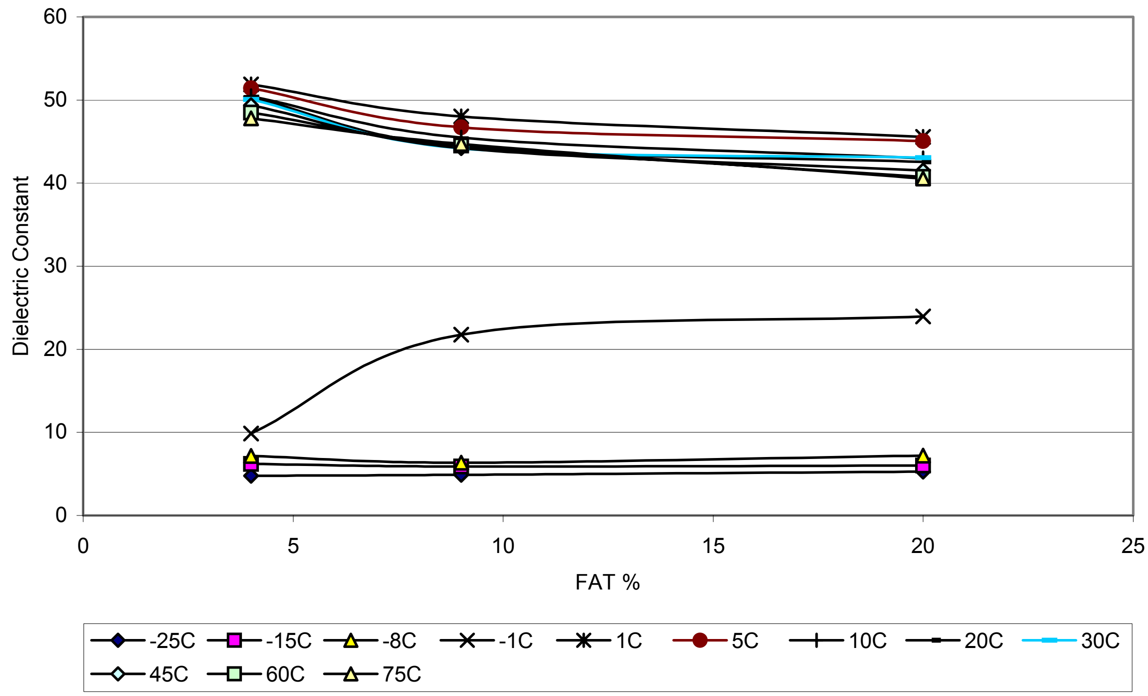

Fig. 8: Dielectric constant at different fat levels, at 915MHz

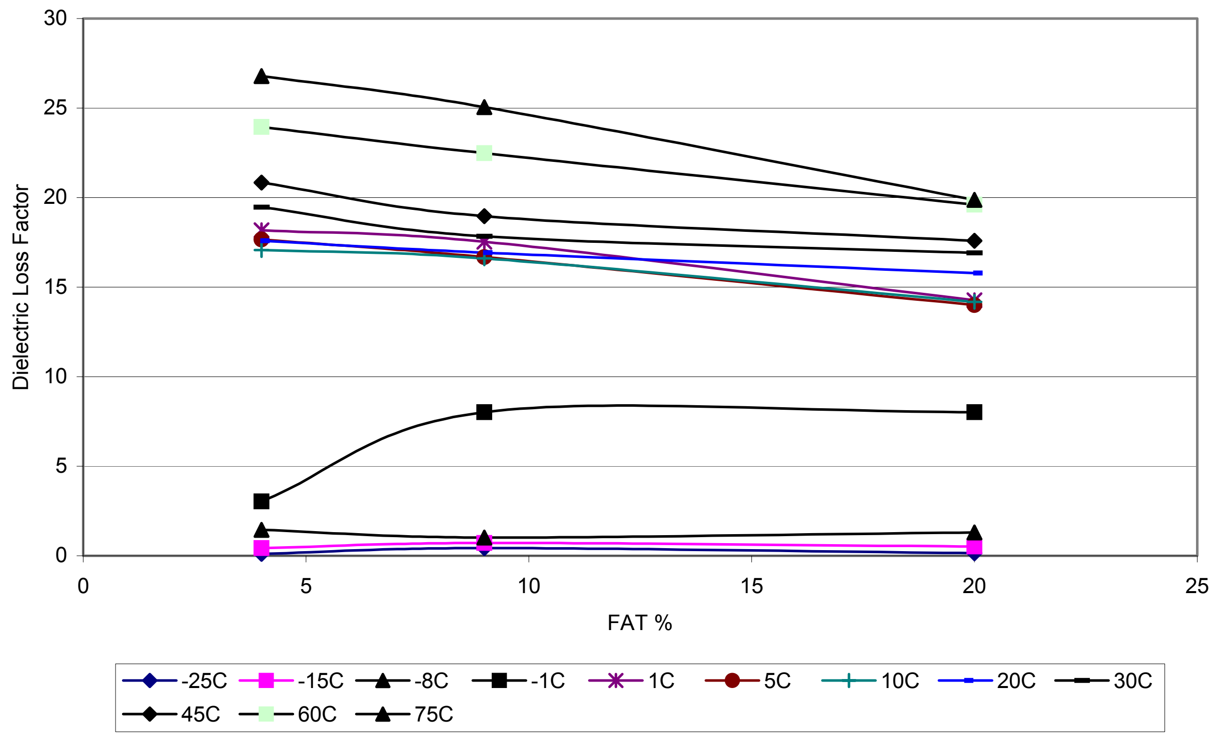

Fig. 9: Dielectric loss factor at different fat levels, at 915MHz

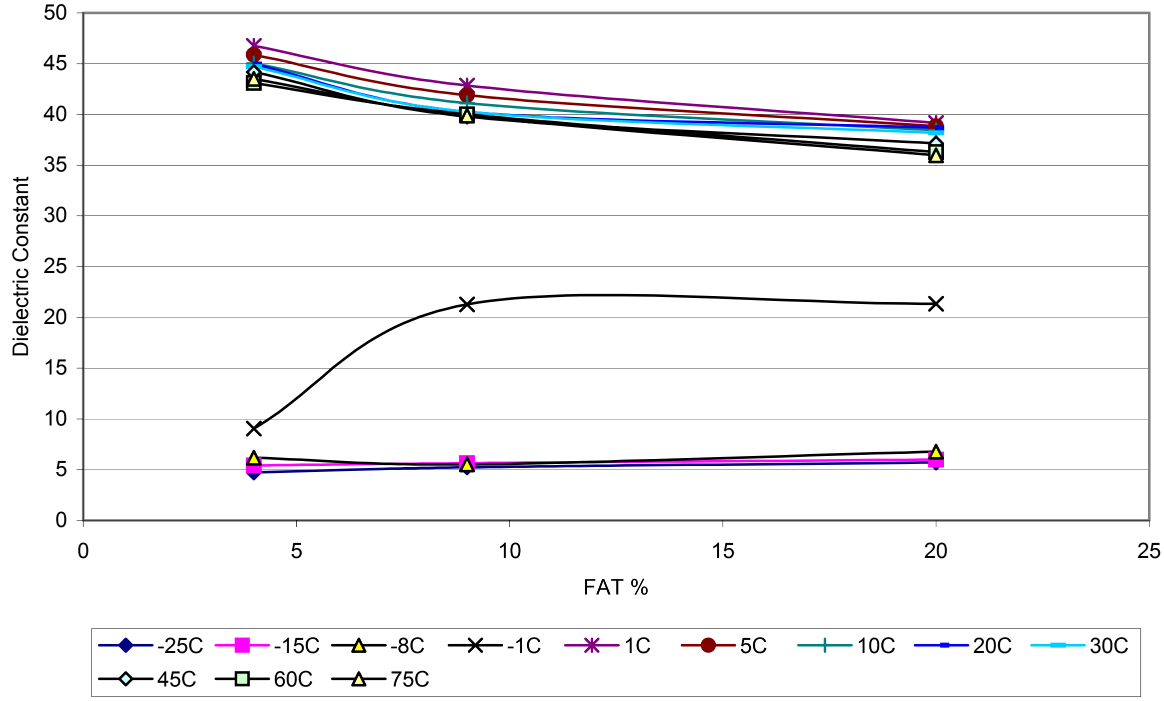

Fig. 10: Dielectric constant at different fat levels, at 2450 MHz

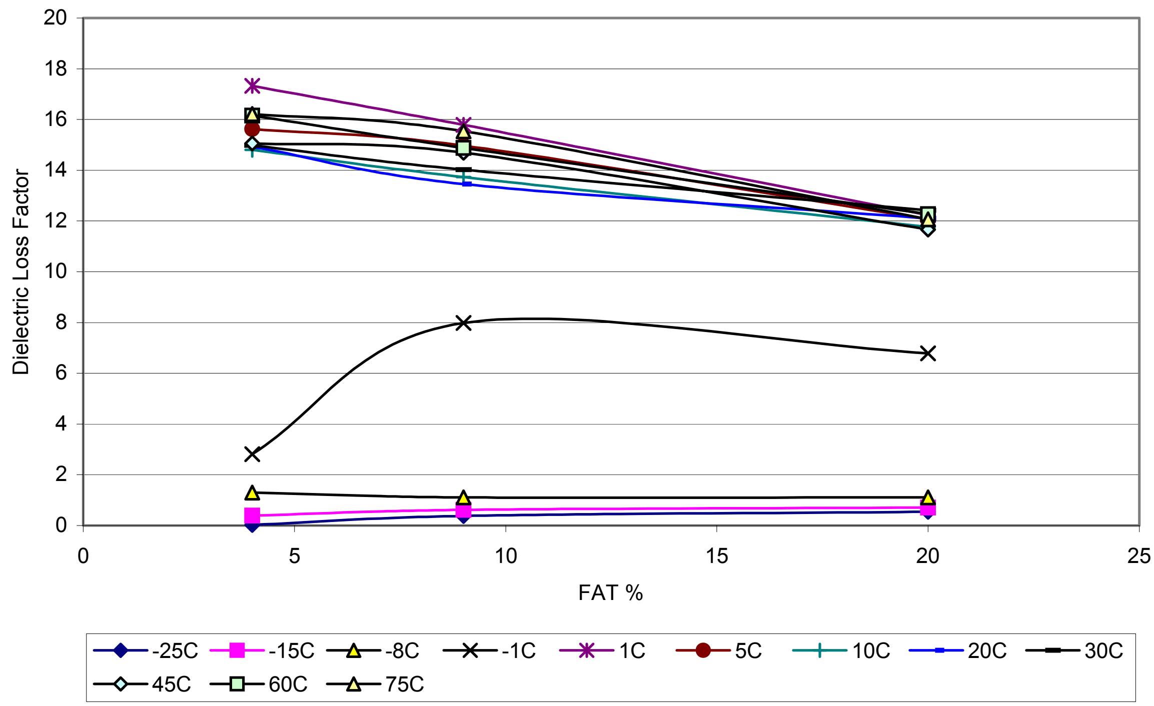

Fig. 11: Dielectric loss factor at different fat levels, at 2450 MHz

Table 1: Coefficients for predictive equation of dielectric constant (Equation 1)

Frequency (MHz)	Temperature	a_0	a_1	a_2	a_3	a_4	a_5	a_6	R^2
915	$<T_f$	-3.07	-0.24	NS	0.026	1.24	-0.03	-12.73	0.87
	$> T_f$	57.08	-0.10	0.0009	-0.001	-1.49	0.045	NS	0.94
2450	$< T_f$	-4.19	-0.24	NS	0.021	1.33	-0.035	-12.62	0.86
	$> T_f$	50.69	-0.08	0.0005	NS	-1.23	0.03	NS	0.95

NS – Not Significant; T_f - Freezing point

Table 2: Coefficients for predictive equation of dielectric loss factor (Equation 2)

Frequency (MHz)	Temperature	a_0	a_1	a_2	a_3	a_4	a_5	a_6	R^2
915	$<T_f$	3.12	0.66	0.02	0.009	0.59	-0.02	NS	0.86
	$> T_f$	20.34	0.05	0.001	-0.002	-0.88	0.03	NS	0.93
2450	$< T_f$	-2.17	NS	NS	0.004	0.57	-0.02	-4.93	0.87
	$> T_f$	16.70	-0.05	0.0007	NS	0.22	NS	NS	0.83

NS – Not Significant; T_f - Freezing point

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Chapter 3: Effect of Plant Parts and Temperature on Dielectric Properties of Broccoli[3]

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ABSTRACT

Microwave heating mainly depends on dielectric properties of food materials. The objective of this study was to determine the dielectric properties of frozen broccoli (floret and stem) in 0.3 - 3 GHz frequency range at temperatures from -25°C to 75°C using a Network Analyzer to help in understanding effect of plant parts and temperature on dielectric properties of frozen broccoli.

The relationship between dielectric properties and temperature was obtained for 915 MHz and 2450 MHz. Below 0°C, dielectric loss factor and dielectric constant increase with increase in temperature at both frequencies. Above 0°C, dielectric constant decreases with increase in temperature. Dielectric loss factor increases with temperature at 915 MHz. At 2450 MHz, it decreased as the temperature increases and became almost constant after 45°C.

