USING WHEY PROTEIN GEL AS A MODEL FOOD TO STUDY DIELECTRIC HEATING OF SALMON

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of YU WANG find it satisfactory and recommended that it be accepted.

Chair

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USING WHEY PROTEIN GEL AS A MODEL FOOD TO STUDY DIELECTRIC HEATING OF SALMON

Abstract

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The dielectric constant (ε') and loss factor (ε'') of whey protein gel with the addition of D-ribose (0.5%, 1%, and 1.5%, wet basis) and at different salt contents (0, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%, wet basis) as well as that of pink salmon fillets (*Oncornynchus gorbuscha*) were investigated over the frequency range of 1-1800 MHz at temperatures ranging from 20 to120 ^{o}C. D-ribose was added as a component of the whey protein gel model as a substrate for chemical marker formation, based on the knowledge that the color changes resulting from Maillard browning reactions involving ribose can be used to predict the location of cold spots in dielectric heated products subjected to commercial sterilization treatments (Kim and Taub 1993). The results show that in the Radio Frequency (RF) and Microwave (MW) ranges, the dielectric properties of whey protein gel containing 1% D-ribose and 0.2% salt were similar to the dielectric behavior of salmon fillets. The salt content had a major impact on the dielectric constant for salmon and whey protein at the lower frequencies. Whey protein gel after its composition has been adjusted to reflect properties of muscle foods or other products has potential to serve as a model food in terms of dielectric properties. Information obtained from this model food can be used for process development to predict the locations of cold and hot spots in real food systems during microwave and RF sterilization processes.

Key words: dielectric properties, salmon, whey protein gel, D-ribose, RF, microwave sterilization

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ABBREVIATIONS

ε^*	complex relative permittivity
ε_∞	relative permittivity (when the frequency is infinite high)
ε_s	the zero frequency related to permittivity
ε'	dielectric constant (real permittivity)
ε''	dielectric loss factor (imaginary permittivity)
Tan δ	loss tangent (tan $\delta = \varepsilon''/\varepsilon'$)
f	frequency (Hz)
f_c	critical frequency
τ	relaxation time
λ_0	free space wavelength
d_p	penetration depth(mm)
E	electric field strength (V/m)

CHAPTER 1

INTRODUCTION

Dielectric Heating and Thermal Sterilization

Dielectric heating, which includes radio frequency (RF) and microwave (MW) heating, can provides more rapid heating than is possible through conventional conductive heating, because of the interactions *(e.g.,* dipole rotation and ionic conduction) of food materials with electromagnetic waves (Datta and Hu 1992). Microwave heating is a well established procedure not only for the domestic preparation of meals, but also it is widely used industrially in food processing (Gabriel *et al.* 1998) most commonly for thawing and reheating applications. The volumetric heat generated by microwaves can significantly reduce the total heating time needed for commercial sterilization (Decareau 1985) and similar effects have been seen for microwave pasteurization processes (Al-Holy 2003).

However, many variables, such as variations in the applied electric field, type and distribution of food constituents, package size and dimensions, and the location of packages within a microwave or RF system, can still lead to non-uniform heating (Berek and Wickersheim 1988). When heating is not uniform, microorganisms could possibly survive in areas within the food that receive the least amount of thermal energy (cold spots) (Schiffmann 1990; Stanford 1990). Hot spots are areas where radiation is concentrated, and the product or the packaging becomes overheated or burned. Thus, to ensure adequate sterility for shelf-stable foods, it is necessary to determine the coldest and hottest locations within food packages during microwave sterilization processes.

It is important for food companies to accurately validate heat processes to determine the impact on food safety and quality. Failing to verify a process results in legal liability (Rasco 1997, 1999; Buzby *et al.* 2001). Process verification and the mapping of heat distribution in foods are difficult for dielectric heating processes. Such limitations include the fact that direct measurement of the product's time-temperature history for various points is not possible under some processing conditions (*e.g.,* continuous microwave sterilization food processes). In the case of dielectric heating, electronic sensors with metallic components cannot be used in microwave or radio frequency (RF) heating systems because they interact with electromagnetic waves giving misleading data.

For conventional thermal processes, heat is transferred from the heating medium (steam or water) to the interior of the food via conduction (solid foods) or convection (liquid foods), and the coldest location in the package is well defined, normally at the geometrical center in solid foods or about 1/5 from the bottom of the cans for liquid foods (Holdsworth 1997). However, in the case of microwave frequency heating, the coldest locations in a product are difficult to predict (Decareau 1985) because the heating patterns are dependent upon the interaction between microwave energy and substances within the food. Biologically, most foods are complex substances which commonly comprised of: carbohydrates, proteins, lipids, polar and ionic compounds (*e.g.,* water and salt). These different components behave differently in an electromagnetic field, and this can cause a food product to heat unevenly, which may adversely affect both sensory and microbiological quality of the treated food product.

Although charting temperature distribution within packaged foods during microwave sterilization is essential, it cannot be determined with a single-point or even variable point temperature measurements (Ohlsson 2001). To solve this problem, a novel solution was developed at Washington State University to determine heating patterns using a computer vision and chemical marker (M-2) system. The heat sensitive chemical marker M-2 that is formed via a Maillard reaction gives the product a brown color, the intensity of the brown color changes with the amount of heat a product receives following a first order reaction (Lau *et al.* 2003). The formation of this colored product can be quantified spectrophotometrically. Based upon this, a computer vision system which tracks the formation of the resultant colored product to map heating patterns of thermally treated chemically homogeneous food products could be developed (Pandit *et al.* 2005). Results of this method can be used to predict the heating pattern of food products of varying composition and for foods of different configurations.

The Chemical Marker Method and Its Use with Model Foods

The chemical marker method was documented by Kim and Taub (1993) from the United States Army Natick Research Center in Massachusetts. They developed this method to correlate heating intensity with the development of brown color formed through the Maillard reaction during heating processes above 95 ^{o}C. The chemical marker M-2 (4-hydroxy-5-methyl-3(2H) furanone) is formed by a reaction between D-ribose and amines through non-enzymatic browning reaction after enolization under low acid condition ($pH > 5$). The yield of M-2 can be used to detect the extent of a thermal treatment at any locations of processed homogeneous foods, presuming that reaction conditions are not substrate limiting. Monitoring this reaction in both mashed potato and whey protein gel model systems can be used to map heating patterns for homogeneous products during thermal processing.

In 1993, Kim and Taub used whey protein gel as a model food to study the uniformity of dielectric heating by a chemical marker method which has been modified for the studies described here. Whey protein was used because the amino acids (methionine, lysine, histidine, and arginine) it contains that lend themselves to formation of these chemical markers. In this study, whey protein was selected for the development of a model food to be used to predict the dielectric heating of salmon fillets or portions. Whey protein has the advantage over other possible choices as a model food: it can be obtained as a chemically well-defined homogeneous powder. When dispersed in water and cooked at 80 ºC for 40 minutes, whey protein forms a firm gel and can be easily cut into a desired shape to simulate a real food, (for example, salmon fillet, beef and chicken portions). The chemical composition of gels made from whey protein can be altered by adding salt for example, so that the gel has dielectric properties that closely match the target food. Another primary advantage of whey protein compared to another commonly used model food, mashed potato, which is also used for evaluation of chemical marker methods (Guan *et al.* 2004, Pandit *et al.* 2005), is that whey protein gels do not have the problem of diffusion of the marker in the whey-liquid phase from the potato solids during heating or separation of an aqueous phase. To model a solid food, a whey protein gel offers improvements since the marker does not diffuse out of it. It can also be cut into different shapes and placed into a sauce or dispersion to model entrée and stews.

The Microwave Heating Group at Washington State University (Pullman, WA) selected whey protein gel as a model food to predict the location of cold and hot spots in salmon fillets using a 915 MHz single-mode microwave sterilization process as a means of validating the thermal process for salmon fillets packaged in polymeric trays.

Developing a Microwave Sterilization Process for Salmon

Salmon is one of the most popular food fish in the world and Alaska is the largest producer of wild salmon worldwide. The annual harvest of Pacific salmon (*Oncorhynchus* spp.) from Alaska is over 300,000 metric tons (AGFG 2003). Canning is still commonly used to process salmon and has been used in Alaskan salmon industry for nearly100 years. The market for canned salmon is dropping as other types of salmon (fresh and frozen) become more popular now that the supply chains are in place to be able to distribute these products effectively. Developing new products from salmon that are shelf stable, and which would be attractive to new market segments is important for the salmon industry. Creating a microwaveable shelf stable salmon product is a new concept and could provide important economic opportunities for the Alaskan industry (Sathival *et al.* 2006). Microwave sterilization is a technology that provides an opportunity to develop a range of new products from salmon using intact fillets or portions, *e.g.*, an entrée comprised of a whole fillet that is ready to heat and consume without additional preparation. This is important since canned salmon products, although ready to eat, are not in a convenient form for the consumer. Normally canned salmon is not consumed directly from the can and requires that the consumer prepare a salad spread, loaf, *etc.* from it before it is eaten.

Developing a microwave sterilization process for salmon requires an understanding of how this product would respond during dielectric heating. The dielectric properties are one of the particular electromagnetic properties that significantly influence the microwave heating performance. The dielectric properties describe the interaction of RF and MW waves with food substances; they are a basis for modeling and simulation of dielectric heating of foods. So far, no research has been conducted on the dielectric properties of salmon fillet; particularly under conditions important for microwave sterilization. Limited information is available for any aquatic food products, with one of the few studies involving pasteurization of salmon caviar (Al-Holy *et al*. 2005). Given the technical difficulties of using chemical marker to study heating patterns in real food systems, such salmon, with their nature color that changes during thermal processes, an alternative has to be developed to predict how salmon would behave during microwave sterilization. Hence, a study using a whey protein gel model which had its dielectric properties altered to match salmon was conducted first as a way of determining important microwave processing parameters. Then these processing parameters were validated using salmon. In this study, a major objective was to obtain a better understanding of the dielectric behavior of pink salmon and how whey protein model systems could be used to develop effective dielectric heating processes for salmon and potentially other muscle foods.

Literature Review

Microwave energy is a form of non-ionizing electromagnetic radiation that generates heat in a dielectric material (Risman 1991; Meredith 1998). The application of microwave energy for heating foods was first patented in 1945 (Buffler 1993). Microwave dielectric heating has been studied for various applications, such as, to inactive enzymes (Copson 1954), blanch foods (Goldblith 1966), defrost, temper, or thaw products (Decareau 1985), bake, pasteurize, or sterilize food (Olsen 1965; Kenyon *et al.* 1971; Sale 1976), and evaporate, dry and freeze dry food products (Sunderland 1982). The microwave and RF frequencies used for food applications as well the heating in industrial, scientific, and medical applications are restricted (Buffler 1993). Of these, only 915 and 2450 MHz are commonly used in microwave food processing in USA, while 896 and 2450 MHz are the dominate frequencies in the United Kingdom and Europe.

Compared to retort cooking, microwave sterilization can bring foods to a higher temperature within a shorter time to reach commercial sterility. For example, in processing packaged foods pouches, instead of operating a retort at 125 °C for 13 minutes (Table 1), process with similar lethality could be conducted in 3 minutes at 128 °C, which means the heating time for packaged food can be reduced by 75%.

Table 1- Effect of Packaging and Process Temperature on C-value of a 225 Gram Pack of Solid Food (Ohlsson 1987)

Package	Dimensions (mm)	Process (°C)	Cook Time (min)	C-value
Can	73 diameter X 49	Retort 120	45	180
Foil Pouch	120 X 80 X 20	Retort 125	13	65
Plastic Pouch	120 X 80 X 18	Microwave 128	3	28

Theoretical Concepts Involved with Dielectric Heating

Microwaves are a form of electromagnetic energy, so are light and computer signals, all traveling at the speed of light (3×10^8 m/s). The difference among these forms of electromagnetic energy is the wavelength. Microwaves are located between 300 MHz to 300 GHz in the electromagnetic spectrum (Fig.1). Light waves are a few hundred billionths of a meter long; microwaves are about 12 million nanometers (12 centimeters) long. The electromagnetic waves, which include microwave, possess energy in the form of high-energy packets known as quantum energy (Knutson 1987). The quantum energy can break chemical bonds when the quantum energy exceeds the chemical bond 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 are a much longer wavelength, lower frequency, and lower energy compared to other electromagnetic waves, do not have enough energy to break chemical bonds (Knutson 1987). Microwaves also have insufficient energy to be considered ionizing radiation. However, microwaves have enough energy to alter how molecules can behave in solutions and biomaterials. Water is the primary component of food by weight. Polar molecules such as water have an uneven charge distribution, essentially with negatively and positive charged "ends". Polar molecules such as water will align themselves in an electromagnetic field and will respond to changes in field polarity. Since microwave field reverse field polarity millions of times per second, water molecules will rotate in response to these changes in field polarity. As a result, heat is then generated because of the molecular friction between dipole molecules. Additional properties of aqueous solutions in foods that are important during microwave heating include migration of charged particles, breakage of hydrogen bonds within the bulk structure of water, and ionic and electrostatic interaction between salt and other food components (Knutson 1987; Saltiel and Datta 1999; Lorenson 1990).

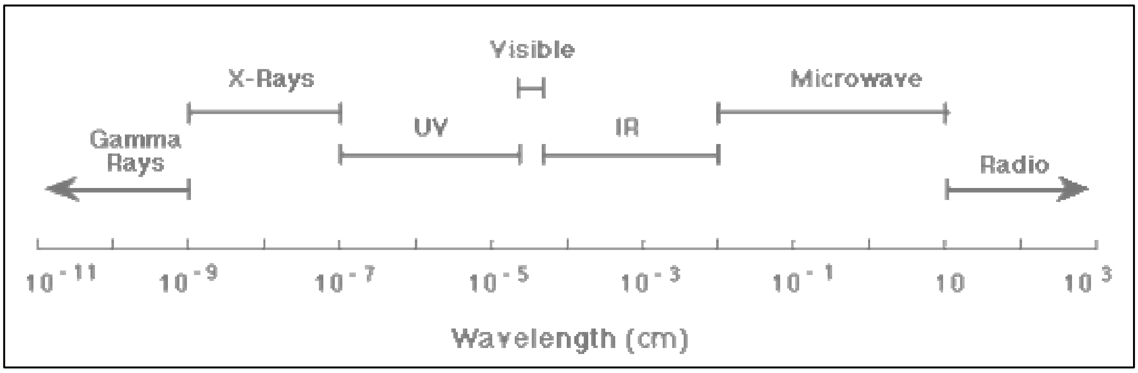

Figure 1- The electromagnetic spectrum

Microwave heating is considered to be a form of volumetric heating. The rate of heat generation per unit volume, *Q* (Equation 1), at a particular location in the food during microwave and radio frequency heating can be characterized by (Buffler 1993; Datta and Anantheswaran 2001):

$$Q = 2\pi f \varepsilon_0 \varepsilon^{''} E^2 \tag{1}$$

where E is the strength of electric field of the wave at that location, f is the frequency of the microwaves or the radio frequency waves, ε_0 the permittivity of free space (a physical constant), and ε'' is the dielectric loss factor representing the material's ability to absorb the wave.