The dielectric constant and the dielectric loss factor of florets were lower than that of stems. At temperatures above freezing point , the dielectric constant for florets was varying between 67 and 58, whereas for stem, the dielectric constant was varying between 79 and 64. The dielectric loss factor was varying from 20 to 15 for stem and 17 to 13 for florets at 2450 MHz. Predictive equations for determining the dielectric properties at different temperatures were obtained for both florets and stems.

INTRODUCTION

Application of microwave technology for cooking or thawing of foods and agricultural products is a rapid and easy method (Lorenson, 1990). Microwave radiation – like visible light – is a form of energy that can move through space, air, and even materials. Like light, microwaves are composed of electric and magnetic fields (electromagnetic radiation). The key difference is the frequency. Microwave frequency generally implies electromagnetic waves of frequency between 0.3 GHz and 3 GHz (Decareau 1985).

Dielectric properties of food and agricultural materials are important in developing microwave heating procedure and in the design of electrical and electronics equipment that interact with the food (Nelson, 1973). The dielectric properties describe the behavior of material when subjected to electromagnetic fields for dielectric heating applications. These properties are important in predicting power absorption rate by the food in a microwave oven. Dielectric properties determine the penetration depth of microwave power and local power absorption rates (Tanaka *et al.,* 1999). This can be useful in developing microwave oven that have pre-programmed cooking time for different type of foods.

Rapid method of moisture content determination is also possible for agricultural products. The dielectric properties of water ($\varepsilon' \sim 75$ below 5 GHz) are much different from that of most dry foods ($\varepsilon' \sim 5$). Therefore, measuring dielectric properties of moist product can provide an indication of moisture content (Engelder and Buffler 1991).

Dielectric properties of interest are dielectric constant (ε') and dielectric loss factor (ε''). Dielectric constant is a measure of ability to store electrical energy. Dielectric loss factor is a measure of ability to convert electrical energy to heat. The magnitude of these parameters determines the interaction of the microwave field with the material.

Broccoli is a commonly used vegetable in the United States. Study by ERS, USDA (ERS, 1999) reveals that American consumers consumed 0.9 billion kilogram of broccoli during 1998. Per capita consumption increased from 2.7 Kg (1990) to 3.65 Kg (1998). Heightened awareness among consumers of the association of broccoli with good health expected to cause high demand of broccoli in future. Frozen broccoli market follows slow but study increase in consumption trend (from 0.9 Kg in 1990 to 1.05 Kg in 1998 per capita consumption).

Cooking by microwave oven is very common nowadays. Developing proper microwave heating procedure for broccoli products becomes necessary to assure food safety. Study of dielectric properties will help in fulfilling this goal and in understanding heating behavior of vegetable products under microwaves. Also, the properties will be useful in developing smart kitchen and microwave oven that had been programmed for heating broccoli for right amount of time.

Objective

The objective of this study is to determine the dielectric properties of frozen broccoli in 0.3 GHz to 3 GHz frequency range at temperatures from -25°C to 75°C.

LITRATURE REVIEW

Dielectric constant of the food is the principle factor in determining the magnitude of reflection, refraction and transmission of microwave radiation. Dielectric loss factor determines the microwave absorptivity of a material. The absorbed microwave energy determines the amount of energy converted to heat. Dielectric constant and dielectric loss factor are real and imaginary parts of relative complex permitivity (ε) (Nelson 1999). It is given by

$$\varepsilon = \varepsilon' - i\varepsilon'' = |\varepsilon|\, e^{-i\delta}$$

ε - relative complex permittivity

ε′ - dielectric constant

ε″ - dielectric loss factor

δ - the loss angle of dielectric

the loss tangent also called as dissipation factor, is given by the equation:

$$\tan\delta = (\varepsilon''/\varepsilon')$$

Both dielectric constant and dielectric loss factor are affected by microwave frequencies, food composition, moisture content, product temperature, physical state of water in the food, and product density. Dielectric properties of various materials were reported in literatures. However, only very few attempts had been made at some particular temperatures and frequencies on measuring dielectric properties of broccoli. This study measures the dielectric properties of broccoli from frozen to cooked temperature.

Measurement of dielectric properties is generally done by cavity perturbation technique, open-ended probe, waveguide and coaxial transmission line method (Engelder and Buffler, 1991). Dielectric measurement of a material-under-test follows four simple steps:

1. generate a microwave signal at frequency of interest,
2. direct the signal at/through the material under test,

3. detect/measure the changes in the signal caused by the material,
4. compute the ε of the material from these changes.

Step (1) to (3) can be performed with help of Network Analyzers. Step (4) can be preformed by a computer program to compute ε.

Waveguide and Coaxial Transmission Line Method

The values of dielectric constant and dielectric loss factor are derived from transmission line theory, which indicates that these parameters could be determined by measuring the phase and amplitude of a reflected microwave signal from a sample of material placed against the end of a short-circuited transmission line, such as a waveguide or a coaxial line (Engelder and Buffler, 1991).

In order to use waveguide technique, rectangular samples that fit into the dimensions of the waveguide at the frequency being measured are required. An annular sample is needed for coaxial line method. The thickness of the sample should be approximately one-quarter wavelength within the sample. Therefore, preparation of optimal sample requires guessing the dielectric constant of the material so that the wavelength can be determined (Engelder and Buffler, 1991). Waveguide technique has very narrow operating ranges and generally used for single frequency measurement. Coaxial transmission line measurement technique is somewhat cumbersome because the sample must be annular geometry. These techniques are more suitable to porous materials (Engelder and Buffler, 1991).

Open-ended Probe Method

Open-ended probe technique measures the dielectric parameters from the phase and amplitude of the reflected signal at the end of an open-ended coaxial line that is in contact with the sample to be measured. Care should be taken to avoid any air gap between the probe and the sample. This technique is convenient for measuring dielectric properties in wide range of frequencies on non-porous material of relatively high loss factor, which includes most of the food materials (Nelson 1994). In the present study, open-ended coaxial line probe method was used.

Cavity Perturbation Method

Cavity perturbation technique measures the dielectric constant and loss factor on the basis of the changes in the frequency and the width of transmission characteristics, when a sample is inserted into a tuned resonant cavity. Cavity perturbation technique is very sensitive and accurate for materials with loss factor less than one. This technique is suitable for non-porous materials (Nelson 1999).

MATERIAL AND METHODS

Sample Preparation

Cut, frozen broccoli was obtained from local grocery store (Blacksburg, VA) and stored at –18 °C. The frozen broccoli was thawed in a refrigerator for 24 h and then samples were prepared. Stem part was carefully selected and given an inclined cut to facilitate the dielectric measurements. Careful observation was done on florets of broccoli to choose florets for experiment. Florets were selected so that dielectric probe can be placed on them properly. The chosen florets had minimum air gap between buds and relatively uniform surface to place the probe comfortably.

Experimental Setup and Procedure

The test sample was first placed in a Ziploc bag, which was then immersed in a constant temperature circulator (Type: 000-7069 Haake A82, Germany) in order to heat or cool the sample. Ethylene glycol was used in the constant temperature bath as the medium to maintain temperatures of –25, -15, -8, -1, 1, 5, 10, 20, 30, 45, 60, and 75º C. The sample was immersed in ethylene glycol until the middle of the product reached the desired testing temperature. The temperature of broccoli samples was regularly monitored for every 2 seconds during the heating/cooling process with a T-type thermocouple connected to a data logger (21X Micrologger, Campbell Scientific Inc. Logan, UT). Figure1 shows a schematic diagram of experimental apparatus. The dielectric properties determinations were made by measurements on open-ended, 3.6 mm diameter, semi-rigid coaxial line with copper conductors, connected to a network analyzer (Model 85107A, Hewlett-Packard, Santa Clara, CA). The coaxial probe was fixed in a place well by a stand arrangement. The sample holder was placed on a vertical movable table in which broccoli sample was sited to facilitate the dielectric properties measurement. The sample holder also had the same temperature as the samples heating/cooling process.

Experimental Measurement

The heater/cooler unit was switched on and desired temperature was set. After the designated temperature was reached, the sample was taken out and put in the sample holder. Then the table was moved up slowly and the sample was brought in contact with the probe tip. Care was taken to avoid any air gap between sample and the probe tip without applying much pressure on the sample. Measurement was triggered and the network analyzer recorded the reflection coefficient at the probe-sample interface. Dielectric probe kit software (Model 85070A, Hewlett-Packard, Santa Clara, CA) was used to calculate the dielectric properties of the frozen broccoli.

Calibration of the system was done by triggering measurement while the probe tip was in air, with metallic short-circuit and with water at 25º C. The frequency range was fixed from 0.3 GHz to 3 GHz and the instrument obtained data for every 5 MHz in that range.

Moisture Content Determination

Moisture content of florets and stems of broccoli was determined by AOAC method 991.01 (AOAC, 1995). The average moisture content of floret part was 89% (wb), and the average moisture content of stem part was 93.1% (wb).

RESULT AND DISCUSSIONS

Effect of Temperature

The effect of dielectric constant and dielectric loss factor with respect to temperature of the sample at 915 MHz and 2450 MHz for stem and florets of broccoli is shown in figures 2 to 5.

For both stem and floret, above 0°C, dielectric constant decreases with increase in temperature and below 0°C, dielectric constant increases with increase in temperature at both 915 MHz and 2450 MHz. Sudden increase in the dielectric constant at the temperature range -1°C to +1°C was observed. The decrease in dielectric constant with increase in temperature above 0°C is reasonable for food materials with moisture content greater than 70% (Nelson and Bartlay 2001; Ohlsson *et al.,* 1974). The relaxation of water molecules could be mainly responsible for decreasing trend of dielectric constant with increase in temperature (Nelson and Bartlay 2001a).

For both stem and floret, below 0°C, dielectric loss factor increases with increase in temperature at both 915 MHz and 2450 MHz. At 915 MHz, above 0°C, dielectric loss factor increases with increase in temperature. This could be due to increase in ionic conduction in the product as the temperature of the product increases (Bengtsson and Risman 1971). Above freezing point and at 2450 MHz, dielectric loss factor decreases with increase in temperature due to water molecule relaxation (Nelson and Bartlay 2001b) until 45°C and remains constant after 45°C as the relaxation stabilizes. This effect was observed for both stem and floret. At 915 MHZ, dielectric loss factor was increasing with increase in temperature. This could occur due increase in activities of ions in the food system as the temperature increases and indicates that the rate of energy absorption with increase in temperature (Tran *et al.,* 1987). At temperatures below the freezing point, increase in dielectric properties with increase in temperature was observed at both frequencies. This could be due to the increase in fraction of water as temperature increases (Ohlsson *et al.,* 1974). Differences between observed values of dielectric properties were seen and could be due to small variations among samples.

Effect of Broccoli Parts

Decrease in dielectric constant and dielectric loss factor was observed for florets comparing to stem part at temperatures above freezing point. Since the stem has high moisture content comparing to floret part, this effect is reasonable. Air space in florets also contributed to the decrease in dielectric properties. At all temperatures below 0°C, the change in dielectric constant and dielectric loss factor was negligible. This was due to frozen state of water and supports the fact that physical state of water significantly affects the dielectric properties (Mudgett, 1986; Schiffman, 1986)

Penetration Depth and Dielectric Properties

Penetration depth can be defined as the distance from the surface of the food material at which the incident microwave power in reduced to 1/e of its value at the surface of the product and given by (Metaxas and Meridith 1983):

$$\delta_p = \frac{\delta_0}{2\pi(2\varepsilon')^{0.5}}\left[\left(1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)^{0.5}-1\right]^{-0.5} \qquad (1)$$

where, δ_0 is wave length of microwave at free space, which is 32.76 cm for 915 MHz and 12.24 cm for 2450 MHz. Equation (1) shows that penetration depth is affected by wavelength of microwaves, dielectric constant and loss factor.

Figures 6 and 7 show penetration depth with respect to temperature at both frequencies. The penetration depth at 915 MHz was greater than that at 2450 MHz. This effect has also been reported by Decareau (1985) and (Ohlsson *et al.,* 1974). At temperatures greater than freezing point and at 915 MHz, floret had higher penetration depth than stem. In contrast, at 2450 MHz, the difference was very little though florets had higher penetration depth than stem parts. At 915 MHz, penetration depth increases till 10°C and then starts decreasing. At 2450 MHz, penetration depth increases till 45°C and then decreases slightly with increase in temperature. Below 0°C, penetration depth increased with decrease in temperature, that is, microwave power absorption decreased with decrease in temperature at both 915 MHz and 2450 MHz frequencies.

Regression Analysis

Predictive equations for dielectric properties at 915 MHz and 2450 MHz were determined using stepwise regression procedure by Statistical Analysis Software (SAS Institute Inc., Cary, NC). Predictive equations were of the form:

$$\varepsilon' = a_0 + a_1 T + a_2 T^2 + a_3 (1/T) \quad (2)$$

$$\varepsilon'' = a_0 + a_1 T + a_2 T^2 + a_3 (1/T) \quad (3)$$

where, T is temperature in °C. The values of the constants are given in the tables 1 and 2. Using these equations, dielectric constant and dielectric loss factor can be determined for florets and for stem part of broccoli.

CONCLUSION

Dielectric properties of florets and stem of broccoli were determined. The dielectric properties of florets were lower than that of stem parts.

Dielectric properties and penetration depth at frequencies 915 and 2450 MHz were shown with respect to temperature.

Equations were obtained by statistical analysis to predict the dielectric constant and loss factor of broccoli florets and stems at different temperature. The dielectric property values given by the equations were in close agreement with the experimental values.

Rapid changes in the dielectric properties were observed at temperatures between -1°C and +1°C.

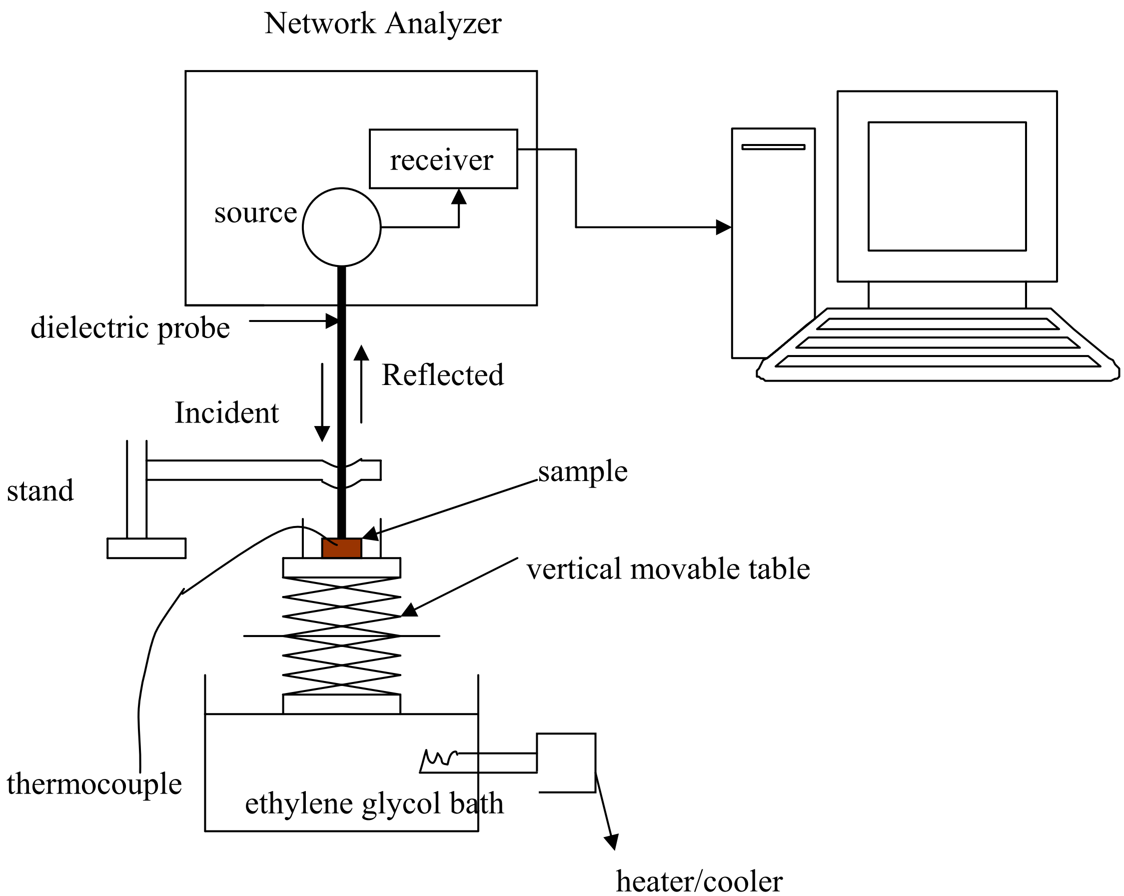

Fig. 1: Schematic diagram of experimental apparatus

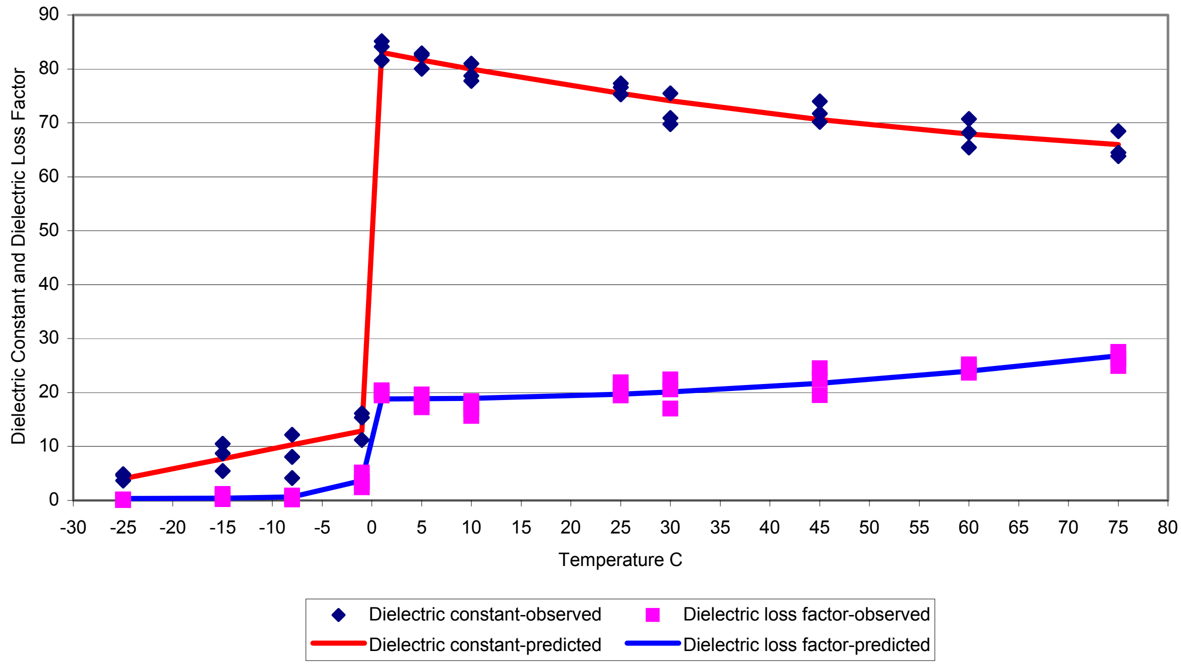

Fig. 2: Dielectric properties of Broccoli stem at 915MHz

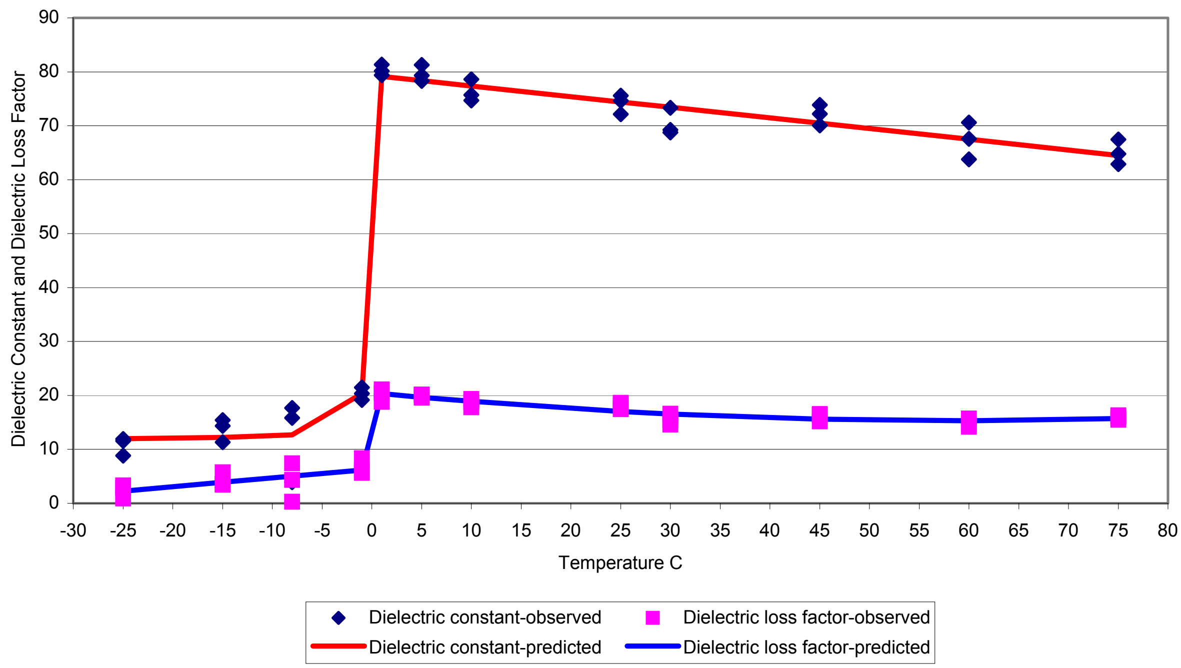

Fig. 3: Dielectric properties of Broccoli stem at 2450MHz

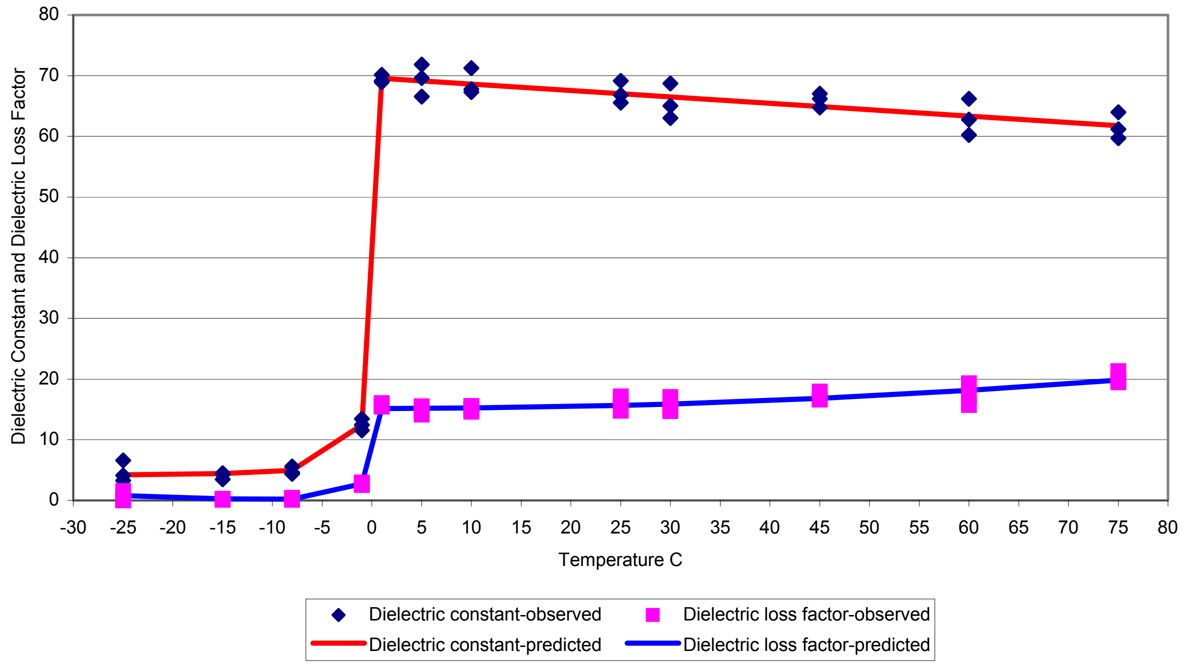

Fig. 4: Dielectric properties of Broccoli florets at 915MHz

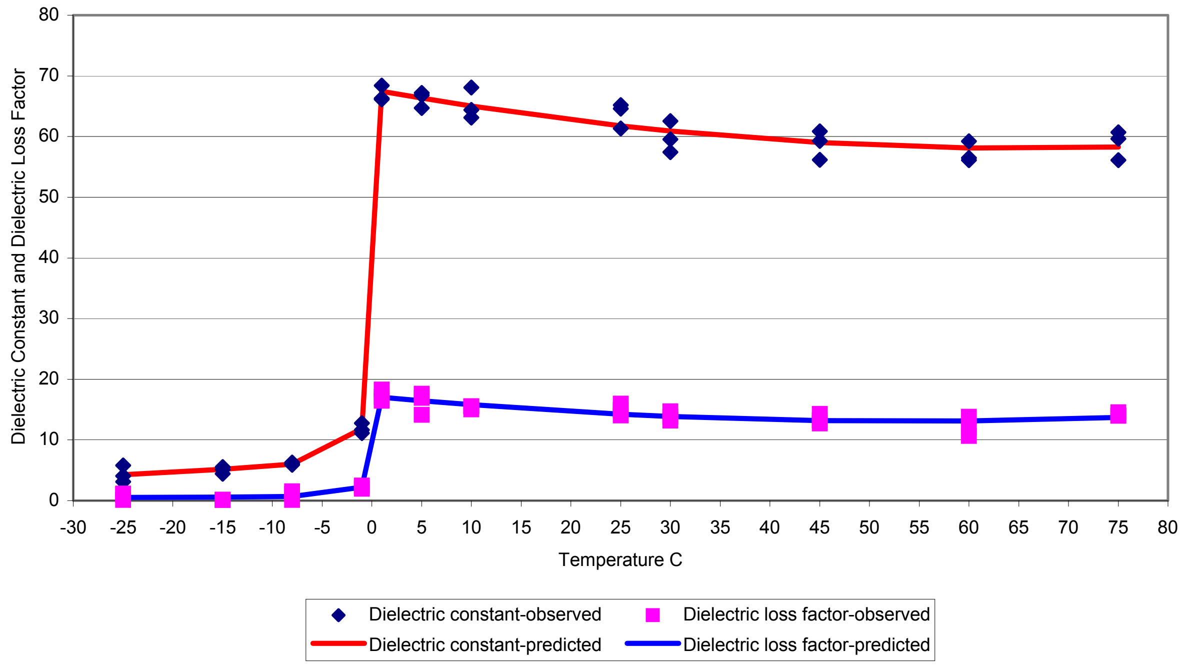

Fig. 5: Dielectric properties of Broccoli florets at 2450MHz

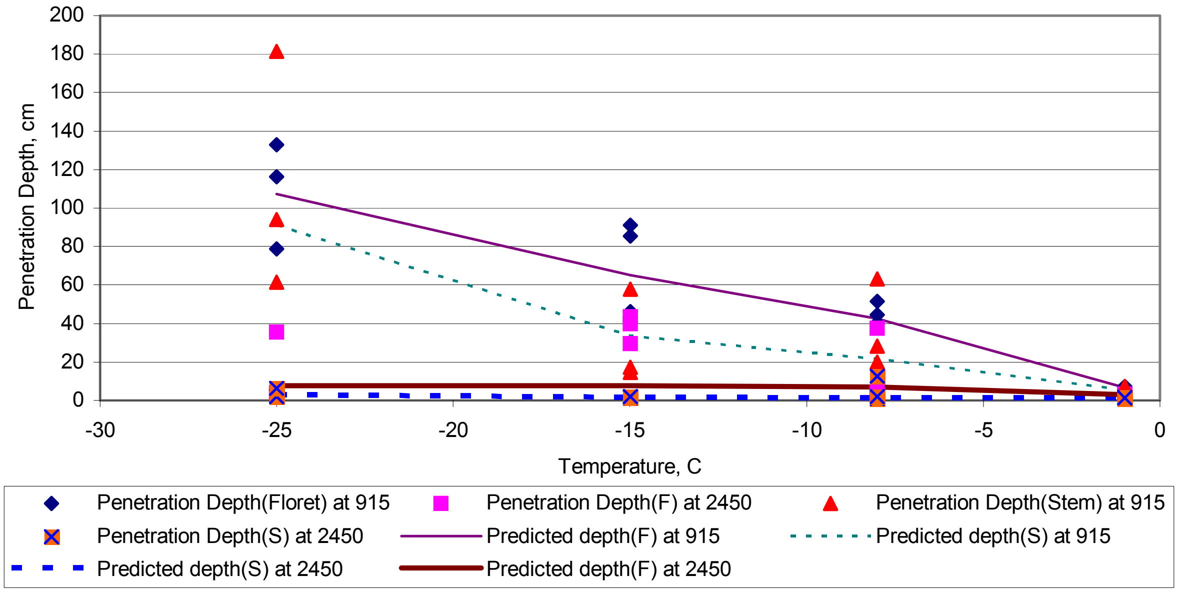

Fig. 6: Penetration Depth of Broccoli at temperatures below 0C

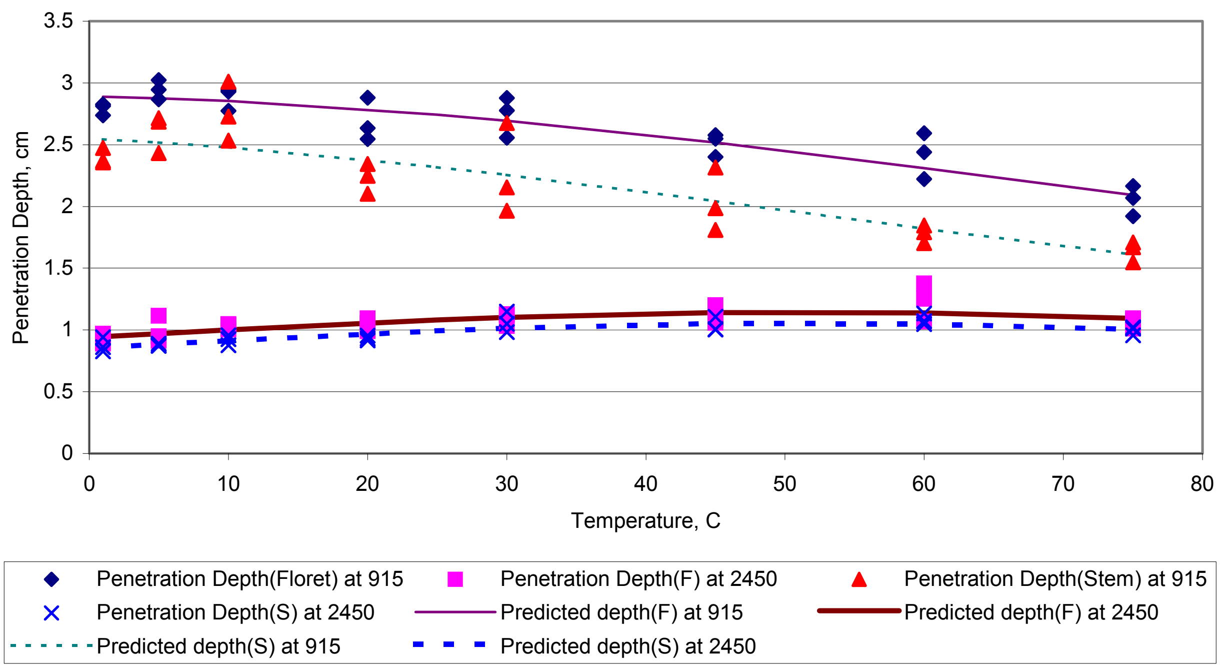

Fig. 7: Penetration Depth of Broccoli at temperatures above 0C

TABLE 1.
COEFFICIENTS FOR PREDICTIVE EQUATION OF DIELECTRIC CONSTANT OF BROCCOLI (Equation 2)

Broccoli part	Frequency (MHz)	Temperature	a_0	a_1	a_2	a_3	R^2
Stem	915	$< T_f$	13.27	0.37	NS	NS	0.64
		$> T_f$	83.43	-0.36	0.002	NS	0.90
	2450	$< T_f$	11.63	NS	NS	-8.7	0.62
		$> T_f$	79.36	-0.20	NS	NS	0.83
Floret	915	$< T_f$	3.86	NS	NS	-8.6	0.93
		$> T_f$	69.69	-0.11	NS	NS	0.68
	2450	$< T_f$	5.85	0.072	NS	-6.08	0.95
		$> T_f$	67.74	-0.30	0.002	NS	0.77

NS – Not Significant; T_f - Freezing point

TABLE 2.
COEFFICIENTS FOR PREDICTIVE EQUATION OF DIELECTRIC LOSS FACTOR OF BROCCOLI (Equation 3)

Broccoli part	Frequency (MHz)	Temperature	a_0	a_1	a_2	a_3	R^2
Stem	915	$< T_f$	0.20	NS	NS	-3.47	0.83
		$> T_f$	18.80	NS	0.0014	NS	0.75
	2450	$< T_f$	6.31	0.16	NS	NS	0.49
		$> T_f$	20.50	-0.18	0.0015	NS	0.82
Floret	915	$< T_f$	-0.27	NS	0.0015	-3.01	0.89
		$> T_f$	15.15	NS	0.0008	NS	0.75
	2450	$< T_f$	0.46	NS	NS	-1.75	0.69
		$> T_f$	17.19	-0.15	0.0014	NS	0.69

NS – Not Significant; T_f - Freezing point

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Chapter 4: Analysis of Microwave Cooking of Ground Beef Patties of Different Fat Levels and Broccoli using Finite Element Method[4]

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ABSTRACT

Microwave heating is a widely used method to prepare food. There are chances for survival of pathogens during and after microwave cooking or reheating. Many factors contribute to pathogen survival. Evaporative cooling, food type, and food composition play a major role. Modeling of microwave heating process helps to understand the heating of food by microwaves. This paper analyses the microwave cooking process of ground beef patties at three different fat levels and broccoli using finite element method. Axisymmetric heat and mass transfer equations were solved using FEMLAB® and predicted temperature values were plotted against observed values. Results showed that the modeling equations used in this study were suitable for cooking food without covering the bowl. High fat ground beef tend to heat faster than low fat ground beef though the high fat beef had less moisture. In low fat ground beef and broccoli, water content was mainly responsible for microwave heating. Deviations between predicted and observed values were calculated and were within 9.6 °C, 7.0 °C, 11.6 °C and 6.0 °C for covered beef patties, uncovered beef patties, covered broccoli and uncovered broccoli, respectively.

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1. INTRODUCTION

Microwave cooking is widely used in developed countries and getting popular in developing countries. Survival of pathogen in microwave-cooked food is higher than that for conventionally cooked food (Anantheswaran *et al.,* 1994). Uneven heating of food by microwaves is one of the main reasons for the survival of pathogens. Though there are food safety problems, consumers increasingly relay on microwave cooking. The reduction in process time compared to conventional methods, (Decareau and Peterson, 1986) and higher food quality in terms of its appearance, flavor and taste can be main reasons for consumer preference to microwave cooking (Harlfinger, 1992).

The elimination of pathogens during microwave cooking is a critical factor in ensuring food safety. Understanding the microwave cooking process and the properties of food are important issues in developing specific recipes and heating instructions to ensure food safety. For example, high level of fat in the food product offers more reduction in pathogen survival than low fat product (Hix, 2000). Heating nature of vegetable products under microwave is more susceptible to pathogen survival than meat products (Hix, 2000). The cooking process has impact on microbial survival, for example, cooking food by covering the bowl has less chances of pathogen survival than that of uncovered cooking (Hix, 2000).