The cooking speed of microwave results from the ability of microwaves to deposit more energy at greater depths (namely, greater penetration depths) in the food than can be achieved by conventional heating techniques (Bakanowski and Zoller 1984). The penetration depth (d_p) can be calculated using dielectric properties. Theoretically, it is defined as the depth below a large plane surface of a material at which the power density of a vertical collision, forward transmit plane electromagnetic wave has decayed by 1/e from the surface value (1/e is about 37 %). The following simplified formula can be used if tan δ (the ratio of ε" to ε' is called the dielectric loss tangent, tan δ = ε"/ε') is smaller than about 0.5, which gives 97% to 100% of accuracy (Risman, 1991 cited by Ryynänen 2002):

$$d_p = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{2}$$

where λ_0 is the free space wavelength, ε' is the dielectric constant and ε" is the dielectric loss factor.

In the case of an infinite inhomogeneous slab, the more exact formula should be used when tan δ is greater than 0.5 (Risman 1991, 1994):

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2}}\left(\varepsilon'\left[\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right]\right)^{-1/2} \tag{3}$$

or

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right]}} \tag{4}$$

where d_p is the penetration depth (cm), λ_0 is the free space wavelength, ε' is the dielectric constant, ε'' is the dielectric loss factor; *c* is the speed of light in free space (3.00×10^8 m/s) and *f* is the frequency of the microwaves or the radio frequency waves (Hz).

Reducing Non-Uniform Heating in Dielectrically Heated Foods

Dielectric heating of food can be uneven due to an uneven distribution of an electromagnetic (EM) field. Accordingly, hot and cold spots exist in the food (Anatheswaran *et al.* 1994). Understanding the non-uniform heating with respect to the dielectric properties is very critical and mathematical modeling is a vital tool to do this (Lorenson 1990; Anatheswaran *et al.* 1994). To reduce the effect of non-uniform heating, many efforts are being made. Domestic microwave ovens, for example, are normally designed with a mode stirrer, which is used to perturb the field distribution inside the oven. Also, the food is rotated on a motorized platter by reducing the concentration of power at certain places in the food (Pozar 1998). Moreover, providing sufficient holding time after the microwave heating gives time for heat conduction continue to transfer heat from the interior portion to the surface of the food and for more uniform temperatures to be reached (Gundevarapu *et al.* 1995).

Dielectric Properties of Foods

The ability of microwaves to heat food depends upon the dielectric properties, which are described by the dielectric constant and the dielectric loss factor (Nelson 1978, Schiffmann 1990). The dielectric constant measures the capability of food to store electric field energy. The dielectric loss factor measures the ability of food material to dissipate electrical energy as heat (Nelson *et al.* 2000). Dielectric properties for some of the common food materials are presented in Figs. 2 and 3. These two electromagnetic parameters of substances determine the interaction between the foods and electromagnetic energy and are key factors in modeling food behaviors as well as determining the efficiency of RF and MW heating. Knowing the dielectric properties of a given food is required to design an effective dielectric heating process since these parameters affect coupling and distribution of electromagnetic radiation during the heating process (Mudgett 1986).

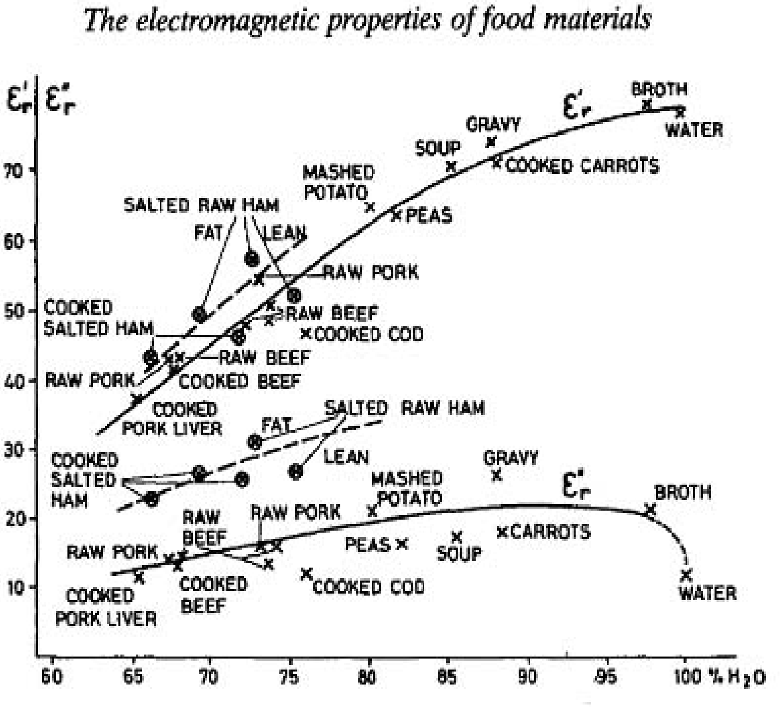

Figure 2- Relationship between water content and dielectric data at 20° C and 2.8 GHz (Bengtsson and Risman 1971)

Factors Influencing Dielectric Properties of Foods

The dielectric properties (dielectric constant ε' and dielectric loss factor ε'') are determined by the chemical composition and physical structure of foods. The dielectric properties vary with frequency, temperature, density, homogeneity, particle size, distribution and state of foods, fat content, moisture content and other food compositions (Ohlsson *et al.* 1974a, 1974c; Mudgett 1986, 1994; Datta *et al.* 1994). Most foods also contain dissolved ions that affect dielectric heating. Therefore, to obtain a better understanding of a food's behavior during dielectric heating, knowledge of dielectric properties of the target food is important and knowing these factors is critical if an effective dielectric heating process is to be developed.

The Influence of Water, Salt and Fat Content

Water, salt and fat content all influence the dielectric properties of foods. The relationship between water and fat content in many food substances has been reported by Bengtsson and Risman (1971), Ohlsson *et al.* (1974b), Ryynänen (2002). The primary role of fat appears to involve a dilution phenomenon, which means, if a given food has a high fat content, then its water content normally becomes low, and this would reduce both the dielectric constant and dielectric loss factors. The influence of water and salt (or ash) content depends up the mobility of these ions within the food matrix, accordingly, the dielectric behavior can vary, and the impact of the salt content on the dielectric properties of the food will depend on whether the migration of the water or salt are limited (Mudgett 1989) for example, by being chemically bound to macromolecules or within cell membranes, or if their movement is restricted in some other manner, *e.g.,* by association within cells, micelles or encapsulation. Most foods are composed of 50-90% water, and it is the free water that contributes predominantly to the heating effect, which is one reason dielectric heating is highly suitable for cooking. For low moisture foods, the relaxation of bound water becomes the major contributor to dielectric heating at MW and RF frequencies range (Tang *et al.* 2002). A relationship between water content and dielectric data at 20° C and 2.8 GHz are shown in Fig. 2; points for high salt material are noted (Bengtsson and Risman 1971). "Salts dissolved in aqueous solutions act as conductors in an electromagnetic field. They simultaneously depress the dielectric constant and elevate the dielectric loss factor" (Ryynänen 2002).

The Influence of Frequency

For moist materials, ionic conductivity plays a major role at lower frequencies (*e.g.,* below 200 MHz), whereas both ionic conductivity and the dipole rotation of free water are important at microwave frequencies (Tang 2005). The conductivity losses caused by the dipolar relaxation are more significant when moving towards higher frequencies (Bengtsson and Risman, 1971; Ohlsson *et al.* 1974a). At higher microwave frequencies, only salty foods show an increase in ε'' with temperature but at lower microwave frequencies there is a general increase in ε'' (Bengtsson and Risman 1971; Ohlsson *et al.* 1974c). At lower microwave frequencies, the ε'' increases with falling frequency (Jain and Voss 1988, Guan *et al.* 2004) for foods with high water content (above 70%), this is caused by the conductivity losses.

In the case of pure liquids with polar molecules (*e.g.,* water or alcohols), polar solvent and the permittivity of free water normally behaves frequency dependent, which can be presented by the Debye model equations (Tang 2005):

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} - j\frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \qquad (5)$$

and

$$\varepsilon^{'} = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \omega^2\tau^2} \tag{6}$$

$$\varepsilon^{"} = \frac{(\varepsilon_s - \varepsilon_{\infty})\omega\tau}{1 + \omega^2\tau^2} \tag{7}$$

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon^{"} \tag{8}$$

where ε_{∞} is the relative permittivity (when the frequency is infinite high), ε_s is the zero frequency related to permittivity, and τ is the relaxation time, ε' is the dielectric constant, ε'' is the dielectric loss factor.

The dielectric loss factor ε'' reaches the maximum at a so-called critical frequency f_c (where, $f_c = \frac{1}{2\pi\tau}$). The critical frequency can be influenced by molecular weight. Larger molecules usually are less mobile and have long relaxation compared to smaller molecules (*e.g.,* water molecules are much smaller than that of alcohols); therefore, critical frequency decreases with rising molecular weight. For instance, as the weight from one carbon alcohol (CH_3OH) to five carbon alcohols ($C_5H_{11}OH$), f_c decreases from about 5000 to 200 MHz, while ε'' decreases from 14 to about 4. Compared to alcohols, water has a much larger dielectric constant and maximum dielectric loss factor (Tang 2005).

The Influence of Temperature

The dielectric properties of foods are often temperature dependent (Tang *et al.* 2002). Therefore, understanding the effect a wide range of temperatures has on the dielectric properties of food materials is vitally important to properly predicting heating behavior. The subsequent temperature rise in the food depends on the duration of heating, the location in the food, convective heat transfer at the surface, and the extent of evaporation of water inside the food and at its surface. The dielectric properties of foods at low temperatures are influenced by concentrations of mobile water and ions. For instance, frozen foods with a high water content, a sharp increase in ε' and ε'' is observed in the melting zone and, after melting, ε' decreases with further temperature increase (Bengtsson and Risman 1971).

Temperature distribution in microwave dielectric heating is controlled by a number of interrelated factors such as microwave field pattern, composition, density, size, shape, thickness of the food and food packaging. The poor control of heat uniformity leads to the survival of microorganisms in the processed food and results in a poor quality product, possibly one that is unsafe as well. Another disadvantage is the difficulty of monitoring and predicting microwave heating patterns in the microwave cavity as well within the tested food product. Validating microwave processes is critical. Before a microwave sterilization or pasteurization process can be accepted as a scheduled process by the US Food and Drug Administration (FDA), and then accepted and adopted by the US food industry, two issues need to be addressed: the development of a system that can deliver predictable and uniform heating to food systems; and the development of a reliable monitoring procedure to ensure the safety of the microwave processed food (Lau *et al.* 2003).

Objectives

The overall objective of this research was to study microwave sterilization processes by better understanding of the dielectric behavior of model food and real food systems to ensure adequate sterility for shelf-stable foods.

The specific objectives were:

(a). Find the composition of whey protein that would most closely resemble the dielectric behavior of frozen/thawed pink salmon.

(b). Determine if a whey protein gel could be used as a model food to model microwave sterilization processes for a shelf-stable commercially sterile salmon product.

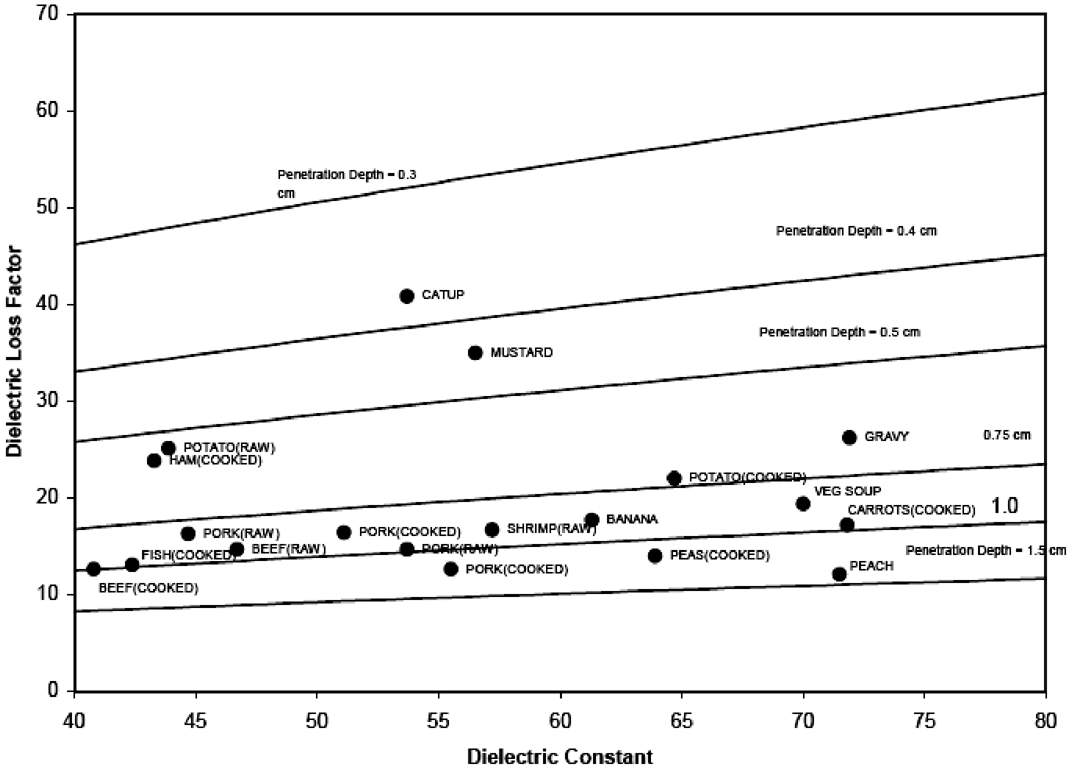

Figure 3 - Food map for dielectric properties (Engelder *et al.* 1991)

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CHAPTER TWO

DIELECTRIC PROPERTIES OF SALMON FILLETS AS A FUNCTION OF TEMPERATURE AND COMPOSITION

ABSTRACT

The dielectric properties of Alaska pink salmon (*Oncornynchus gorbuscha*) fillets at four positions (anterior, middle, tail, and belly) were measured at 27, 433, 915 and 1800 MHz from 20 to 120 °C. Fat, moisture content, ash and water activity were also determined. Equations were developed to relating dielectric properties of pink salmon as function of temperature. The four parts of pink salmon fillet (anterior, middle, tail, and belly) exhibited a similar trend for dielectric constant and loss factors as a function of temperature (20-120 °C) at 915 MHz. With the increasing of temperature, dielectric constant decreased while the dielectric loss factor increased slightly for all the cases of four parts of salmon fillets at 915 MHz. Compositional differences are reasons for the differences observed in the dielectric properties. There are small differences in fat content with the belly having a higher fat content and lower ash content compared to other parts of the fillet.

Keywords: dielectric properties, dielectric constant, loss factor, salmon, temperature dependence, dielectric heating

INTRODUCTION

How a product behaves during dielectric heating depends upon the dielectric properties of the material, food composition, physical state of water in the food, the thermal process temperature and frequencies evaluated. In conventional thermal processes, slow heat conduction from the heating medium to the coldest-spot in a solid food often results in treatment of the material at the periphery of the container that is far more severe than that required to achieve commercial sterility (Meredith 1998). In dielectric heating, the heating rate and temperature distribution within the food are controlled by the dielectric properties of the material to be treated.

Dielectric properties are a measurement of how food interacts with electromagnetic energy. Complex relative permittivity is defined as $\varepsilon^* = \varepsilon' - j\varepsilon''$, where the real part is the dielectric constant (ε') and the imaginary component is the dielectric loss factor (ε''). The dielectric constant ε' is a measure of the ability of the material to store electromagnetic energy. The loss factor ε'' reflects the ability of the food to dissipate electromagnetic energy into heat (Mudgett 1994). These two parameters are important in determining power absorption and penetration depth and the temperature profile within the sample as it heats.

The dielectric constant ε' increased sharply with the increasing of temperature at the low frequency range ($f < 400$ MHz) for most foods, this is due to the greater importance of conductivity losses at lower frequencies (Bengtsson and Risman 1971, Guan *et al.* 2004). Losses caused by the dipolar relaxation are more important when moving towards higher frequencies. Over high frequencies, the conductivity is usually quite independent of frequency (Ohlsson *et al.* 1974).

The temperature dependent dielectric properties for a wide range of foods have been well documented. For example, Tran and Stuchly (1987) measured the dielectric properties of uncooked beef, beef liver, chicken and salmon at frequencies from 100 to 2500 MHz for temperatures between 1.2 °C and 65 °C. Sun *et al.* (1995) developed equations of a series of foods including meat as a function of temperature, moisture and ash content up to 70 °C. Wang *et al.* (2003) conducted research on the dielectric properties of cooked macaroni noodles, cheese sauce, macaroni cheese, and whey protein gel over a temperature range from 20 to 121.1 °C. Guan *et al.* (2004) investigated the dielectric behavior of mashed potatoes at temperature from 20-120 °C within microwave and radio frequency range. Notwithstanding, no previous research has dealt with the dielectric behaviors of fish at commercial sterilization temperatures, or has taken into consideration how the compositional or structural differences across a salmon fillet could affect dielectric properties. Furthermore, of the muscle foods tested, little if any reliable information has been provided as to the storage or treatment history (*e.g.,* age of product, whether product had been previously frozen), composition or anatomical characterization of the tissue examined. There is a general lack of dielectric properties data for products at sterilization temperature 121.1 °C, in particular for commercially important aquatic foods. In this study, the dielectric properties of pink salmon at a temperature range from 20-120 °C were investigated.

Exposure of fish muscle to heat causes protein denaturation including melting of tissue collagen. The native structure of the muscle is lost and undergoes several changes, for example, muscle shrinkage, tissue hardening, and release of intracellular water and soluble constituents that includes both polar molecules and ions (Hamm and Deatherage 1960; Bouton *et al.* 1976; Bowers *et al.* 1987). Water is the major constituent of fish muscle tissue. Fish muscle has more water than terrestrial muscle foods. There is essentially no carbohydrate, and variable amounts of fat (Weatherly and Gill 1987). The live weight of the majority of fish usually consists of 70-80%, water, on a wet basis (wb); 20-30% proteins, wb; 2-12% fat, wb (Love 1980). However, these values vary considerably within and between species and also with size, gender, sexual maturity and fecundity, feeding conditions, time of year, water temperature and salinity (Weatherly and Gill 1987; Shearer 1994). The distribution of these constituents among the various organs and tissues of the body may also show considerable differences. The compositional effect on the dielectric properties of food is complex and yet not well defined. For instance, Calay *et al.* (1995) reported that the dielectric constant appears to consistently increase with moisture content for most foods. Guan *et al.* (2004) observed that dielectric constant changed little within the tested moisture range (0.8%-2.8%) in their study. Feng, Tang and Cavalieri (2002) indicated that dielectric constant of red delicious apples (*Malus domestica Borkh*) increased with increasing temperature at 915 and 1800 MHz when the moisture content of apples was less than 70%, and decreased when moisture content was more than 70%. The effect on the dielectric loss factor by moisture content is not clearly defined indicating that other compositional factors play an important role. For example, the dielectric loss factor has been reported to increase (Bircan and Barringer 1998; Nelson 1978; Van Dyke *et al.* 1969), decrease (Guan *et al.* 2004), increase at 27 and 40 MHz but relatively little changes at 915 and 1800 MHz (Wang *et al.* 2003), be constant (Padua 1993; Roebuck *et al.* 1972), or peak at a certain moisture content (Roebuck *et al.* 1972; Mudgett *et al.* 1980; Padua 1993; Funebo and Ohlsson 1999).

The dielectric properties of foods are temperature dependent (Nelson 1992, Wang *et al.* 2003, Guan *et al.* 2004), and studies must be conducted over the wide range of temperatures experienced by the product during thermal processing to predict dielectric heating behavior.

OBJECTIVE

The primary objective of this study was to measure the dielectric properties for different sections of pink salmon fillet from 20 to 120 °C. Predictive equations were developed at different temperatures and frequencies. The effect of compositional changes (fat, ash content, and either moisture content or water activity) was determined.

MATERIALS AND METHODS

Salmon Fillet Sample Preparation

Samples of 12 deep frozen pink salmon fillets (*Oncornynchus gorbuscha*, female, deep-skinless, boneless) were used for dielectric properties measurement. The fish samples were fresh wild Alaska pink salmon from the same catch harvested in Aug., 2005 near Kodiak, Alaska, provided by Ocean Beauty Seafood, Inc. with an average weight of 1.35 ± 0.1 kg and were of similar size (370 ± 10 mm in length and 120 ± 10 mm in width). The fish were filleted and deep skinned immediately after slaughter and then gutted, iced, stored (-31 ^{o}C) and shipped overnight to Washington State University, Pullman, WA. Frozen fish fillets were layered in a styrofoam shipping container with a plastic fold-over liner. Gel ice was included inside the container to keep the product frozen during shipment. Upon arrival, they were stored at -30 ^{o}C. Fish samples were defrosted overnight before measurements were taken. Fillet were subdivided into four sections: ‘anterior’, ‘middle’, ‘tail’, and ‘belly’ (as shown in Fig. 1).

Fat Content, Ash and Moisture Determinations

The flesh from each part of the salmon fillet was homogenized and analyzed separately in triplicate for moisture, fat, ash and water activity. Samples covered a fat content range of 1.67 to 2.17% (wet basis), moisture range of 74.97 to 76.14% and an ash range of 4.78 to 5.34% (Table 1). Ash content was determined by a dry ashing method at 550 °C in a muffle oven (Thermolyne, Dubuque, Iowa, U.S.A.) according to AOAC (1995), Part 942.05. The moisture content was determined by drying in a vacuum oven (National Appliance Co., Skokie, Ill., USA) according to AOAC (1995), Part 934.06, for 6 hours at 75 °C and 65 mmHg. Fat content was determined by Modified Folch Method. Water activity was determined using a water activity analyzer (CX-2, Decagon Devices Inc., Pullman, Wash., U.S.A.). Mean values for fat, moisture, ash and water activity were compared using t-tests (Microsoft Excel, 2003)

Experimental Set up and Dielectric Properties Measurement

The dielectric properties analysis was carried out by using an Agilent 4291 B Impedance analyzer and a custom built temperature control test cell (Wang *et al.* 2003) connected to an oil bath (PolyScience Products, Niles, Ill., USA). The system was calibrated before each independent measurement to avoid possible variations in the connections, ambient temperature and other factors that might affect the system's performance. The first measurement was made when the temperature reading inside the sample stabilized at 20 °C. A temperature range of 20-120 °C was measured in 10 °C increments at between 1 and 1800 MHz. It took about 8 to 10 min for the oil bath to raise the temperature of the sample with a 10 °C increase. The entire run took about 2 to 3 hours. All measurements were performed in triplicate, with new pink salmon fillet samples, which were cut by a metal cutter (1 inch in diameter, 4 inches in length) for loading into the temperature controlled test cell.

Table 1- Water activity, fat, moisture and ash content of pink salmon samples (on a wet weight basis)

Sample Position	**% Fat**	**% Moisture**	**a_w**	**% Ash**
Anterior	$1.67 \pm 0.01^{a*}$	75.25 ± 0.18^{a}	0.99 ± 0.01^{a}	5.34 ± 0.06^{a}
Middle	1.66 ± 0.01^{a}	74.97 ± 0.52^{a}	1.00 ± 0.01^{a}	5.28 ± 0.04^{a}
Tail	1.67 ± 0.02^{a}	76.14 ± 0.25^{a}	0.99 ± 0.01^{a}	4.98 ± 0.03^{a}
Belly	2.17 ± 0.01^{b}	75.69 ± 0.09^{a}	1.00 ± 0.01^{a}	4.78 ± 0.08^{b}

* Different letters within a column indicate that means are significantly different ($P<0.05$)

Table 2- Comparison of raw pink salmon fat content (Modified Folch Method) with literature data (on a wet weight basis)

Salmon Fillet Position	**% Fat Content**	
	Measured	**Literature Values**
Anterior	1.67 ± 0.01	1.5±0.1(Head)*
Middle	1.66 ± 0.01	0.6-2.1(Smolt)**
Tail	1.67 ± 0.02	2.2-5.4(Adult)
Belly	2.17 ± 0.01	

* From Sathivel *et al.,* 2006

** From Iverson *et al.,* 2002

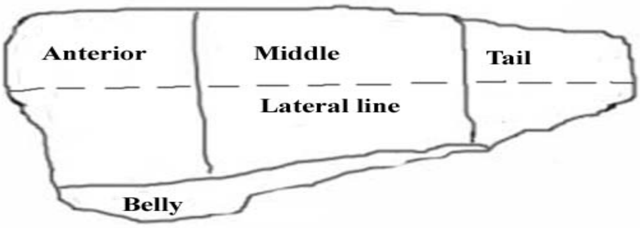

Figure1 - Schematic showing parts the pink salmon fillets used for analyses

Table 3- Mean ± standard deviation of dielectric properties[a] for pink salmon[b] at four positions