Mathematical modeling is widely used for representing transport phenomena using numerical equations. The solutions for these equations, when solved properly, would be close agreement with the behavior of the material. In microwave heating, modeling can be a design tool to understand and develop optimum heating procedure for food.

Numerical models can simulate the microwave-cooking process. It plays an important role in designing and optimizing the best possible improvement in microwave heating. If a model can successfully simulate the heating behavior of an item in a microwave oven, product developers will be able to test the effects of the changes in the food formulations without excessive time or money. This time-and-cost-saving aspect is main advantage of modeling. The modeling process provides better understanding of the microwave cooking process (Lorenson, 1990). Thus, the mathematical models are useful in improving the microwave cooking procedure.

In the modeling process, the food system is broken down into many small elements. These discrete elements are joined together to make up the product. Simulation of the source of microwave is possible and solution to the electric field equations can be obtained. It is also possible to model temperature distribution in the material (Lorenson, 1990).

In the present study, a mathematical modeling technique, called the finite element method was employed to analyze the heating behavior of ground beef patties with three different fat levels and frozen broccoli. Thus, the objectives of this study are to:

(1) Study the role of fat in the food, steam, and food type on heating characteristics of food during microwave cooking process.

(2) Developing a mathematical model to simulate the microwave heating process.

(3) Validating the model data against observed values.

2. LITERATURE REVIEW

Uneven distribution of dipolar molecules is common in a food material. Non-uniform heating of food can be expected since the heating rate of microwaves largely depends on dipolar molecules (Anatheswaran *et al.,* 1993). A study by Schiffman (1993) showed that a three-level temperature gradient occurs in microwave-heated food: The top of the food being the coolest region, the bottom being the intermediate temperature range and the middle being the hottest temperatures. Studies by Aleixo *et al.,* (1985) showed that the minimum temperature range of 70°C to 75°C at the product's coolest point required for microbial safety of microwave heated food. This range could vary depending on the study and food tested.

The rapidly varying electric field of microwaves is responsible for most of the heating in the food. The electric field causes the water molecules to produce rise in temperature, magnetic field components are not normally important in determining the heating behavior since food does not interact with magnetic fields (Lorenson, 1990). The source of microwaves can be simulated and the equation for the electric field can be solved numerically.

Computational approaches that are appropriate to model microwave environment are Transmission-Line Matrix (TLM) method, Finite Difference Time Domain (FD-TD) method, Finite Element Method (FEM), and the method of moments. A closer look at each method reveals that FEM can be the best suitable method (Lorenson, 1990). TLM approach models the electric field and magnetic field component of Maxwell's equation equivalent to the current and voltage on each transmission line. Oven cavity space is assumed as conducting wires and the food load as electrical component. This method is a complex approach for modeling microwave-cooking process. Though FD-TD is the one of the methods commonly used for microwave modeling, its processing time is higher and less flexible than FEM. The method of moments needs more memory than other numerical methods. FEM can simulate simultaneous heat and mass transfer and changes in physical and dielectric properties as function of temperature and moisture content during microwave heating (Puri and Anantheswaran, 1993).

Ayappa *et al.,* (1991) used Maxwell's equation as a general formulation for power absorbed in a homogeneous, isotropic, multi-layered medium. They also modeled Lambert's law and compared with Maxwell's equations. The result of this study showed that Lambert's law could be used to estimate temperature profiles for sufficiently thick samples (basis for assuming infinitely thick sample when using Lambert's law). They suggested that for an exact description of microwave heating patterns, Maxwell's equation should be used. Another study by Ayappa *et al.,* (1992) modeled the cylindrical and square samples by solving Maxwell's and heat equations simultaneously. Two dimensional, finite element analysis was employed. Non-linear equations were solved by Newton's iteration method.