Sample	T (°C)		27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
Anterior	20	ε'	97.94 ± 9.33	87.56 ± 8.80	59.37 ± 7.61	55.14 ± 6.68	51.72 ± 6.28
		ε''	430.57 ±79.98	296.26 ±53.87	36.43 ± 5.85	22.59 ± 4.05	17.42 ± 2.68
	40	ε'	105.37 ±8.94	92.62 ± 8.30	58.64 ± 6.51	54.16 ± 5.79	50.49 ± 5.20
		ε''	603.63 ±110.44	413.93 ± 74.33	48.34 ± 7.80	27.60 ± 4.58	18.96 ± 2.78
	60	ε'	117.10 ±12.11	100.75 ± 10.91	56.62 ± 7.22	51.38 ± 6.45	47.47 ± 5.80
		ε''	766.06 ±157.87	525.49 ±106.28	60.76 ± 10.98	33.01 ±5.92	21.03 ± 3.53
	80	ε'	128.44 ±17.36	109.09 ± 15.28	55.17 ± 8.44	48.91 ± 7.26	44.77 ± 6.33
		ε''	877.77 ±227.92	603.01 ± 154.28	70.39 ±15.96	37.72 ±8.07	23.10 ± 4.72
	100	ε'	133.81 ±19.12	112.81 ± 16.60	54.35 ± 9.11	47.47 ± 7.05	43.36 ± 5.69
		ε''	1048.00 ±309.78	717.90 ± 209.30	82.55 ± 21.05	43.99 ± 9.74	25.74 ± 6.02
	120	ε'	139.61 ±20.06	116.82 ± 17.31	55.14 ± 10.01	47.13 ± 7.38	42.33 ± 5.80
		ε''	1305.26 ±434.96	890.81 ± 292.90	100.12 ± 28.95	52.89 ± 13.35	30.33 ± 8.01
Middle	20	ε'	94.72 ± 1.16	85.29 ± 0.89	60.75 ± 0.44	56.95 ± 0.63	53.75 ± 0.76
		ε''	458.32 ± 28.25	313,86 ± 18.38	37.42 ± 1.21	22.77 ± 1.22	17.80 ± 0.56
	40	ε'	101.23 ± 3.13	89.25 ± 1.92	59.50 ± 1.13	55.59 ± 0.99	52.39 ± 1.33
		ε''	650.04 ± 85.35	443.81 ± 56.60	49.96 ± 4.37	28.07 ± 2.68	19.42 ± 1.26
	60	ε'	115.54 ± 5.17	99.09 ± 2.81	58.43 ± 1.52	53.70 ± 1.68	50.17 ± 2.10
		ε''	850.75 ± 155.75	581.40 ± 103.98	64.65 ± 8.33	34.76 ± 4.24	22.32 ± 1.99
	80	ε'	129.52 ± 3.19	109.04 ± 2.95	57.08 ± 0.70	51.51 ± 1.08	47.94 ± 1.65
		ε''	1001.68 ± 185.92	685.44 ± 123.62	76.83 ± 9.30	40.65 ± 4.22	24.64 ± 2.09
	100	ε'	137.76 ± 5.45	114.41 ± 2.34	56.71 ± 1.74	50.75 ± 1.86	47.00 ± 2.56
		ε''	1241.43 ± 313.97	847.59 ± 209.10	93.53 ± 16.69	49.03 ± 7.36	28.10 ± 4.44
	120	ε'	147.37 ± 13.24	119.67 ± 2.30	57.91 ± 2.84	50.74 ± 2.92	46.59 ± 3.69
		ε''	1594.12 ± 482.08	1085.17 ± 23.49	116.79 ± 26.55	60.41 ± 11.76	34.12 ± 6.91
Tail	20	ε'	101.43 ± 2.50	90.85 ± 3.22	63.70 ± 3.58	59.53 ± 3.34	56.18 ± 3.46
		ε''	479.39 ± 36.31	328.63 ± 23.43	39.33 ± 1.30	24.35 ± 1.24	18.91 ± 1.18
	40	ε'	108.68 ± 3.25	95.46 ± 3.79	62.09 ± 3.93	57.74 ± 3.81	54.41 ± 3.95
		ε''	646.88 ± 71.88	442.56 ± 47.05	50.81 ± 3.54	28.95 ± 1.99	20.34 ± 1.74
	60	ε'	123.03 ± 3.76	105.50 ± 3.77	60.84 ± 4.08	55.73 ± 4.21	52.11 ± 4.36
		ε''	840.86 ± 119.70	575.67 ± 78.75	65.33 ± 5.62	35.35 ± 2.54	23.01 ± 1.98
	80	ε'	137.86 ± 3.86	116.32 ± 4.37	59.07 ± 3.58	52.64 ± 3.60	48.67 ± 3.94
		ε''	955.87 ± 130.62	655.92 ± 86.81	75.75 ± 6.94	40.35 ± 3.43	25.20 ± 2.40
	100	ε'	145.61 ± 3.81	121.92 ± 4.30	58.04 ± 2.79	50.71 ± 2.90	46.63 ± 3.64
		ε''	1104.64 ± 103.35	757.13 ± 69.40	87.24 ± 5.75	46.35 ± 3.24	27.71 ± 2.40
	120	ε'	152.81 ± 3.09	126.93 ± 3.46	58.31 ± 1.80	49.51 ± 2.38	45.19 ± 3.30
		ε''	1334.53 ± 82.54	912.03 ± 55.95	102.97 ± 4.46	54.68 ± 3.00	31.94 ± 3.04
	20	ε'	97.01 ± 6.87	85.18 ± 4.29	57.76 ± 2.00	54.42 ± 2.11	50.90 ± 1.42
		ε''	378.41 ± 11.75	260.74 ± 6.93	32.71 ± 0.48	20.18 ± 0.22	16.06 ± 0.21

Belly	40	ε'	107.57 ± 9.03	91.84 ± 5.91	56.28 ± 1.35	52.56 ± 1.02	49.30 ± 0.35
		ε"	523.45 ± 32.09	359.98 ± 20.76	43.10 ± 0.99	24.70 ± 0.34	17.27 ± 0.54
	60	ε'	122.68 ± 8.66	102.36 ± 5.12	55.49 ± 0.70	50.86 ± 0.98	47.40 ± 0.92
		ε"	677.35 ± 58.76	466.01 ± 38.35	55.17 ± 2.39	30.24 ± 1.01	19.54 ± 0.65
	80	ε'	138.26 ± 6.31	113.77 ± 2.91	55.03 ± 1.15	48.99 ± 1.80	45.13 ± 2.02
		ε"	790.80 ± 110.75	544.86 ± 73.38	65.46 ± 5.86	35.36 ± 2.78	21.96 ± 1.35
	100	ε'	148.26 ± 7.00	120.64 ± 3.12	55.02 ± 0.90	47.65 ± 1.88	43.54 ± 2.28
		ε"	956.69 ± 139.53	657.49 ± 93.12	77.66 ± 7.54	41.63 ± 3.52	25.34 ± 1.63
	120	ε'	158.71 ± 9.02	127.59 ± 3.76	55.41 ± 0.17	46.82 ± 1.73	43.56 ± 3.96
		ε"	1178.25 ± 199.19	807.07 ± 133.29	92.88 ± 11.45	50.81 ± 6.98	30.62 ± 3.52

[a.] ε' is the dielectric constant and ε'' is the dielectric loss factor.

[b.] Results of each position of pink salmon fillet are the mean values based on at least three independent trials.

RESULTS AND DISCUSSION

The results of the dielectric properties of pink salmon fillet for four positions at Radio frequency and MW waves range at four Federal Communications Commission for Communications (FCC) allocated frequencies (27, 40, 433, 915 MHz) for industrial heating and at the maximum measured frequency (1800 MHz) are given in Table 3.

Dielectric Constant

At a temperature scale from 20 to 120 °C, the dielectric constant (ε') of pink salmon fillet (overall average) continuously increased with temperatures at low frequencies (27 and 40 MHz), but moderately decreased at high frequencies (433, 915 and 1800 MHz) as shown in Fig. 2 and Table 3. At 27 MHz, for example, the dielectric constant for overall average of pink salmon $\varepsilon' = 97.78$ for 20 °C, $\varepsilon' = 149.63$ for 120 °C, respectively. The difference between the two temperatures is 51.85. It was also observed at 40 MHz that the difference between the dielectric constant at 20 and 120 ^{o}C is about 36. While at 915 MHz, $\varepsilon' = 56.51$ for 20 ^{o}C, $\varepsilon' = 48.55$ for 120 ^{o}C, respectively. It shows a small difference between 20 and 120 ° C, which is about 7.96. The reduction of dielectric constant may be due to the dispersion of water molecules at higher frequencies (Feng *et al.* 2002), increasing the medium temperature causes an increase in intermolecular vibration which in turn depresses the dielectric constant (Tang 2005), while at low frequencies (*e.g.,* <200 MHz), ionic and molecular dominate the translation mechanism and increases with temperature in accordance with the kinetic theory of molecular translation (Tang 2005).

Another phenomenon was observed during analyzing the dielectric properties data. At any particular temperature within the range from 20 to 120 °C, the dielectric constant at 915 MHz was larger than the one at 1800 MHz. The microwave frequency affected the dielectric properties have a similar fashion as reported by Tannka (1991), Wang *et al*. (2003), Guan *et al*. (2004).

Salmon was a high moisture content (*e.g.,* >70%), water molecules absorb the majority of the EM energy and dissipate it through dipolar rotation (Ohlsson *et al*. 1974; Nelson and Bartley 2002). Therefore, it is reasonable that salmon would have high dielectric constant and a high dielectric loss.

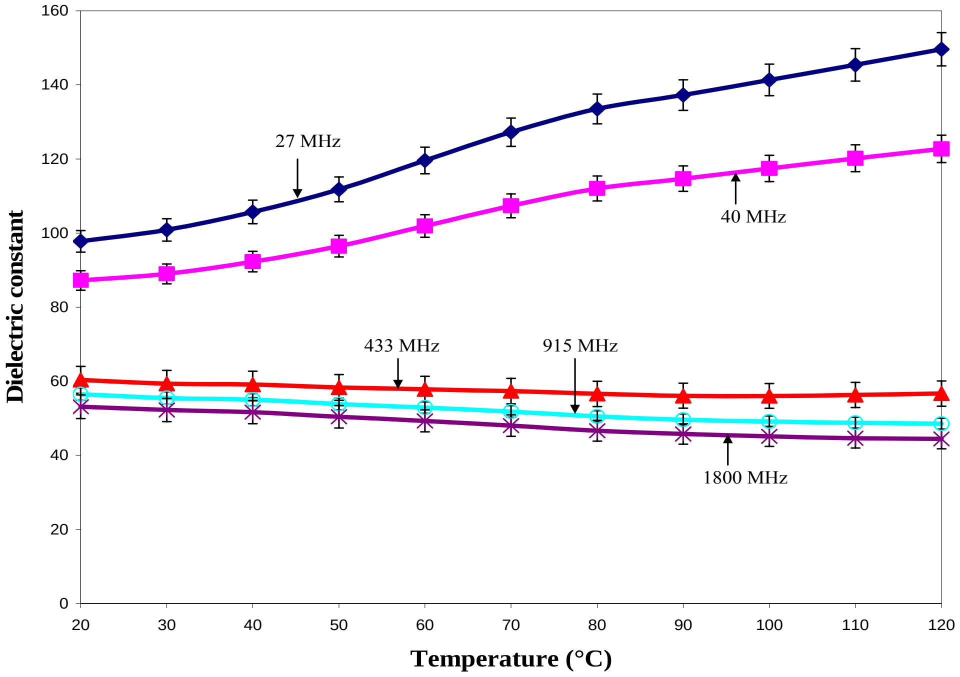

Figure 2- Change of dielectric constant of pink salmon (overall average) with temperature at 5 frequencies

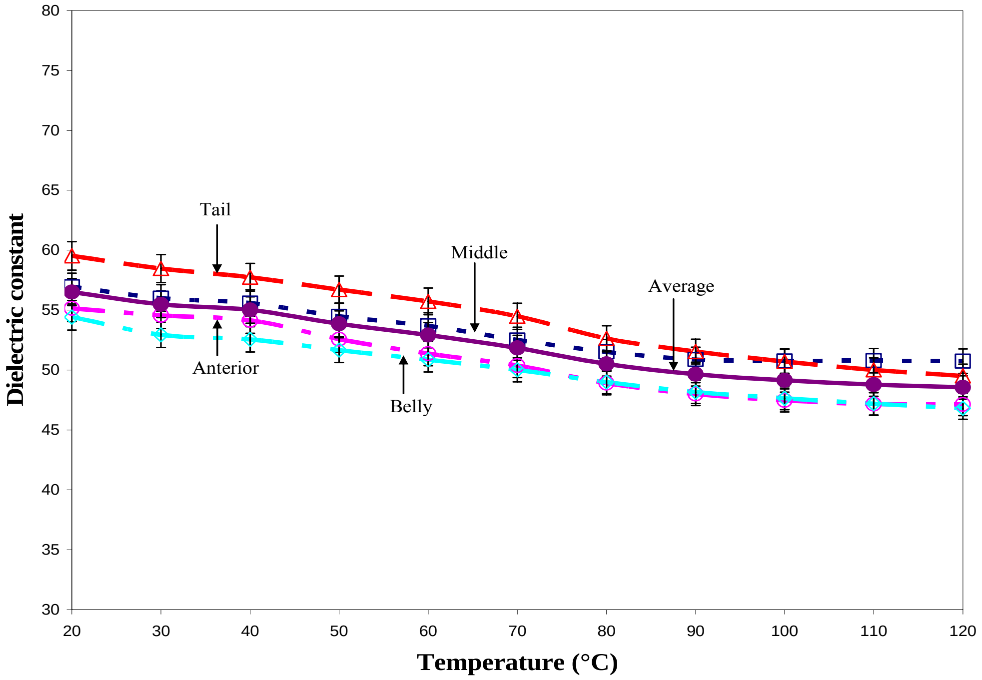

Figure 3- Dielectric constant of pink salmon at four positions as a function of temperature at 915 MHz

Dielectric Loss factor

Dielectric loss factor (ε''**)** could be effected by two components: dipole loss and ionic loss. Dipole loss results from the rotation of water dipoles and decreases with temperature, while ionic loss results from migration of ions and the ionic loss component increases with temperature at 915 and 2450MHz (Tang *et al.* 2002; Wang *et al.* 2003, cited by Al-Holy *et al.* 2005). The ε'' increased sharply with the increasing of temperature from 20 to 120 °C at 27 and 40 MHz (Fig. 4a and 4b). This is caused by the fact that the ionic conductivity predominantly affects the dielectric loss factor at low frequencies (*e.g.,* f< 200 MHz) (Guan *et al.* 2004; Wang *et al.,* 2003). The ε'' increased moderately (as shown in Fig.5) at 433, 915 and 1800 MHz, which suggested that, when moving towards higher frequencies (*e.g.,* f> 400 MHz), the effect of the dipole rotation of water molecules becomes more important since water is the major component in muscle foods contributing to the dielectric properties (Ryynänen 1995). In addition, with the increasing temperatures, hydrogen bonds formation rate might be lower depressing ε'' value as temperature increases (Bengtsson and Risman, 1971; Ohlsson *et al.* 1974; Ohlsson, 1987, Al-Holy *et al.* 2005).

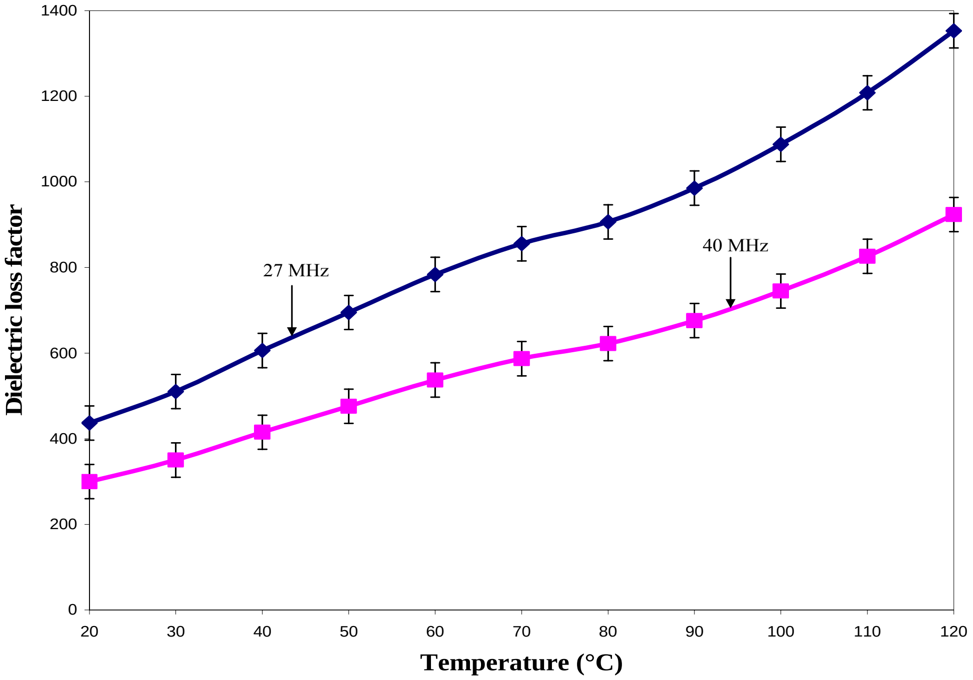

Figure 4a- Changes of dielectric loss factor of pink salmon (overall average) with temperature at 27 and 40 MHz

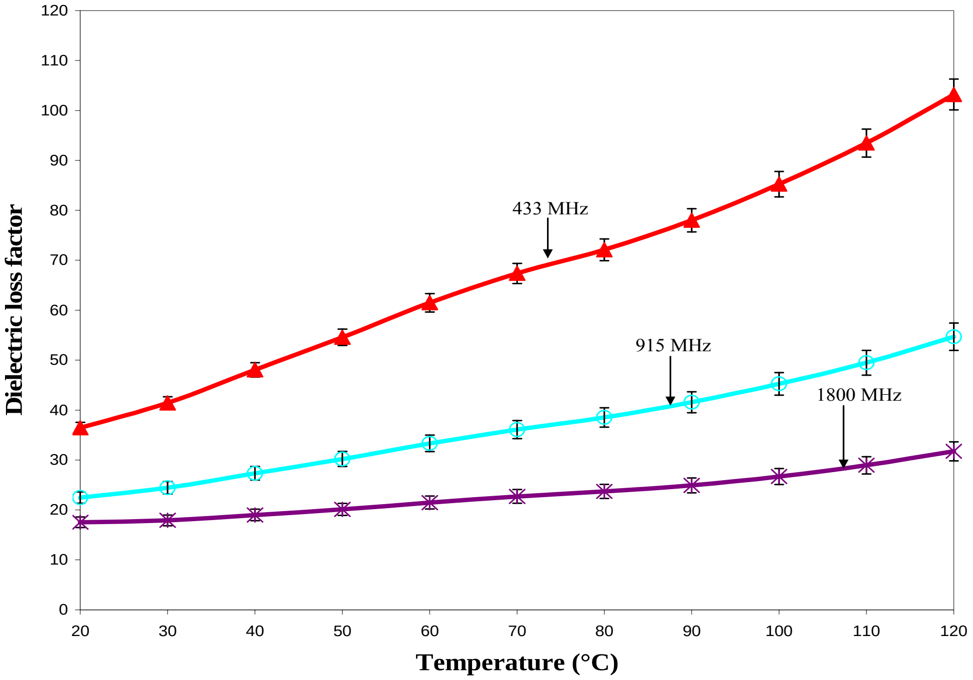

Figure 4b- Changes of dielectric loss factor of pink salmon (overall average) with temperature at 433, 915 and 1800 MHz

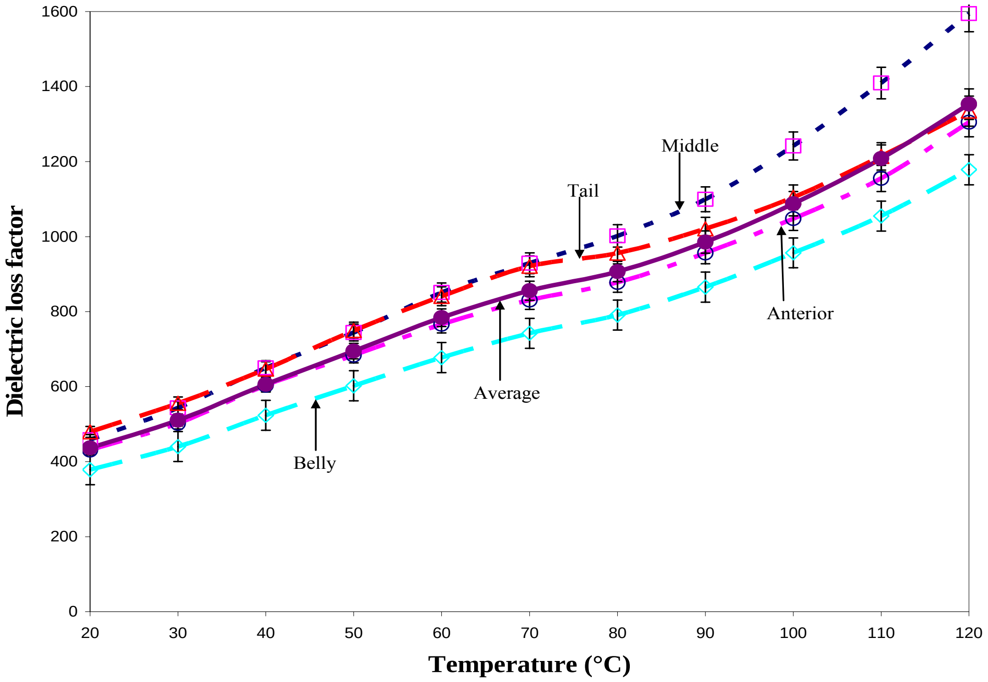

Figure 5- Dielectric loss factor of pink salmon at four positions as a function of temperature at 27 MHz

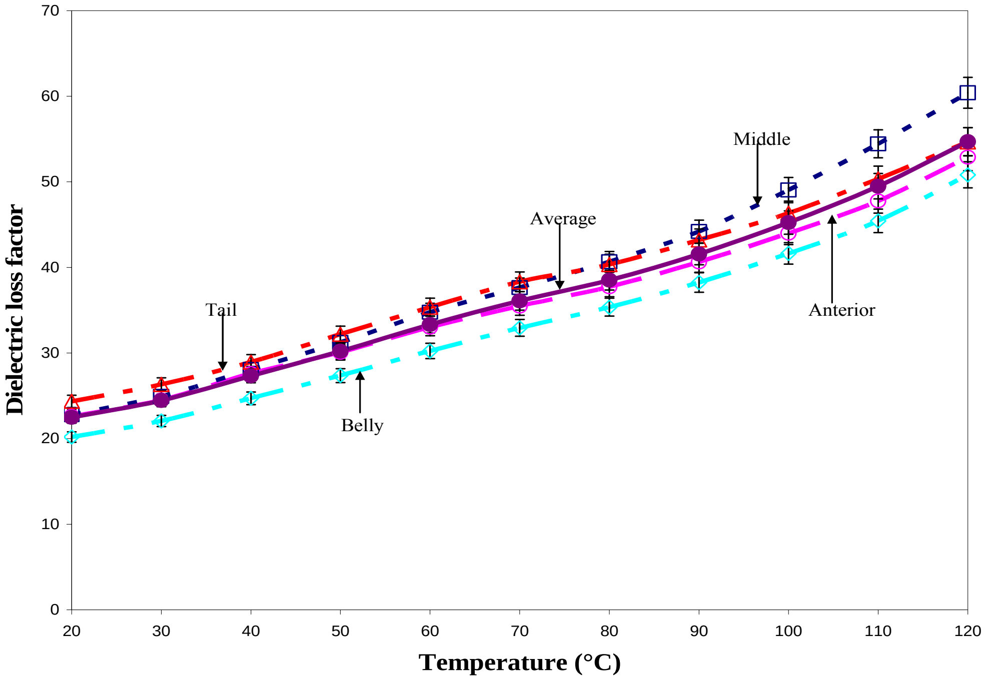

Figure 6- Dielectric loss factor of pink salmon at four positions as a function of temperature at 915 MHz

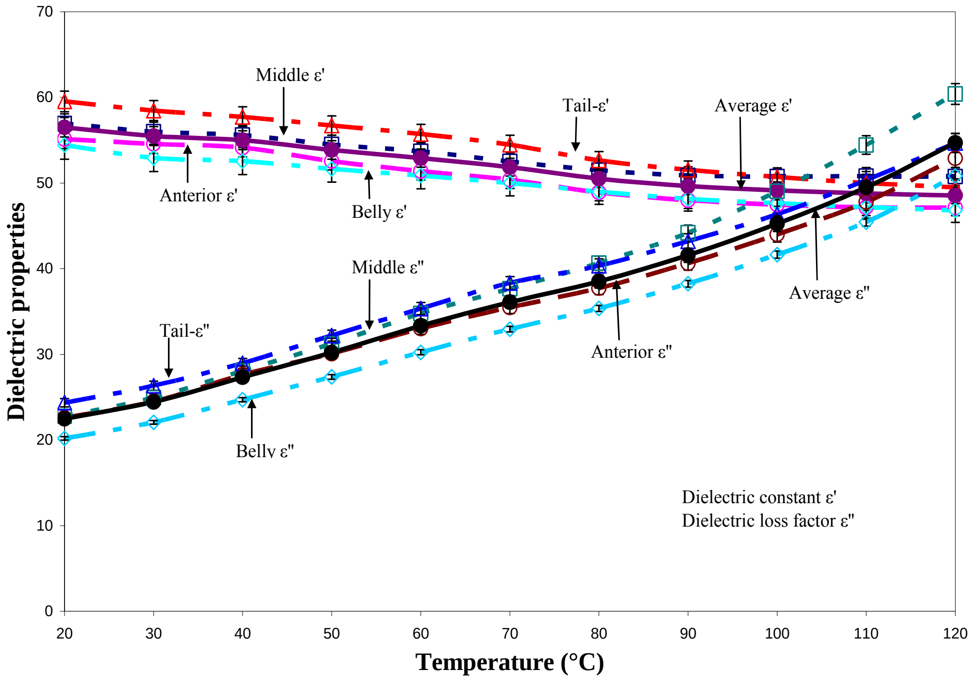

Figure 7- Temperature dependence of dielectric properties of pink salmon at four positions at 915 MHz

The belly part of the salmon had lower dielectric constant and loss factors (as shown in Fig 3, 5, 6, 7 and Table 5) than other parts of salmon fillets possibly due to minor difference in composition or to factors associated with muscle structure. The salmon belly flap area was also found to be of high lipid content by Aursand *et al.* (1994), Zhou *et al.* (1996) and Katikou *et al.* (2001). In general, four parts of pink salmon fillet (anterior, middle, tail, and belly) exhibited a similar trend for dielectric constant and loss factor as a function of temperature at 915 MHz with a temperature range 20-120 °C. Compositional differences are reason for different dielectric properties. These results were anticipated. Proximate compositions of the four different positions (moisture content, fat content and ash content) are similar to each other, however, there were small differences in fat content for terminal female pink salmon, particularly in the belly region. The belly has a little bit higher fat content as well as lower ash content compared to other parts (Table 1).

The values (shown in Table 3) for dielectric loss factor were similar to results by Tran and Stuchly (1986). They measured the dielectric properties of uncooked salmon meat at frequencies between 100 and 2500 MHz at selected temperatures. They reported dielectric properties of salmon (moisture content 71%, wet basis) $\varepsilon'=53.7$; $\varepsilon''=24.3$ at 20 °C at 900 MHz and $\varepsilon'=57.7$; $\varepsilon''=39.0$ at 64 °C at 2000 MHz, while experimental results in my study indicated the dielectric properties of pink salmon (female, moisture content 75%, wet basis) $\varepsilon'=50.9$; $\varepsilon''=18$ at 20 °C at 915 MHz, $\varepsilon'=51.6$ and $\varepsilon''=24.7$ at 60 °C at 1800 MHz. In summary, the results of the dielectric measurements presented in this research agree reasonably well with those in the published literature.

Penetration Depth

Penetration depth is generally used to select appropriate thickness of food inside packages to ensure a relatively uniform heating along the depth of a food during dielectric heating processes (Wang *et al.* 2003). The equation used to determine the penetration depth is (Equation 1):

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \qquad (1)$$

where d_p is the power penetration depth (cm), ε' is the dielectric constant, ε'' is the dielectric loss factor, c is the speed of light in free space (3.00×10^8 m/s) and f is the frequency of the microwaves or the radio frequency waves (Hz).

Penetration depths for salmon on average were about 66 mm at 27 MHz and 18 mm at 915 MHz at 20 °C. Penetration depth was reduced to 36 mm at 27 MHz and 7.5 mm at 915 MHz at 120 °C (Table 4). Penetration depth at 915 MHz was greater than that of 1800 MHz (Fig. 8

and Table 4). A higher penetration depth at 915 MHz was also reported by other researchers (Decareau 1985; Tanaka *et al.* 1999, Gunasekaran 2005). In summary, penetration depths was reduced by about one-half when the temperature was increased from 20 °C to 120 °C at frequencies from 27 to 1800 MHz. (Table 4). Results from other researchers also indicated that for most foods, the power penetration depths decrease as temperature increases. The change of frequency from RF range (27 and 40 MHz) to microwave range (915 and 2450 MHz) impacted penetration depth much more than change of temperature from 20 to 120 °C (raw data shown in Table 4).

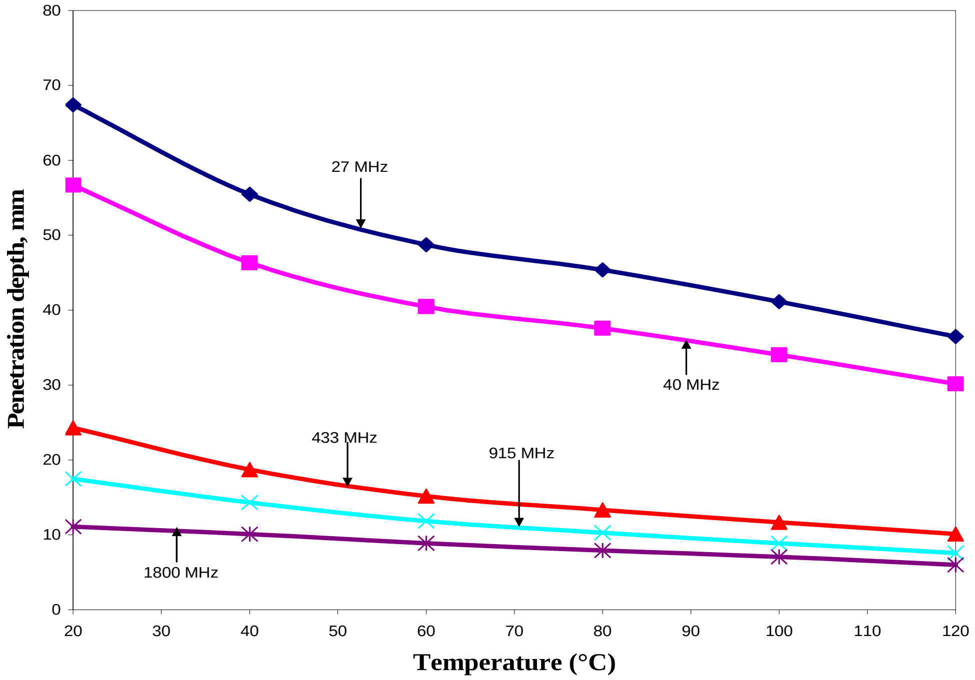

Figure 8- Penetration depth at temperatures from 20 to 120 °C of pink salmon anterior part (Triplicate measurements)

Table 4- Penetration depth (mean value [a], mm) for pink salmon fillet at four positions.