Fu and Metaxas (1994) used Method of Lines (MOL), which is deviation of FDTD method, to solve Maxwell's equations. MOL can also be used for solving heat transfer problem of parabolic type. They used numerical schema called MAXEMOL (MAXwell's Equation's using the MOL) to predict power density distribution using time dependent Maxwell's equations. In addition, they used MAXEMOL as a design tool to analyze the effect of entry port orientation on uniform power distribution in a dielectric load.

Zhang and Datta (2000) studied the temperature distribution of a microwave oven by coupling Maxwell's equations and heat transfer equations. Two separate finite element software were used and coupling of these software done using a special script at operating system level. They suggested that 3D modeling could give accurate prediction as the rate and spatial variation of temperature of materials change during microwave heating. They also emphasized that the solution to Maxwell's equations in 3D would be more appropriate for multi mode cavity ovens such as domestic microwave oven.

Mallikarjunan *et al.,* (1995) used Lambert's law to estimate microwave power absorbed by food material. A simultaneous heat and mass transfer model was developed to predict thermal inactivation of pathogenic bacteria on chicken breast during microwave cooking. The predicted data agreed well with the experimental data. Zhou *et al.,* (1995) numerically solved the diffusional heat and mass transfer equations in three - dimensional rectangular and two dimensional cylindrical shape samples. Mallikarjunan *et al.,* (1996) developed mathematical model that includes heat and mass transfer and microbial inactivation kinetics. Two dimensional axisymmetric circular slab shape was considered and finite difference method was employed. Variation of dielectric properties with respect to temperature was taken into account in the simulation process. Model predictions were in close agreement with the experimental data.

Chen *et al.,* (1993) modeled temperature distribution in microwaved cylindrical potato tissue using FEM. Lambert's law was used to obtain heat generation term. Increasing number of elements resulted in closer fit of FEM and experimental profiles. This study showed that dielectric properties contributes a critical role and largely depends on product’s temperature. Axisymmetric problem approach was employed. Taylor polynomial was used to approximate non-linear characteristics of heat generation term.

Tong and Lund (1993) predicted the temperature profiles and total moisture loss for microwave heating of bread from room temperature using one-dimensional model. Ni *et al.,* (1999) used mathematical model to predict moisture profiles during microwave heating and studied the non-uniformities of heating and moisture loss. The results showed that the most of the moisture loss occurred from the edges due to high temperature at these locations. They also found that the uniformity of heating increases and total moisture loss reduces, when surface area increases for a given volume of the product.

Lambert’s law has been widely used to estimate microwave power absorption (Decareau 1985). Many researchers use Lambert’s law to model microwave heat generation (Ayappa *et al.,* 1991). Van Remmen *et al.,* (1996) developed mathematical models using Lambert’s law, considering internal reflections. They used slab, sphere, and cylinder geometries. The purpose of those models was to provide an insight in microwave heating. Mathematical modeling will never totally replace experimental work in the field of microwave heating, but it can provide valuable insight on which experiments to do (Lorenson, 1990).

3. MATERIALS AND METHODS

3.1 Sample Preparation

Ground beef with fat levels of 4%, 9%, and 20% were obtained from local grocery store (Blacksburg, VA). Patties of 11cm diameter and 1.3cm thickness were made. Each patty weighed 225±10gm. Patties were then stored in freezer and thawed in refrigerator for 24h before start of experiment.

Frozen broccoli was obtained from local grocery store (Blacksburg, VA) and used in the experiment. Frozen broccoli was thawed in a refrigerator for 24h. Then the broccoli was weighed for 225gm. Attempts were made to keep the shape of the broccoli in a cylindrical shape of 11cm diameter and used in the microwave cooking. Samples were tested in five replications.

3.2 Heating Procedure

A 1,200W, household type microwave oven was used in this study (Model NN-S740BAW, Panasonic® Consumer Electronic Company, Secaucus, NJ, The USA 07094). Two-liter beaker test was used for calibrating the microwave oven (Buffler, 1993). The food was placed in a microwave-safe glass bowl and cooked for 120 seconds. The food was heated by covering using lid and without covering the bowl. The lid had small hole to act as steam vent through which probes were taken inside the bowl. With the help of Statistical Consultancy Center at Virginia Tech, it was determined that five replications had to be performed in this experiment. Therefore, the total number of experiments was forty. The weight of samples was recorded using a balance (Model ARC 120, Ohaus® Corporation, Pine Brook, NJ, The USA 07058) attached with microwave oven (Figure 1) for every 5sec.

One headspace and three internal temperature measurements were recorded using fiber optic sensors connected to UMI 4 (FISO® Technologies Inc, Sainte-Foy, Canada G1N 4N6). Temperatures were recorded by a personal computer for every 0.6 seconds.

Probes were placed at various locations in the food, one probe at bottom corner, one at half thickness and half radius from a side of the sample, one at center-top surface, and one in the headspace of the container (Figure 2). The placement included the approximate cold spot of the product (usually near top surface of the product).

3.3 Model Development

Food products release their moisture as steam during microwave cooking. When the food is cooked in a closed container, steam will accumulate in the headspace and this increases cooking efficiency. The model to be developed will take into account both the heat and mass (moisture) transfer during microwave cooking. To simplify the model following assumptions are considered.

(1) The food product in the container was modeled as axisymmetric cylinder geometry (Figure 3).

(2) Initial temperature and moisture distribution in the sample were assumed uniform.

(3) Shrinkage of food product during microwave cooking was neglected.

(4) Surface cooling is considered only due to evaporation and natural convection.

(5) Bottom of the bowl receives negligible amount of energy due to reflection from the floor of the microwave oven during microwave heating.

Conduction heat transfer with heat generation with in the food is the primary mode of heat transfer during microwave heating. Axisymmetric transient heat transfer problem in cylindrical co-ordinates is governed by the partial differential equation:

$$K_{rr}\frac{\partial^2 T}{\partial r^2}+\frac{K_{rr}}{r}\frac{\partial T}{\partial r}+K_{zz}\frac{\partial^2 T}{\partial z^2}+Q=\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

Assuming the thermal conductivity (k) as constant,

$$K\frac{\partial^2 T}{\partial r^2}+\frac{K}{r}\frac{\partial T}{\partial r}+K\frac{\partial^2 T}{\partial z^2}+Q=\rho C_p\frac{\partial T}{\partial t} \qquad (2)$$

With initial condition: $T(r, z) = T_0$ at t=0 (3)

and the boundary conditions are:

$$-KA\frac{\partial T}{\partial r}=h_t A(T_s-T_a)+\lambda_v\frac{\partial m}{\partial t} \qquad \text{at } r=R \qquad (4)$$

$$-KA\frac{\partial T}{\partial z}=h_t A(T_s-T_a)+\lambda_v\frac{\partial m}{\partial t} \qquad \text{at } z=L \qquad (5)$$

The increase in temperature in the head space because of the steam release from the food during microwave heating can be calculated by heat balance:

$$V_h\rho_a C_{pa}\frac{\partial T_a}{\partial t}=h_t A(T_s-T_a) \qquad (6)$$

and mass transfer is given by,

$$\frac{\partial m}{\partial t}=h_m A(P_s-P_a)+\frac{\rho V C_p}{\lambda_v}\left(\frac{\partial T}{\partial t}\right) \qquad (7)$$

Microwave energy entering the food from radial direction (r) and from longitudinal direction (z) must be considered in calculating the heat generation term (Q). Q is given by,

$$Q=Q_r\exp\left(\frac{-(R-r)}{\delta_p}\right)+Q_z\exp\left(\frac{-(L-z)}{\delta_p}\right) \qquad (8)$$

The finite element method was used and the equations were solved over time by commercial software, FEMLAB®. Linear triangle elements were used and the number of elements was 1634 and the number of nodes was 878 (Figure 4).

3.4 Model Parameters

Thermal properties such as thermal conductivity, specific heat, density, and latent heat of vaporization are obtained from Polley *et al.,* (1980) and Sanz *et al.,* (1987) and used in the modeling. The effect of latent heat of vaporization will be considered only during heating and not during holding or cooling. Specific heat of steam was used as the specific heat of food at temperatures greater than 106°C.

The surface heat transfer coefficient was calculated by (Toledo, 1991),

$$h_t = 1.3196\left(\frac{|T_s - T_a|}{D}\right)^{0.25} \tag{9}$$

The surface mass transfer coefficient is given by (Sereno and Medeiros, 1990)

$$\frac{h_t}{h_m \lambda_v} = 64.7 P_a / K \tag{10}$$

The penetration depth is given by (Nelson *et al.,* 1994),

$$\delta_p = \frac{\delta_0}{2\pi(2\varepsilon')^{0.5}}\left[\left(1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)^{0.5} - 1\right]^{-0.5} \tag{11}$$

The dielectric properties ε' and ε" were calculated for ground beef patties using predictive equations given by Gunasekaran *et al.,* (2002a)

$$\varepsilon' = 50.69 - 0.08T + 0.0005T^2 - 1.23F + 0.03F^2 \tag{12}$$

$$\varepsilon'' = 16.70 - 0.05T + 0.0007T^2 + 0.22F \quad (13)$$

For frozen broccoli, ε' and ε" were calculated using equations given in Gunasekaran *et al.,* (2002b). The average of coefficients for florets and stem parts were used to obtain coefficients for ε' and ε",

$$\varepsilon' = 73.55 - 0.25T + 0.001T^2 \quad (14)$$

$$\varepsilon'' = 18.85 - 0.165T + 0.00145T^2 \quad (15)$$

The saturated vapor pressure of air with respect to temperature is given by Weiss (1977):

$$P_s = 614.97 \exp\left[17.2694\left(\frac{T-273}{T-35.7}\right)\right] \quad (16)$$

Partial vapor pressure will be calculated by multiplying the saturated vapor pressure by relative humidity of air or by water activity of food.

4. RESULTS AND DISCUSSIONS

Uniform initial temperature of 10°C was assumed through out the product at the start of the experiment. Figure 5 to 10 shows predicted and observed temperature values for beef patties with three fat levels and broccoli at the calibrated microwave oven output of 950 W.

The deviation between the predicted and observed temperature values were shown in the table 1. Deviations were calculated using the equation (17):

$$\sigma = \frac{\sqrt{{}_{i=1}^{N}\Sigma(T_p - T_o)^2}}{N} \quad (17)$$

The deviations might have occurred mainly due to the model assumptions. The differences between predicted and observed temperature values of broccoli might also include the assumption that broccoli was considered as continuous like beef patty. It also appears that the contribution of steam cover on increase in temperature for covered cooking condition has not captured well in the modeling equations. Though thermal and dielectric properties of food were calculated with respect to temperature, changes in these properties in the presence of steam cover were not considered. Literatures on changes in properties in the presence of steam were hard to find. In addition, equations used for calculating the thermal properties were derived based on composition food, which may not be accurate enough to produce proper results.

Discontinuity of broccoli sample and negligence of shrinkage effect of beef patties and broccoli caused observed temperatures to be higher than the predicted temperatures. Similar observations were reported for modeling microwave cooking of shrimp by Mallikarjunan *et al.* (1996). However, the deviation value for beef patties was within 9.6 °C (for covered) and 7 °C (for uncovered). The deviation value for broccoli was within 11.6 °C (for covered) and 6 °C (for uncovered). For location 1 of uncovered cooking of broccoli, model values are higher than the observed values. This might be due to the high evaporative cooling effect from the skin of the broccoli. Another reason for deviation could be the use of Lambert's law instead of Maxwell's equations for calculating power distribution in the food.

Edges and corners were heated faster than other parts of the food due to exposure of microwaves coming from different directions. This effect is well documented in many literatures (Mallikarjunan *el at.,* 1995; Lin *et al.,* 1995; Knutson *et al.,* 1987; Datta, 2001; Chen *et al.,* 1993). After 50 sec of microwave heating, the temperature reached near the boiling point of water at the edges. The phenomenon of heat loss due to convection and evaporative cooling at the boundary was well observed in the model output temperature profile.

An interesting observation is that the 20% fat beef patties had higher temperatures than that of 4% and 9% fat patties though the 20% fat patties had lesser moisture content. For 20% fat, when the temperature increases the fat becomes oil and oil + water mixer could have been formed. Considerable amount of water could be trapped in the oil and thus increasing the temperature during microwave heating. In addition, the oil could have prevented the heat loss during heating. On the other hand, 9% fat patties recorded lower temperatures than that of 4% fat patties. The moisture content of 4% fat was higher that that of 9% fat patties. It can be reasoned that though water is the main contributor for microwave heating, at lower fat levels, effect of fat is less pronounced than that at high fat levels.

Broccoli was heated up more than that of 4% fat and 9% fat patties. It is clear that the water content of food is mainly responsible for microwave heating as the moisture content of ground beef patties were lesser than the moisture content of the broccoli.

However, 20% fat patties had higher temperatures than that of broccoli due to the reason already mentioned before.