Sample	**T (°C)**	**27 MHz**	**40 MHz**	**433 MHz**	**915 MHz**	**1800 MHz**
	20	67.41	56.69	24.29	17.48	11.09
Anterior	40	55.48	46.32	18.70	14.32	10.10
	60	48.72	40.47	15.16	11.85	8.88
	80	45.37	37.58	13.31	10.28	7.92
	100	41.14	34.04	11.68	8.88	7.05
	120	36.48	30.17	10.13	7.57	6.00
	20	64.68	54.45	23.93	17.61	11.06
Middle	40	52.96	44.24	18.27	14.26	10.04
	60	45.84	38.08	14.54	11.51	8.61
	80	42.11	34.87	12.54	9.82	7.68
	100	37.49	30.99	10.74	8.28	6.73
	120	32.78	27.05	9.15	6.95	5.61
	20	63.39	53.34	23.32	16.85	10.65
Tail	40	53.42	44.62	18.30	14.09	9.77
	60	46.35	38.51	14.61	11.51	8.51
	80	43.43	35.97	12.81	9.97	7.57
	100	40.15	33.21	11.40	8.69	6.79
	120	36.22	29.94	10.06	7.49	5.88
	20	72.92	61.34	26.54	19.37	11.92
	40	60.49	50.44	20.39	15.70	10.93
Belly	60	52.54	43.57	16.33	12.79	9.53
	80	48.47	40.08	14.11	10.91	8.33
	100	43.64	36.04	12.30	9.33	7.17
	120	38.93	32.12	10.73	7.81	6.02

a. Results are the mean values of at least three independent trials.

Regression Analysis

Polynomial equations were developed for dielectric properties at 27 and 915 MHz by using regression calculations (Microsoft Excel, the least square technique). Similar equations for other frequencies (40, 433 and 1800 MHz) can also be achieved by using this technique.

The regression equations and all the predictors in the equations had a significance of $P<0.001$, and the adjusted coefficients of determination of the equation R^2 values greater than 0.95 (Table 5). Significant polynomial relationships were found for all combinations, which demonstrated that these empirical relationships could be used to predict the raw dielectric properties data for pink salmon fillet and incorporated into models for dielectric heating processes. Within the same frequencies range, for example, at 915 MHz, the coefficients of the equations for both dielectric constant and loss factors at different positions of pink salmon fillet have small variations (± 0.05). But at the same position of pink salmon fillet, for instance, salmon anterior, the equation coefficients at 27 MHz are greater than the one at 915 MHz, which showed good agreement with the experimental results that both dielectric constant and dielectric loss factor increase sharply with increasing of temperature at lower frequencies (*e.g.,* <200 MHz). In general, the four parts of pink salmon fillet (anterior, middle, tail, and belly) show a very similar trend for dielectric constant and loss factor as a function of temperature between 20 and 120 °C at 27 and 915 MHz. Small compositional differences are the reason for the small differences in the dielectric properties of different part of a salmon fillet. But proximate compositions of the four different positions (moisture content, fat content and ash content) are similar. Therefore, it is reasonable to use the average values of dielectric properties the whole salmon fillets for regression analyses instead of each dividual position. In summary, these equations can be used to obtain the temperature dependent dielectric properties of salmon within a temperature range 20-120 °C, if the compositions of samples are close to those in this study.

Table 5- Predictive equations for the dielectric properties [a] of pink salmon as a function of Temperature at 27, and 915 MHz

	Salmon fillet position	**Regression equations**	**R^2**
27 MHz	**Dielectric constant**		
	Anterior	$\varepsilon' = -1.750E\text{-}03T^2 + 0.6930T + 82.211$	0.989
	Middle	$\varepsilon' = -0.643E\text{-}03T^2 + 0.6556T + 78.736$	0.990
	Tail	$\varepsilon' = -1.315E\text{-}03T^2 + 0.7409T + 84.245$	0.988
	Belly	$\varepsilon' = -1.093E\text{-}03T^2 + 0.7980T + 79.255$	0.996
	Average	$\varepsilon' = -1.200E\text{-}03T^2 + 0.7219T + 81.112$	0.991
	Dielectric loss factor		
	Anterior	$\varepsilon'' = 16.188E\text{-}03T^2 + 5.8935T + 324.572$	0.991
	Middle	$\varepsilon'' = 41.830E\text{-}03T^2 + 4.8515T + 370.135$	0.993
	Tail	$\varepsilon'' = 0.871E\text{-}03T^2 + 8.0040T + 327.514$	0.991
	Belly	$\varepsilon'' = 16.297E\text{-}03T^2 + 5.3514T + 275.575$	0.995
	Average	$\varepsilon'' = 18.797E\text{-}03T^2 + 6.0251T + 324.449$	0.993
915 MHz	**Dielectric constant**		
	Anterior	$\varepsilon' = 0.384E\text{-}03T^2 - 0.1459T + 58.570$	0.978
	Middle	$\varepsilon' = 0.530E\text{-}03T^2 - 0.1431T + 59.974$	0.977
	Tail	$\varepsilon' = 0.096E\text{-}03T^2 - 0.1211T + 62.193$	0.989
	Belly	$\varepsilon' = 0.250E\text{-}03T^2 - 0.1119T + 56.473$	0.994
	Average	$\varepsilon' = 0.315E\text{-}03T^2 - 0.1305T + 59.302$	0.987
	Dielectric loss factor		
	Anterior	$\varepsilon'' = 0.916E\text{-}03T^2 + 0.1623T + 19.259$	0.996
	Middle	$\varepsilon'' = 1.619E\text{-}03T^2 + 0.1379T + 19.719$	0.997
	Tail	$\varepsilon'' = 0.620E\text{-}03T^2 + 0.2104T + 19.834$	0.997
	Belly	$\varepsilon'' = 1.053E\text{-}03T^2 + 0.1475T + 17.009$	0.997
	Average	$\varepsilon'' = 1.052E\text{-}03T^2 + 0.1645T + 18.955$	0.997

[a] ε' is the dielectric constant and ε'' is the dielectric loss factor

CONCLUSION

The dielectric properties of Alaska pink salmon fillet at four positions were investigated at frequencies from 27 MHz to 1800 MHz and at temperatures from 20 to 120 °C. The influence of temperature, frequency and fish composition on the dielectric properties was examined and quantified. The following conclusions can be derived:

- Dielectric constant increased at 27 and 40 MHz, but decreased at 433, 915 and 1800 MHz while the dielectric loss factor increased sharply at 27 and 40 MHz with increasing of temperature, but increased slightly at 915 and 1800 MHz.
- The penetration depths at RF range (27 and 40 MHz) were about five times deeper than microwave frequencies range (915 and 1800 MHz) at each measured temperature.
- Dielectric constant and dielectric loss factor of pink salmon belly were lower than other parts of salmon fillet due to a higher fat content in the fish belly.
- Regression equations for predicting dielectric constant and dielectric loss factor at various temperatures and different positions of fish fillet were developed. The predictions of dielectric properties by these equations were in good agreement with the experimental results.

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CHAPTER THREE

USING WHEY PROTEIN GEL AS A MODEL FOOD TO STUDY THE DIELECTRIC HEATING OF SALMON FILLETS

ABSTRACT

The dielectric constant (ε') and loss factor (ε'') of whey protein gel with addition of D-ribose (0.5%, 1%, 1.5%) at different salt content (0, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%) and frozen and thawed pink salmon (*Oncorhynchus gorbuscha*) fillets were investigated over the frequency range of 27-1800 MHz at temperatures ranging from 20 to120 $^{\circ}$C, respectively. Results were compared for both. The dielectric properties of whey protein gel with 1% D-ribose and 0.2% or 0.3% salt matched the dielectric behavior of salmon both in the Radio Frequency (RF) and Microwave **(**MW) ranges. Salt content played a more significant role at the lower treatment frequencies. Whey protein gel can be used as a model food after altering its compositional properties to more closely match the dielectric properties of the target product. This indicates that whey protein gel can be a useful tool for process development, particularly for predicting the locations of cold and hot spots in foods.

Key words: dielectric properties, salmon, whey protein gel, D-ribose, RF, microwave sterilization

INTRODUCTION

The dielectric properties (dielectric constant ε' and loss factors ε'') of food determine how they react to an applied electromagnetic field (Kuang and Nelson 1998). ε' reflects the ability of a material to store electromagnetic energy, and ε'' measures the ability of a material to dissipate electric energy as heat. The need to know a food's dielectric parameters (dielectric constant ε' and loss factors ε'') has been expanded upon as the technological need arose to obtain a better understanding of heating uniformity and considerable efforts has been directed towards this because of the stringent requirements for predicting heating uniformity for microwave sterilization processes. A validated, reliable and repeatably thermal process is critical to ensure adequate sterility for shelf-stable foods, and it is essential to be able to accurately predict and then to determine the locations of cold and hot- spots during microwave sterilization. Because of the important role dielectric properties of a food play in how it heats, both dielectric constant and dielectric loss must be known for foods at the specific treatment frequency and at the temperatures the food will experience during the thermal process. There is a need to develop reliable and rapid methods to determine heating uniformity and how the heating pattern, especially the size, location, and thermal energy at the cold spots could change with food composition as well as with the dimensions of the food and the geometry of the package. Dielectric heating is different from conventional heating, in which the heating patterns are dependent upon the direct interaction between microwave energy and food and are difficult to predict (Decareau 1985). Direct measurement of time and temperature history for various points in food packages is not possible during microwave sterilization processes because of unrealistic amount of time this would take. But more importantly it is impossible to insert the required number of thermocouples or fiber optic probes into a product to allow reliable determination of cold spot locations.

A novel approach to determine heating patterns uses computer vision and chemical marker (4-hydroxy-5-methyl-3(2H) furanone) (M-2) formed by heating a reducing sugar and an amine (Kim and Taub 1993). Pandit *et al.* (2005) reported that M-2 formation is proportional to thermal treatment in aqueous and also in a heated whey protein gel doped with ribose. The amount of heating can be measured, and then converted to interpret visual images. This system can be used to detect the relatively deposition of thermal energy at any location in a processed homogeneous food and to provide maps of the heating patterns for homogeneous food products. Whey protein gel were selected for the research here because the composition could be altered to match the dielectric properties of salmon by changing the moisture and salt content without affecting the ability of the whey protein to form a stable gel. Whey protein gel has an additional advantage in that it can also be formed into different shapes to resemble food products, an important feature for studying muscle foods which have non uniform dimensions and weight.

In this thesis, several formulations of whey protein gel were developed and tested, and the gel with the composition most closely matching frozen/thawed pink salmon was selected for further study. Temperature distribution studies and thermal penetration for these whey protein gels were determined. Then, pink salmon was tested to determine whether the model developed using whey protein could be used as a valid method for estimating heating for salmon under microwave sterilization conditions. The dielectric property parameters developed here will provide the basis for related computer simulation work on dielectric heating processes and assist the development of a reliable method for determining the locations of the cold and hot spots of salmon and potentially other important muscle food products in 915 MHz microwave sterilization systems.

OBJECTIVES

The main objectives in this study were to:

- Find the composition of whey protein that would most closely resembles the dielectric behavior of frozen/thawed pink salmon.
- Determine if a whey protein gel could be used as a model food to develop microwave sterilization processes for a shelf-stable commercially sterile salmon product.

MATERIALS AND METHODS

Whey Protein Gel Preparation

Whey Protein Gel (WPG) with the addition of D-ribose (Sigma-Aldrich, St. Louis, MO), and with or without salt (Plain salt, sodium chloride, Morton International, Chicago, IL., USA) was used for dielectric properties measurement. Whey protein gel was made of 20% Alacen 878 (powder) whey protein concentrate (New Zealand Milk Products, Santa Rosa, CA) containing 72.89% protein on a wet basis, with additional of D-ribose and sodium chloride to distilled water. The suspension was mixed continuously in a beaker for 2 hours at room temperature (about 25 °C) using a magnetic stirring device to achieve homogeneity; after this, the whey protein suspension was transferred into a metal tube (1 inch in diameter and 4 inch in thickness) and cooked at 80 ^{o} C in a water bath for 40 min. A cooked whey protein gel sample is shown in Fig. 1.

Previous studies have shown that the 20% whey protein solution forms a firm gel after heating at 80 ºC for 40 minutes (Lau *et al.* 2003; Wang *et al.* 2003) without causing any detectable M-2 formation. Salt levels in this study covered the range of the sodium levels for several fully cooked or canned food products based upon proximate composition values reported in the literature (Lyng 2005). D-ribose was selected because it is efficiently converted to a furanone in browning reactions. The ribose concentration selected as not to be substrate limiting, but also at a level where the formation of browning product is slow enough so that the formation of the furanone increases proportionately during the heating process but is not likely to reach a point of color saturation. The time necessary to reach a saturation point during heating can vary with ribose concentration; a whey protein sample with 1% added D-ribose will reach saturation within a reasonable time (F_o = 18 min at 121 ºC temperature). These reaction parameters will make it possible to visualize heating patterns during microwave sterilization processes and then use these determinations to model heat distribution in model foods (Lau *et al.* 2003). Thus, samples were prepared to the following proportion in this study: D-ribose: 0.5% , 1% , and1.5%; sodium chloride: 0, 0.1% , 0.2% , 0.3% , 0.4% , and 0.5% ; whey protein concentration: 20% ; water: 78.5-79% (Example whey protein mixture: Whey protein 100 g, D-ribose 5 g, Salt 1.5 g, Water 393.5 g). In this study, eight formulations of whey protein gel were tested to find best possible match to salmon among the formulations tested (Table 1).