Statistical analysis of observed temperatures was performed by Statistical Analysis Software (SAS Institute Inc., Cary, NC) using mixed procedure. Analysis showed that meat products significantly differ ($p < 0.05$) from vegetable product in microwave heating pattern. In addition, the heating trend significantly different ($p < 0.05$) between cooking with or without covering the samples. These results are supported by model results. In addition, SAS analysis showed evidence that there is difference among beef patties of different fat levels ($p < 0.05$). Analysis of moisture loss data of covered and uncovered cooking exhibited significance difference ($p < 0.05$), which is obvious as covered cooking traps more moisture inside the bowl and in the food. The reduction in loss of moisture in covered samples could be important as it increases free water (Hix, 2000). The heating efficiency of microwave could be improved due to increase in amount of water.

5. CONCLUSIONS

Current model and boundary conditions were better for cooking food without closing the lid, especially for location 1 than for cooking by closing the lid. The comparison of model predictions for location 2 and 3 with observed values were almost similar for covered and uncovered conditions. Therefore, the current model is more suitable for modeling the uncovered cooking process for ground beef patties and frozen broccoli.

High fat ground beef patties reaches higher temperature than low fat patties as the contribution of low-level fat on increasing the temperature is less.

Water content of vegetable product is mainly responsible for microwave heating, whereas, in high fat meat products, fat content also contributes to increase in temperature during microwave heating.

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NOTATIONS

ε' – dielectric constant

ε'' – dielectric loss factor.

δ_p – penetration depth, m [δ_0=12.237 cm at 2450 MHz]

λ_v – latent heat of vaporization, J/kg.

ρ_a – density of air, kg/m^3

A – area of cross section, m^2

C_p – specific heat of food, J/Kg K

C_{pa} – specific heat of air, J/Kg K

D – characteristics dimension to calculate h_t, m

F – fat content, %

h_m - surface mass transfer coefficient, kg of water/ m^2.Pa.s

h_t - surface heat transfer coefficient, W/m^2.K

k – thermal conductivity of food, W/m.K

m – moisture content, kg water/kg soids

N – number of observations

p_a - partial vapor pressure of air, P_a

p_s - partial vapor pressure at the product surface, P_a

Q – heat generation, W/ m^3

Q_r – heat generation through the radial side of the cylinder, W/ m^3

Q_z – heat generation through an axial end of the cylinder, W/ m^3

t – time, s

T – temperature, K

T_a – ambient temperature, K

T_s – surface temperature, K

T_p – predicted temperature, K

T_o – observed temperature, K

V – product volume, m^3

V_h – head space volume, m^3

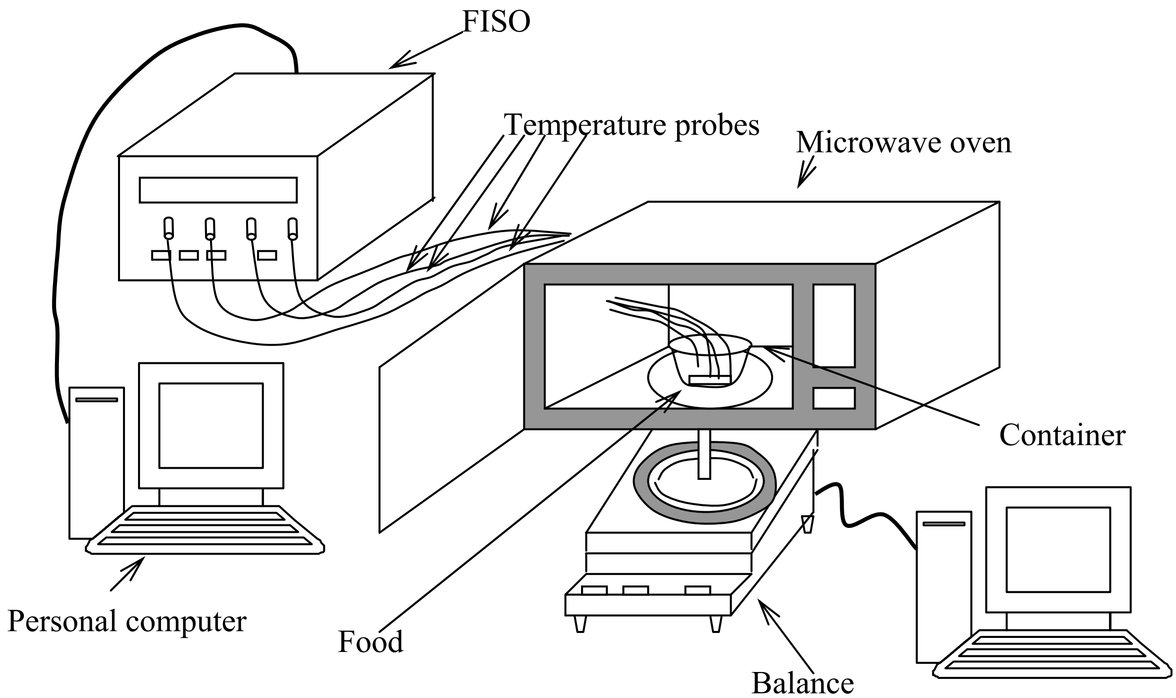


Fig. 1: Schematic Diagram of Experimental Set up

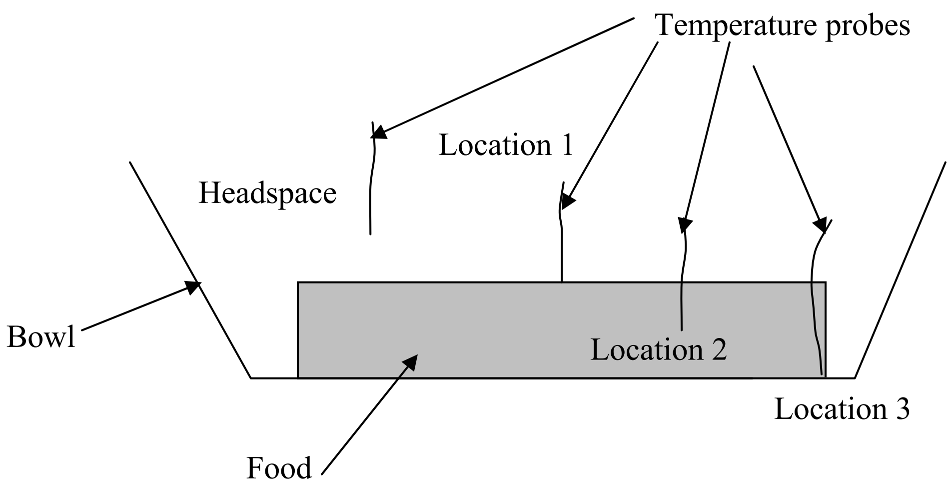


Fig. 2: Diagram Showing Probe Locations in the Food

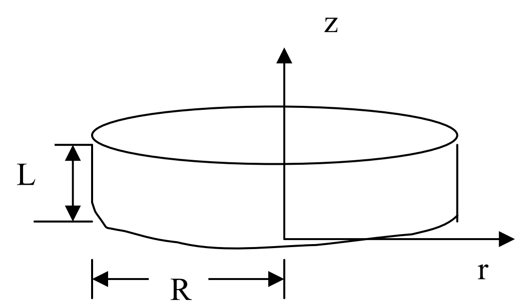


Fig. 3: Axisymmetric Model of the Food System

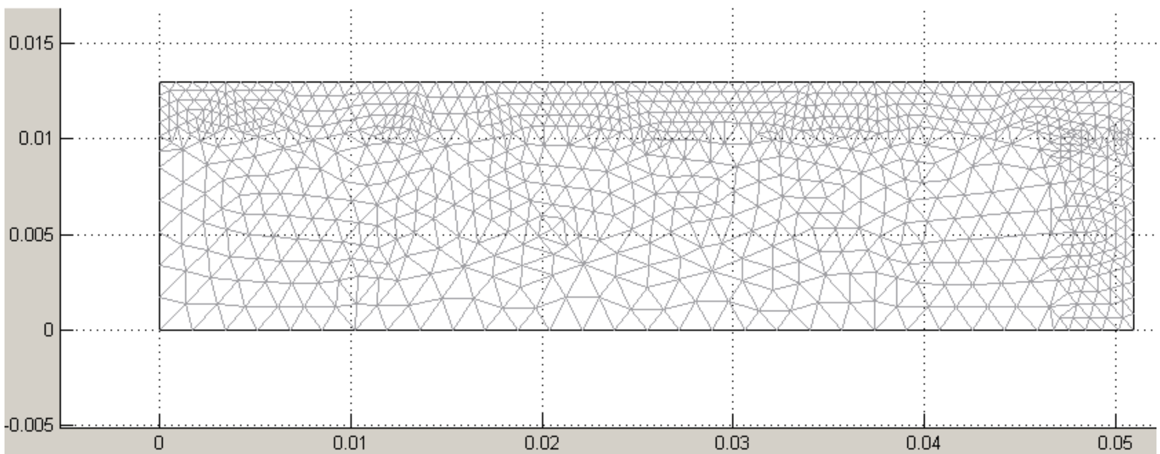


Fig. 4: Finite Element Mesh

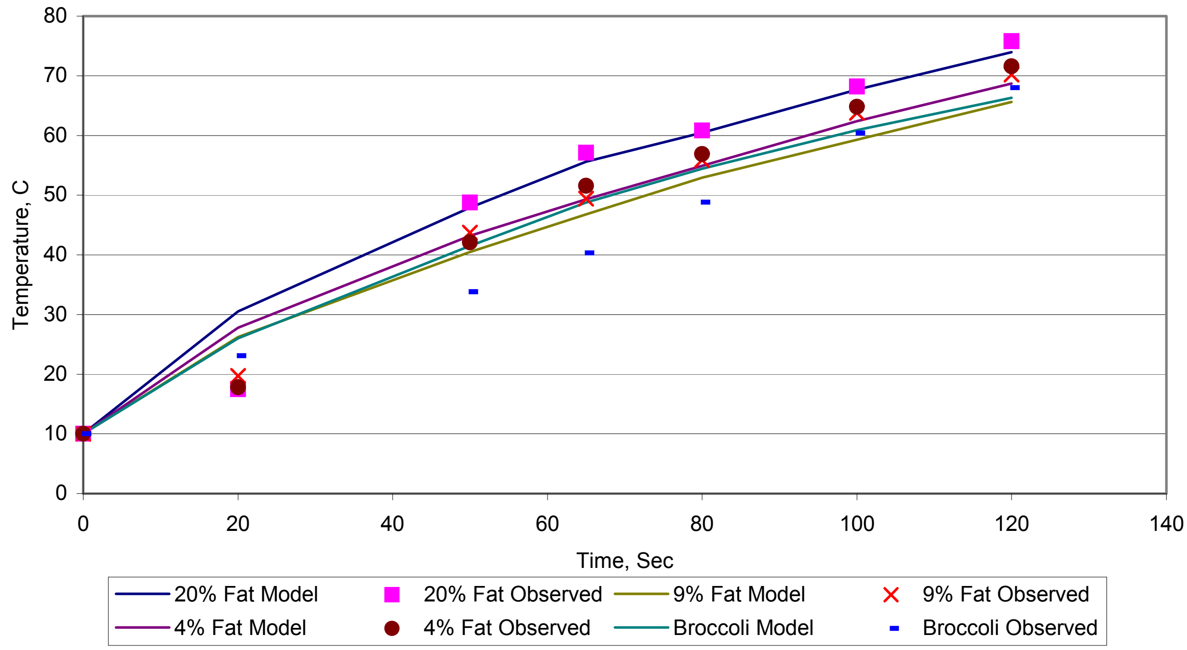


Fig. 5: Comparison predicted and observed values for location 1, cooking without lid

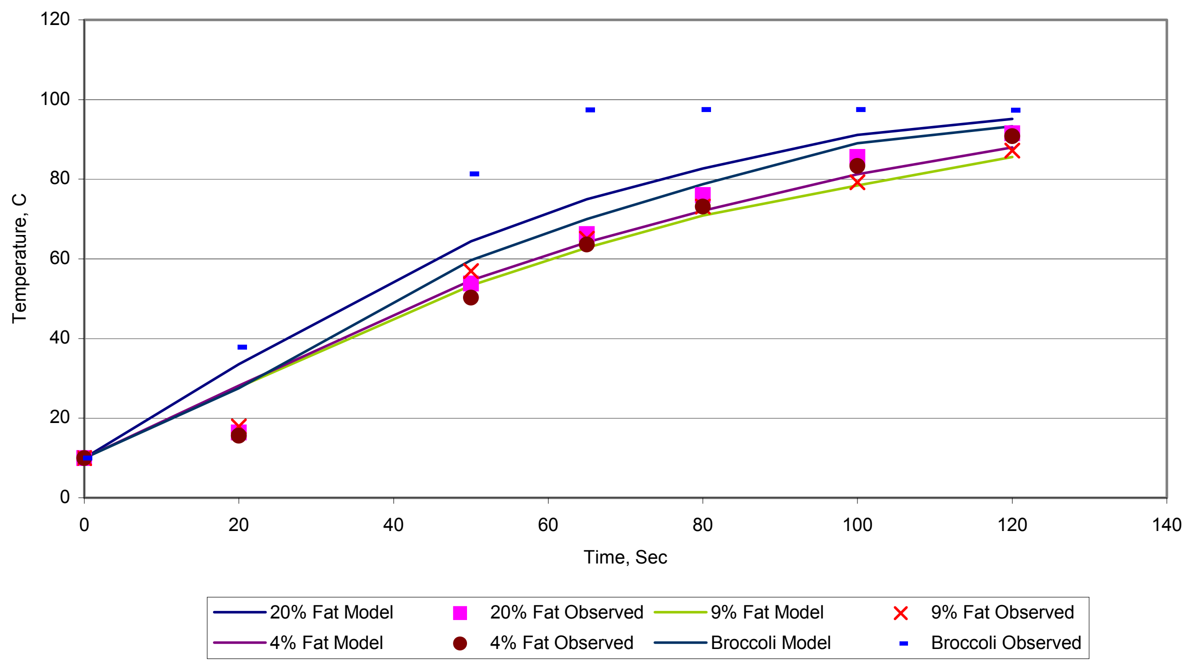


Fig. 6: Comparison predicted and observed values for location 2, cooking without lid

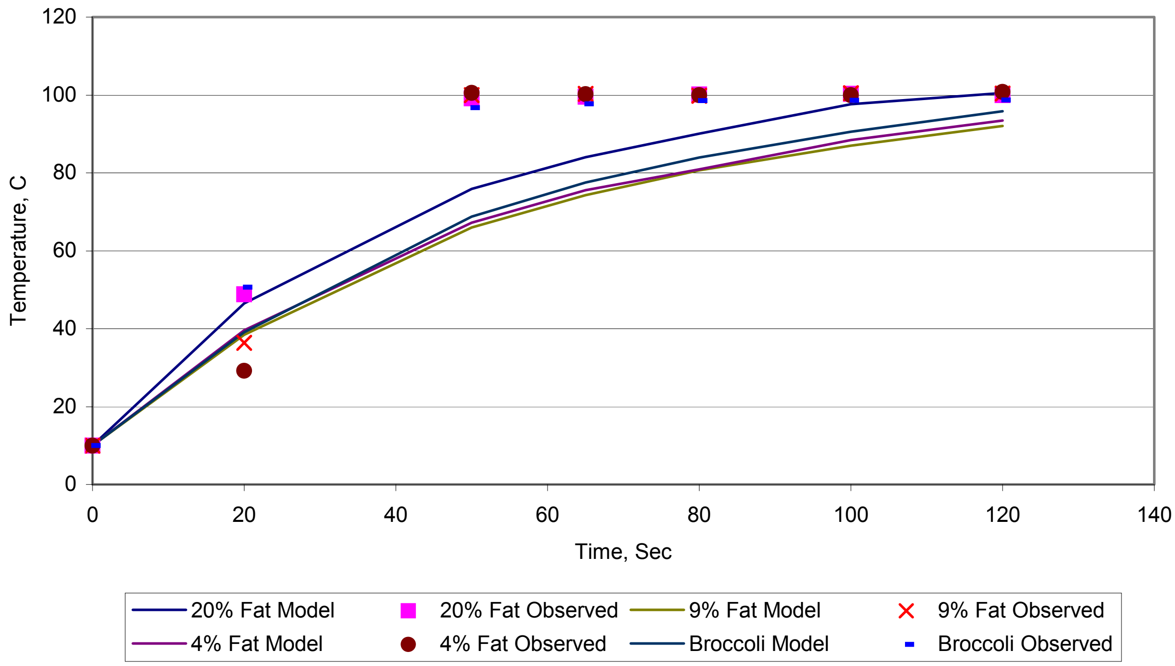


Fig. 7: Comparison predicted and observed values for location 3, cooking without lid

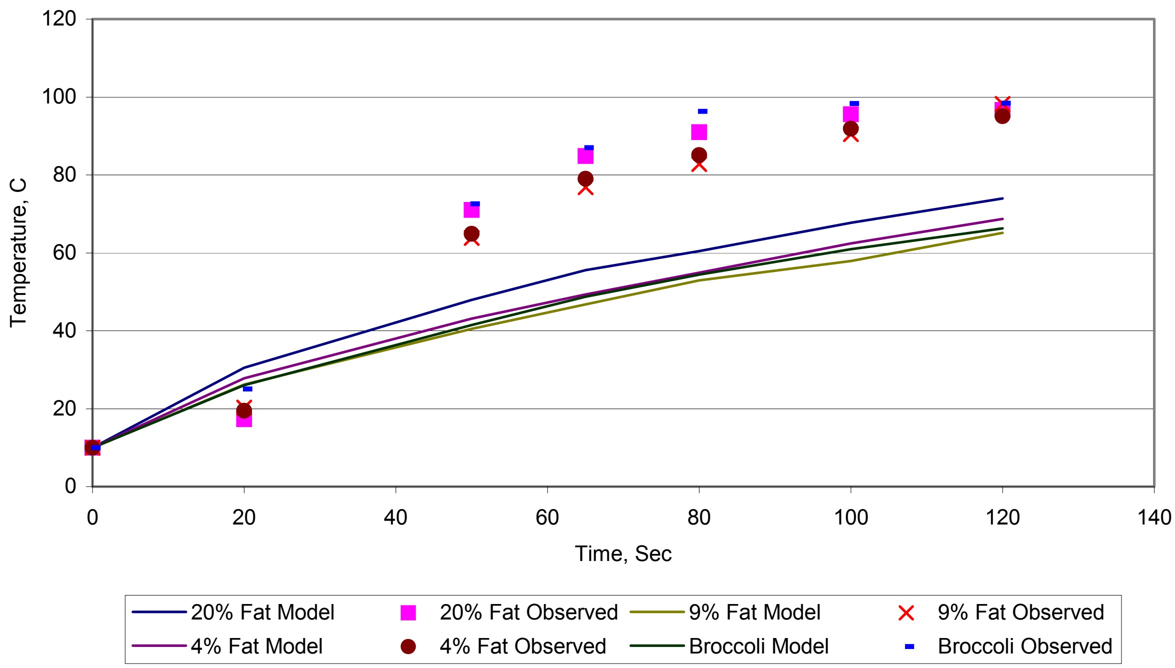


Fig. 8: Comparison predicted and observed values for location 1, cooking with lid

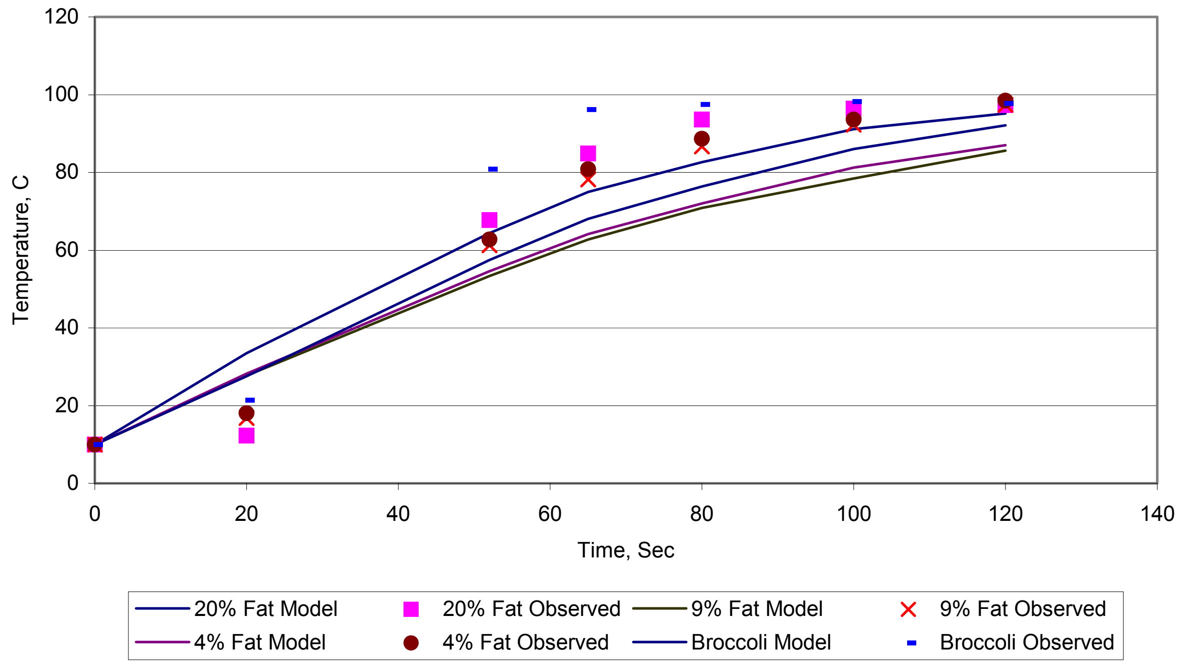


Fig. 9: Comparison predicted and observed values for location 2, cooking with lid

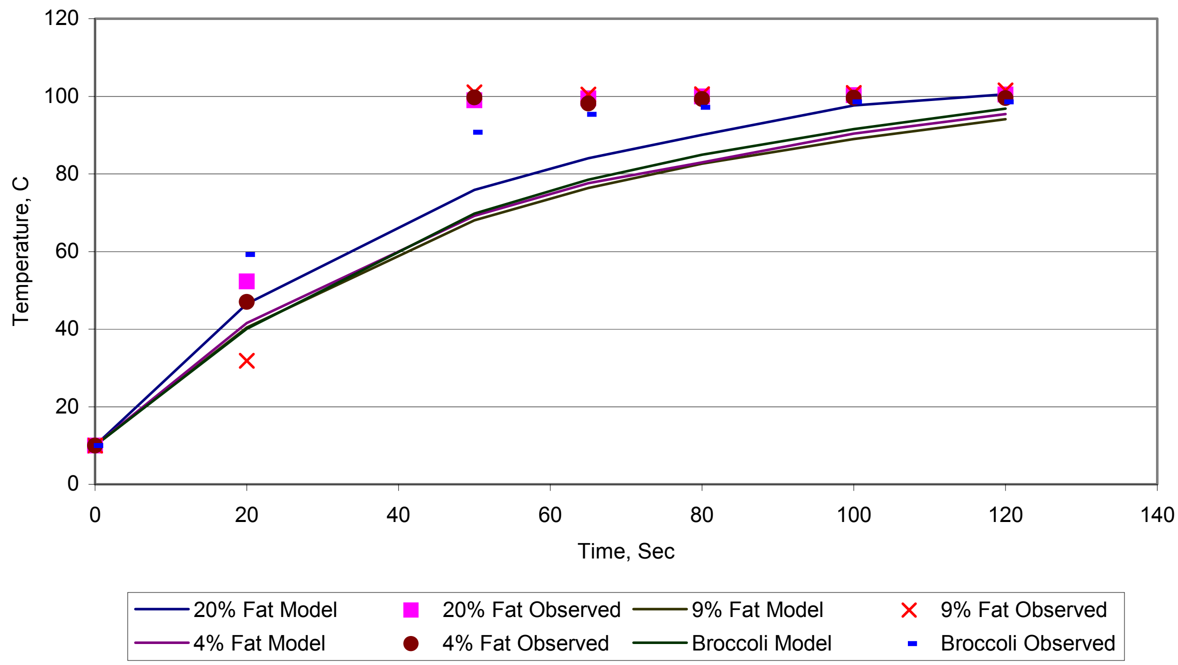


Fig. 10: Comparison predicted and observed values for location 3, cooking with lid

Table 1. Deviation between observed and predicted temperatures

Deviation for	Deviation (σ) temperature (°C)	
	Covered	Uncovered
Location 1, 20% fat	8.79	1.89
Location 2, 20% fat	3.81	3.41
Location 3, 20% fat	4.31	4.26
Location 1, 9% fat	9.62	1.49
Location 2, 9% fat	4.52	1.57
Location 3, 9% fat	6.79	7.06
Location 1, 4% fat	8.91	1.58
Location 2, 4% fat	4.53	2.97
Location 3, 4% fat	5.98	6.96
Location 1, Broccoli	11.61	1.88
Location 2, Broccoli	6.38	5.99
Location 3, Broccoli	5.13	5.73

SUMMARY AND CONCLUSIONS

Food safety is one of the most important issues in microwave cooking. Though many experiments have been dedicated to understand the behavior of food materials during microwave cooking, there are still problems in developing proper cooking procedure that assure food safety. Therefore, there is a need for better understanding of various factors influencing the microwave heating of food.

In this study, the finite element method was used to determine the role of fat in a muscle food, difference between heating behavior of a muscle food and a vegetable product, and the influence of covered and uncovered cooking of food during microwave cooking. As the dielectric properties of food plays a critical role in microwave heating, experiments were conducted to determine dielectric constant and dielectric loss factor at different temperatures, and used in the mathematical modeling.

Dielectric properties of ground beef patties at 4%, 9%, 20% fat levels and frozen broccoli were determined using an open-ended coaxial probe connected to a network analyzer at various temperatures. Results showed that dielectric constant and dielectric loss factor of low fat ground beef were higher than that of high fat level ground beef, and the dielectric properties of florets were lower than that of stem parts for frozen broccoli. Predictive equations were developed and were used in the modeling to calculate dielectric properties.

Temperature profiles in ground beef patties at 4%, 9%, 20% fat levels and frozen broccoli during microwave heating were calculated using finite element method and validated with actual values. The actual values were obtained by experiments conducted using a household microwave oven. Modeling and experimental results revealed that the high fat ground beef patties reach higher temperature than the low fat patties and vegetable food. Temperatures at boundaries of food product in a covered cooking process were higher than that in uncovered cooking.