Figure 1- Whey protein gel samples used for analyses in this study

Table1- Compositions of whey protein gel (contained 20% whey protein) with different levels of D-ribose and salt concentration (on a wet basis)

Formulations	1	2	3	4	5	6	7	8
D-ribose Content	0.5%	1%	1%	1%	1%	1%	1%	1.5%
Salt Content (NaCl)	0.3%	0%	0.1%	0.2%	0.3%	0.4%	0.5%	0.3%
Distilled Water	79.2%	79%	78.9%	78.8%	78.7%	78.6%	78.5%	78.2%

Salmon Fillet Sample Preparation

Samples of 12 frozen/thawed pink salmon fillets (female, deep-skinless, and boneless) were used for dielectric properties measurement. The fish samples were freshly harvested wild Alaska pink salmon from the same catch in Aug., 2005 near Kodiak, Alaska, handled as described in Chapter 2.

Experimental Set up and Dielectric Properties Measurement

Dielectric properties of whey protein gel and pink salmon were measured over a temperature range 20 to 120 ºC and a frequency range 1 to 1800 MHz. The dielectric properties measurement system used in this study consisted of an Agilent 4291B Impedance Analyzer with a calibration kit (Agilent Technologies, Palo Alto, CA), a custom built test cell, a circulating bath with a VWR Model 1147P programmable/Digital Controller Models circulator (PolyScience Products, Niles, Illinois, USA), a high-temperature coaxial cable, and a dielectric probe comes from the Hewlett Packed 85070B dielectric probe kit. The impedance analyzer can make measurements over the frequency range 1 to 1800 MHz. The probe was suited for use in the temperature range -40 to +200 °C. As described by Wang (2003), the impedance analyzer was connected through an IEEE-488 (GPIB) bus to a desktop personal computer, which controlled the impedance analyzer and logged measured data by a installed custom-designed software DMS 85070 (Innovative Measurement Solutions). This dielectric properties measurement system was suitable for sample temperatures up to 130 °C.

Prior to the measurements, the impedance analyzer was warmed up for at least 30min, per the manufacturer's recommendations. All electrical connections were checked and cleaned with 95%+ reagent grade ethanol to remove any residue. The system was calibrated before each independent measurement to avoid possible variations in the cable position, connections, ambient temperature, and other factors that might affect the performance of the system. Four calibration standards (Agilent 4291B calibration kit) were used in this study to calibrate the impedance analyzer. Following this, the testing probe which is extremely sensitive was calibrated by an Agilent 85070B dielectric probe kit.

Measurements on samples were conducted at every 10 °C increment from 20 to 120 °C; intervals of 8 to12 min were given between measurements for each 10 °C increment to allow for temperature equilibrium before dielectric properties of the sample were measured (Wang 2003). All measurements were performed in triplicate with fresh samples. The dielectric constant values of whey protein gel with same amount of 0.3% salt concentration at three levels D-ribose (0.5%, 1%, 1.5%) were compared using t-test (Microsoft Excel, 2003) at P=0.05 level. The dielectric properties were automatically calculated from the phase and amplitude of the reflected signal by the computer.

RESULTS AND DISCUSSION

In this study, particular attention was paid on the following factors that influence on the dielectric properties of foods: frequency, temperature, and salt content of selected model food whey protein gel and pink salmon.

Effect of Frequency

Figure 2 shows the measured dielectric constant and loss factor; figures 3a and 3b show the measured dielectric loss factors at RF and microwave frequencies range, respectively, for whey protein gel with 1% D-ribose, 0.3% NaCl at frequencies 27, 40, 433, 915 and 1800 MHz. The loss factors generally increase with rising temperature at RF and lower microwave frequencies. The great trend of the dielectric properties (dielectric constant ε' and loss factor ε'') with respect to temperature and frequency are similar for both high and low salt samples.

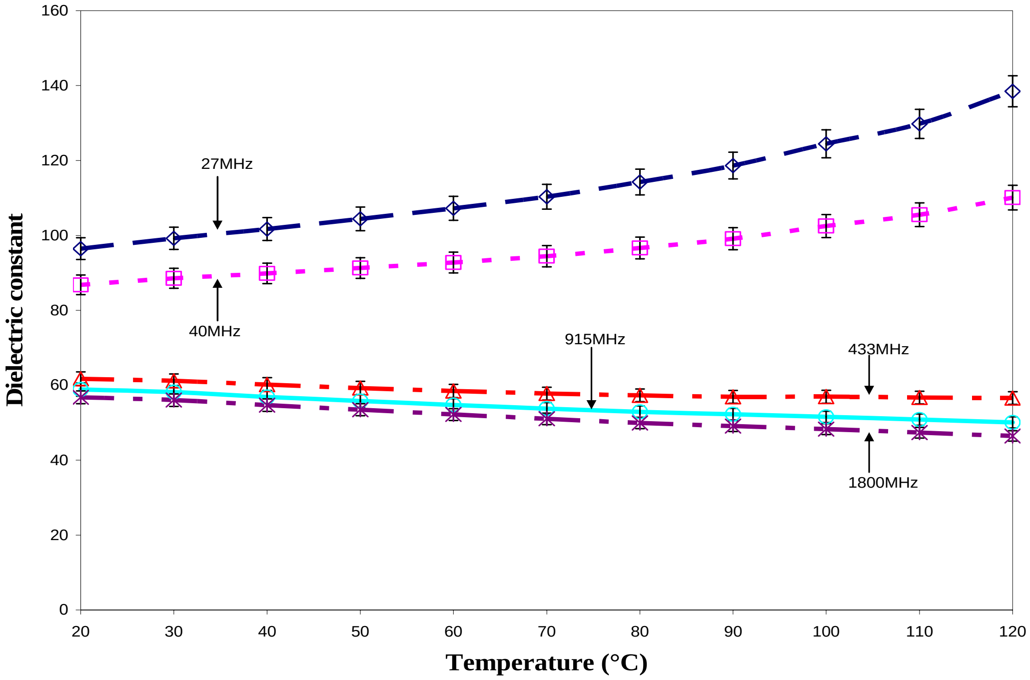

Figure 2- Dielectric constant of whey protein gel with 1% D-ribose and 0.3% NaCl at 27, 40, 433, 915 and 1800 MHz

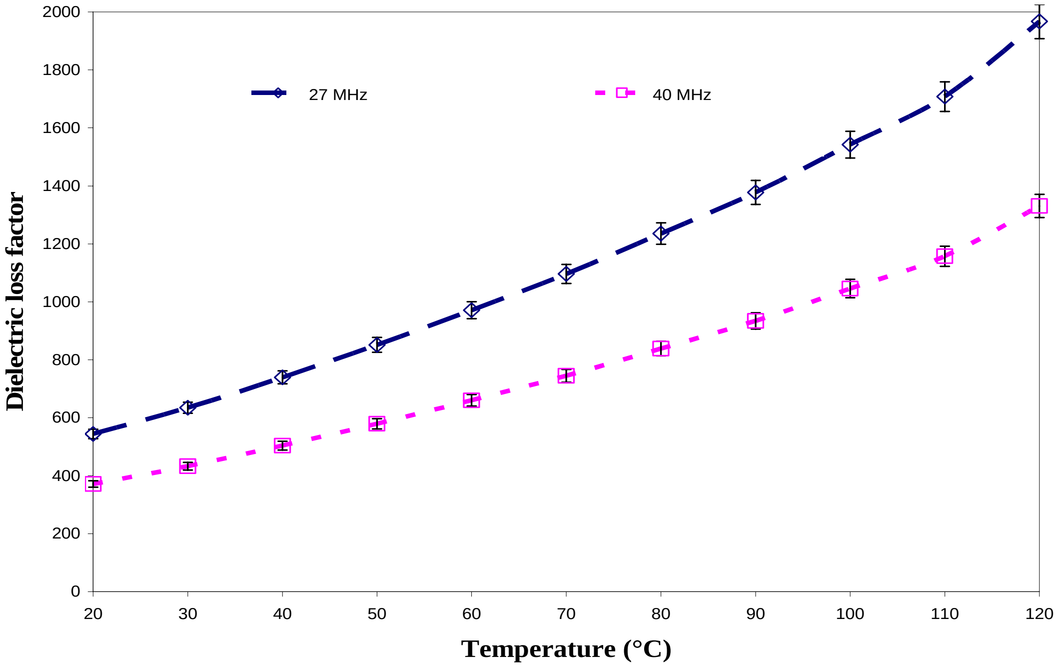

Figure 3a- Dielectric loss factor of whey protein gel with 1% D-ribose and 0.3% NaCl at 27 and 40 MHz

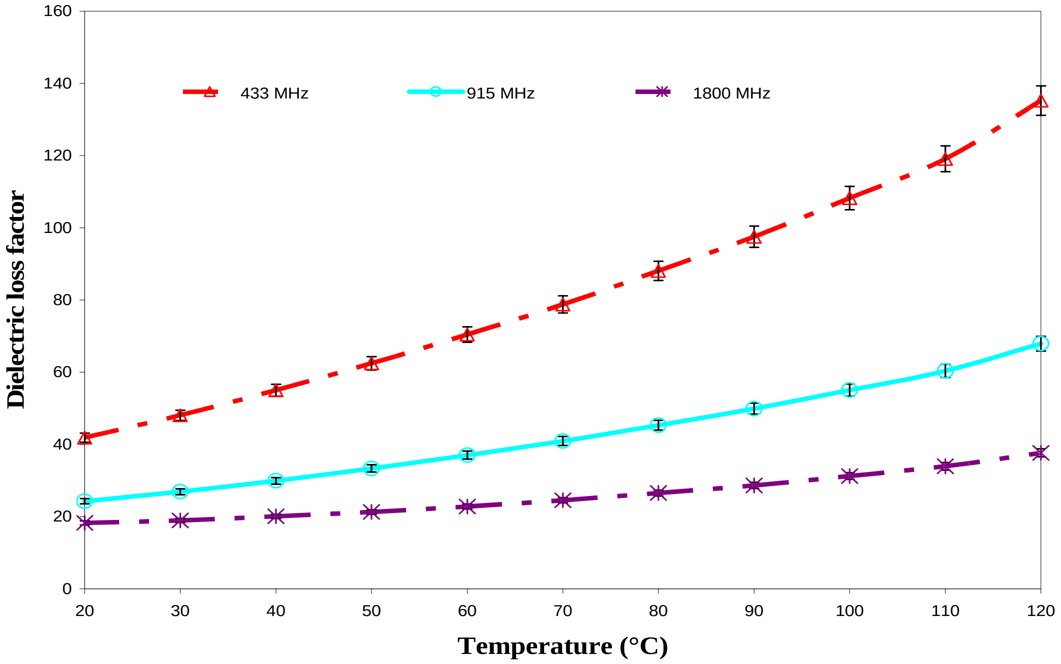

Figure 3b- Dielectric loss factor of whey protein gel with 1% D-ribose and 0.3% NaCl at 433, 915 and 1800 MHz

Effect of D-ribose Concentration

Figures 4 and 5 demonstrated the degree of the variation of the dielectric properties in D-ribose at three levels (0.5%, 1%, and 1.5%) in whey protein gels. A low or moderate D-ribose content does not modify the e' values much. With the same amount of salt (0.3%), whey protein gel with an added 1% D-ribose provided a better match for dielectric properties (dielectric constant ε' and loss factor ε'') to pink salmon compared to other proportions. These results indicate that D-ribose as a chemical marker formation ingredient has a minor effect on dielectric properties in this food system and less effect than salt. No significant difference was observed for dielectric properties of whey protein gel at the three levels D-ribose concentration (P>0.05). The results also agree with Lau’s report (Lau *et al.* 2003) that whey protein sample with 1% D-ribose had suitable kinetic properties allowing for the effective visualization of heat distribution.

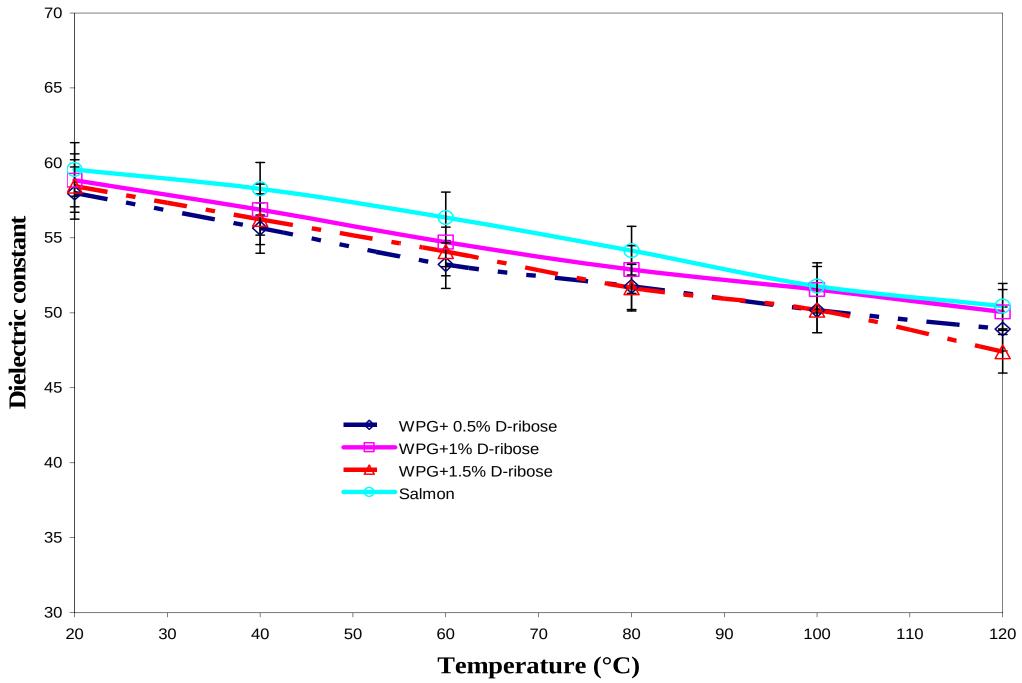

Figure 4- Dielectric constant of pink salmon and whey protein gel with 0.3% NaCl at different D-ribose levels (0.5%, 1%, and 1.5%) at 915 MHz