The following conclusions can be derived from this study:

1. Fat content and temperature influenced dielectric constant and dielectric loss factor.
2. Dielectric constant and dielectric loss factor of low fat ground beef were higher than that of high fat level ground beef. The dielectric properties of florets were lower than that of stem parts.
3. The temperatures between –1 and +1°C were critical as the dielectric properties changes significantly.
4. The dielectric properties' predictions obtained from the regression equations were in good agreement with observed values.
5. The modeling equations used in this study were more suitable for predicting temperature profile in an uncovered cooking process for ground beef patties and frozen broccoli than in a covered cooking process.
6. High fat ground beef patties reached higher temperature during microwave cooking than low fat patties.
7. Water content of vegetable and low-fat meat product is mainly responsible for microwave heating, whereas, in high fat meat products, fat content also contributes to increase in temperature during microwave heating.

APPENDIX A: List of Variables

ε' – dielectric constant

ε'' – dielectric loss factor.

ε_0 – permittivity of free space (8.86 x 10^{-12} F/m)

δ_p – penetration depth, m [δ_0=12.237 cm at 2450 MHz]

λ_v – latent heat of vaporization, J/kg.

μ - permeability, H/m

ρ_a – density of air, kg/m^3

ω – angular frequency of microwave, 1/s

A – area of cross section, m^2

B – magnetic field vector, A/m

C_p – specific heat of food, J/Kg K

C_{pa} – specific heat of air, J/Kg K

D – characteristics dimension to calculate h_t, m

D_m – diffusivity, m^2/s

E – electric field vector, V/m

F – fat content, %

h_m - surface mass transfer coefficient, kg of water/ m^2.Pa.s

h_t - surface heat transfer coefficient, W/m^2.K k – thermal conductivity of food, W/m.K

m – moisture content, kg water/kg soids

N – number of observations

p_a – partial vapor pressure of air, P_a

p_s – partial vapor pressure at the product surface, P_a

Q – heat generation, W/ m^3

Q_0 – heat generation at the surface of the product, W/ m^3

Q_r – heat generation through the radial side of the cylinder, W/ m^3

Q_z – heat generation through an axial end of the cylinder, W/ m^3

S – shape factor, m

t – time, s

T – temperature, K

T_a – ambient temperature, K

T_s – surface temperature, K

T_p – predicted temperature, K

T_o – observed temperature, K

V – product volume, m^3

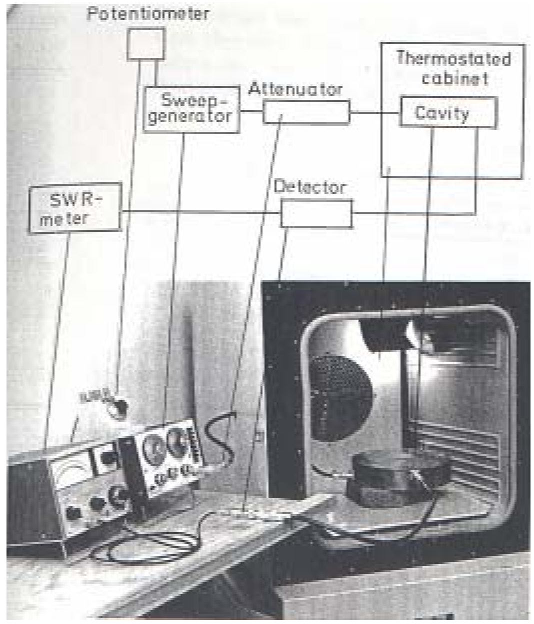
V_h – head space volume, m^3

V_m– vector function described by the magnetic filed distribution on the waveguide port.

APPENDIX B: Dielectric Properties Measurement Techniques - Figures

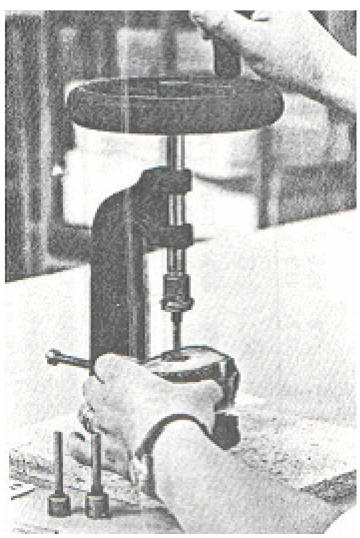
Open-ended coaxial probe

Open ended Probe Method – Coaxial Probe and Network Analyzer



Cavity Perturbation Technique – Measuring Circuit and Experimental Apparatus

(Ohlsson *et al.,* 1974)

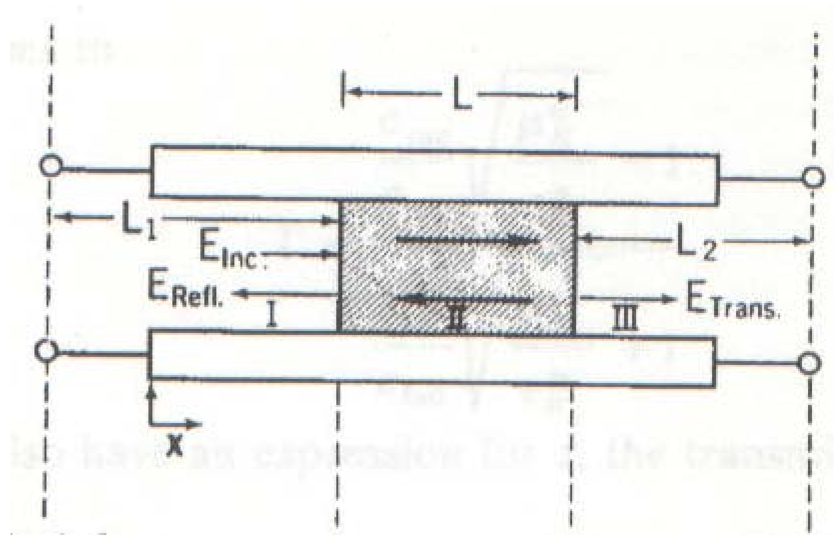


Inserting semi-frozen sample core into sample tube

Cutting sample core from semi-frozen food slab

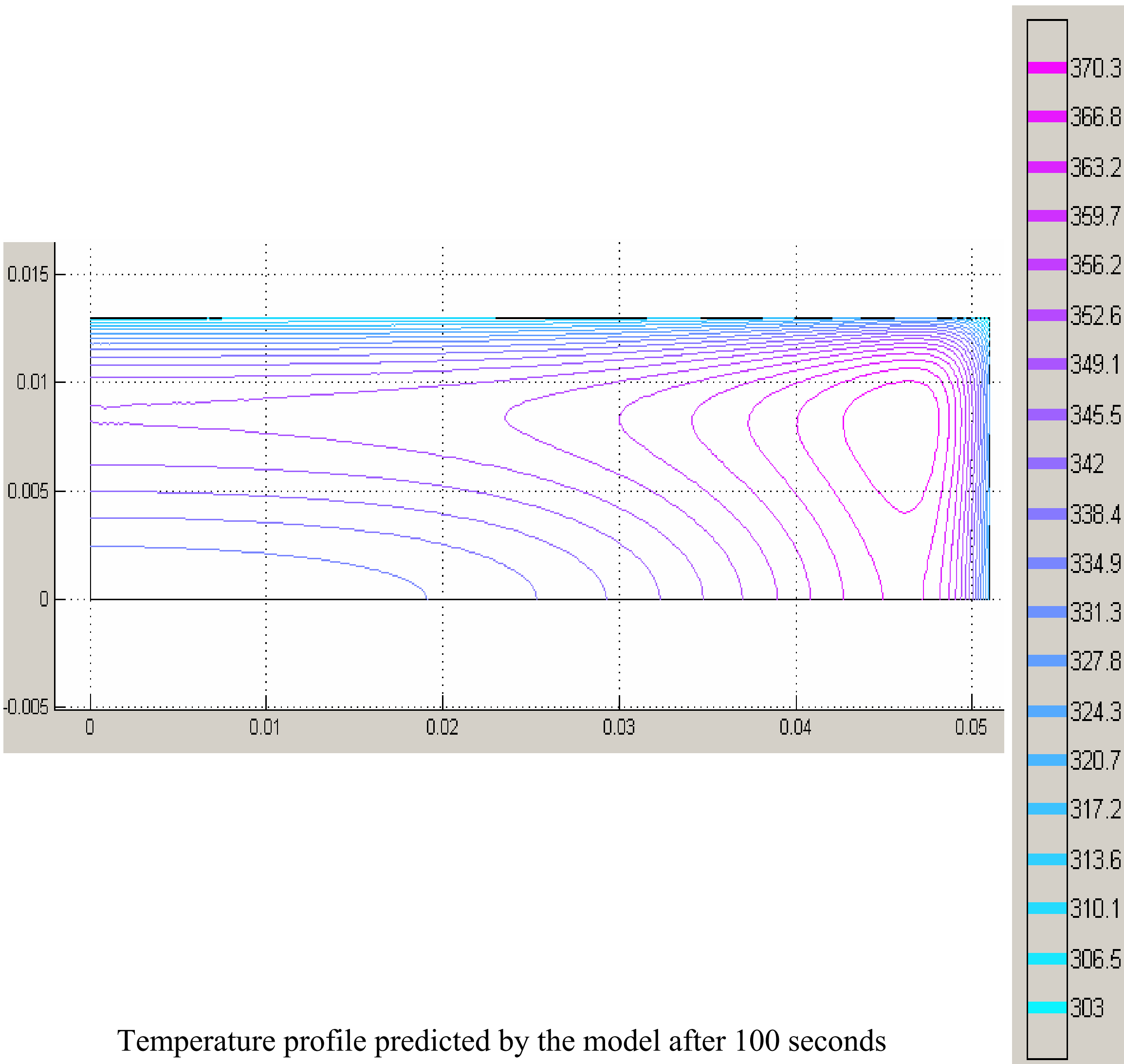
Sample Preparation for Cavity Perturbation Technique

(Bengtsson and Risman, 1971)



Transmission Line Method - A dielectric sample in a transmission line and the incident (inc) and reflected (refl) electric field distribution in regions I, II, and III. (Baker-Jarvis *et al.,* 1989)

APPENDIX C: Sample Model Output



Temperature profile predicted by the model after 100 seconds

APPENDIX D: Steps in using FEMLAB®

1. Start the FEMLAB®, a window called Model Navigator pops up.
2. From the Model Navigator, select the dimension required, for example 2D.
3. For heat and mass transfer models, double click on Chemical Engineering Module and then Axisymmetry and Energy Balance.
4. Under Energy Balance, select Heat Transfer and then Time-dependent problem.
5. A main window appears. From Options menu, axis can be set according to dimensions of the problem.
6. Then, go to Draw menu button and select Draw mode.
7. Again go to Draw menu and using the menu list, draw the required size and shape of the product.
8. Go to Boundary menu and select Boundary mode.
9. Again go to Boundary menu and click Boundary settings. A window pops up and using Domain Selection option, values at the boundary can be specified.
10. Next, select the Sub domain menu. Select Sub domain mode. Here, the values for the variables in the governing equations can be specified.
11. Use the Init tab to specify the initial condition. The type of element can be selected using Element tab.
12. Mesh menu allows mesh generation on the problem domain. It also has option to refine the mesh at the location of interest or the whole domain.

13. The final step is solving the problem using Solve menu. Using Solve Parameters and Time Stepping tab, output time and incremental time steps can be specified. Suitable algorithm to solve the time dependent problem can be selected from ODE/DAE solver drop down menu.

14. Under Options menu, equations can be specified to calculate variables using Add/Edit Expressions. If the variable is highly non-linear, Matlab® program can be used interactively to calculate the variable. For example, the following program was used for calculating Cp in the current model. The program uses interpolation function called 'spline.'

```
function yi = cp1(T)

x = [273 283 293 303 313 323 333 343 353 363 368 369 370 371 372 373 374
    375 375.5  376 376.5 377 377.5 378 379 380 381 382 383 385 387 389 391
    393 397 401 405];
y = [3254 3254.54 3262.81 3298.85 3397.87 3616.51 4050.77 4882.48 6501.99
    9862.04 12889.33 13671.05 14527.30 15466.66 16498.87 17634.99 18887.60
    23024 21809 20594 19379 18164 16949 15734 15610.4 15624.8 15639.2
    15653.6 15668 15696.8 15725.6 15754.4 15783.2 15812 15869.6 15927.2
    15984.8];
yi = interp1(x,y,T,'spline');
```

15. Multiphysics is another useful menu. Using Multiphysics menu, coupled problems can be solved. Additional models can be selected from the Multiphysics menu and the whole problem can be solved in a coupled manner.

16. User manuals and online resources at www.femlab.com would be very helpful.

VITA

Nishkaran Gunasekaran is from Dharmapuri, Tamil Nadu, India. He did his Bachelors of Engineering degree in Agricultural Engineering from the great Tamil Nadu Agricultural University (TNAU), India. He then worked as Instructor in a community college for one and half years. He entered the Biological Systems Engineering department of Virginia Polytechnic Institute and State University to work toward his Masters of Science in Food Engineering and completed his work in August 2002.