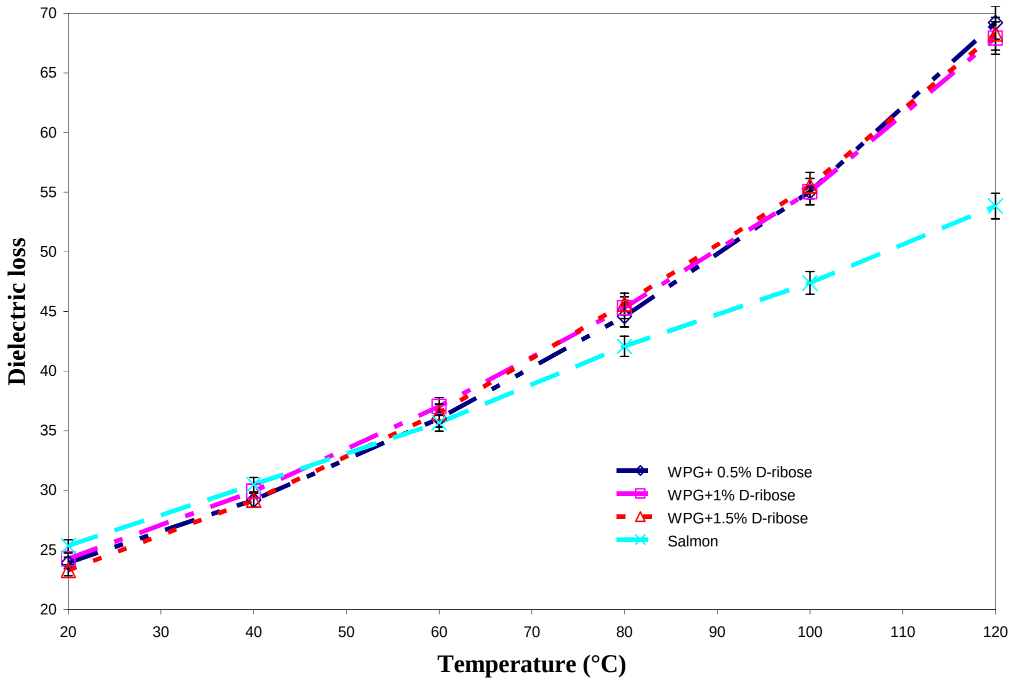

Figure 5- Dielectric loss factor of pink salmon and whey protein gel with 0.3% NaCl at different D-ribose levels (0.5%, 1%, and 1.5%) at 915 MHz

The ε' observed in Fig. 5 for salmon was lower than for WPG at 0.3% NaCl as temperature exceeded 60 °C. This shows that protein denaturation and presence of an intact tissue structure has a significant impact on ε'' at higher temperature and that this effect is independent of salt concentration. Therefore, it will be important to verify, ε'' at higher temperatures to ensure that processes developed are valid. This may prove WPG systems may need to be reformulated to use as a model food for dielectric sterilization protocols to account for these differences.

WPG is a relatively uniform homogenous matrix made from denatured protein. It allows for free migration of ions and rotation of water molecules. Salmon (Fig. 5) is undergoing thermal denaturation. Also, the salmon tissue structure could impede migration of ions leading to or reduce ε'' compared to WPG of the same salt concentration.

Effect of Salt Concentration

Salt concentration had the greatest effect upon the dielectric properties of whey protein gel compared to the other components evaluated in this study. Figure 6 shows the changes in dielectric loss factor of whey protein gel with added D-ribose (1%) at different salt levels (0, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%) at 915 MHz. The great trends from the figure suggested that sodium chloride content greatly affect the dielectric loss factor. These results support those of Sun *et al.* (1995). Positive and negative ions from dissolved salts in foods, such as common table salt, interact with an electrical field by migrating in the field; this migration disrupts hydrogen bonds of water to generate additional heat (Lund 1977). The results show significant differences in the dielectric loss as a result of different salt concentration in whey protein gel. The higher salt concentration the greater the dielectric loss factor (Fig. 6). The dielectric constant was higher at 27 and 40 MHz, but lower at 433, 915 and 1800 MHz while the dielectric loss factor increased sharply at all the measured frequencies (27 40, 433, 915 and1800 MHz) with increasing temperature. This rapid increase in dielectric loss with temperature could create a smaller possibility of run away heating for samples heated at RF frequencies compared to MW frequency range.

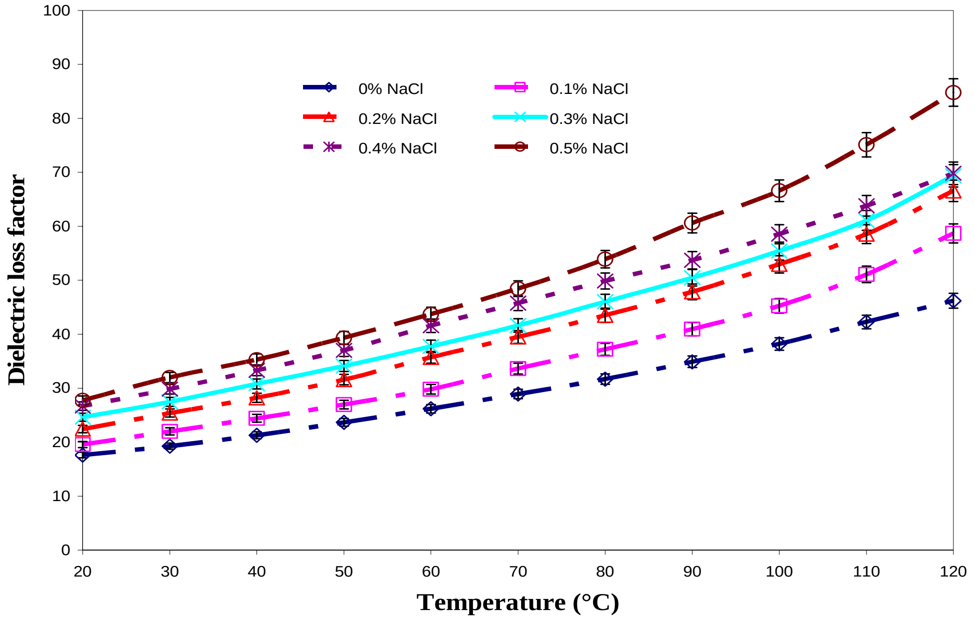

Figure 6- Dielectric loss factor of whey protein gel with added D-ribose (1%) at different salt levels (0, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%) at 915 MHz

Comparison of Dielectric Properties of Whey Protein Gel and Salmon

A gel with1% D-ribose and 0.2% or 0.3% NaCl had dielectric properties similar to pink salmon filets (Table 2 and Fig. 7). At lower temperatures (below 70 ° C), a gel with 0.3% salt and 1% D-ribose was most similar to salmon; at higher temperatures (above 70 ° C), a gel with 0.2% added salt and 1% D-ribose content was a better match. Salmon is a high moisture food, around 75-80%, whey protein gel used in this study also has a water content of 78.2-79.2%, which is close to salmon moisture content. Alaska pink salmon has 26% protein content according to USDA Handbook (1987) and (Sidwell 1981; Nettleton 1983; Pennington *et al.*1989; Exler 1987). Whey protein gel in this study has 20% protein (on a wet weight basis), which is also similar to salmon protein content. All these characteristics provide possibilities to use whey protein gel as a model food to study salmon during dielectric heating processes.

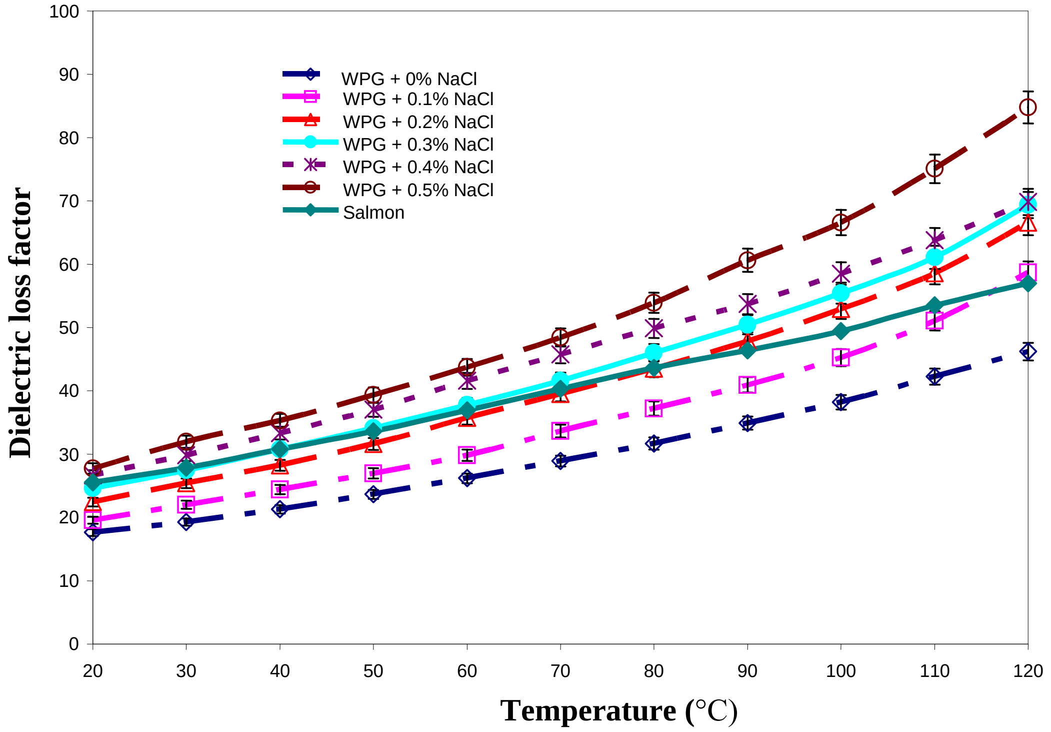

Figure 7- Dielectric loss factor of pink salmon and whey protein gel with added D-ribose (1%) at different salt levels (0, 0.1%, 0.2%, 0.3%, 0.4% and 0.5%) at 915 MHz

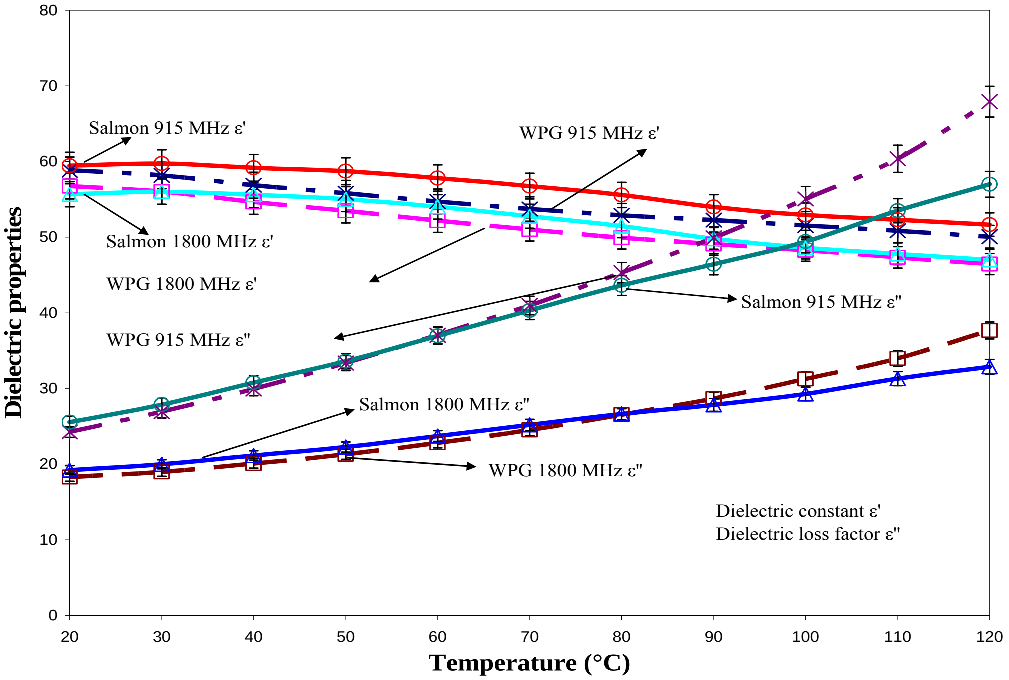

Figure 8- Dielectric constant and loss factor of pink salmon and whey protein gel with1%D-ribose, 0.3%NaCl at 915 and 1800 MHz

Table 2- Mean ± standard deviation of the dielectric properties [a] for pink salmon and whey protein gel [b] with D-ribose 1% at different salt levels at 5 frequencies

Samples	**Salt levels**	**T (°C)**		**27 MHz**	**40 MHz**	**433 MHz**	**915 MHz**	**1800 MHz**
Whey Protein Gel +0.5% D-ribose	0.3%	20	ε'	90.38 ± 3.81	82.85 ± 3.17	60.84 ± 2.75	57.99 ± 2.37	55.69 ± 2.53
			ε"	540.23 ± 17.62	368.31 ± 11.94	41.04 ± 1.27	23.93 ± 0.37	17.44 ± 0.66
		40	ε'	92.89 ± 5.15	84.04 ± 4.15	58.92 ± 3.10	55.65 ± 2.63	53.52 ± 2.87
			ε"	732.87 ± 38.18	498.00 ± 25.71	53.45 ± 2.24	29.18 ± 0.98	18.89 ± 0.83
		60	ε'	96.30 ± 5.16	85.78 ± 3.91	57.36 ± 2.48	53.22 ± 2.39	50.97 ± 2.85
			ε"	969.78 ± 45.74	657.67 ± 31.10	68.84 ± 2.54	36.03 ± 1.54	22.06 ± 0.45
		80	ε'	101.29 ± 5.02	88.58 ± 3.43	56.42 ± 1.90	51.77 ± 1.37	49.54 ± 1.79
			ε"	1241.17 ± 53.49	840.50 ± 35.91	86.59 ± 2.90	44.59 ± 1.37	25.69 ± 1.05
		100	ε'	109.20 ± 5.21	93.37 ± 3.21	56.23 ± 1.24	50.18 ± 1.28	47.97 ± 2.13
			ε"	1573.67 ± 74.08	1064.27 ± 49.68	107.64 ± 4.81	55.05 ± 1.95	31.71 ± 0.53
		120	ε'	119.55 ± 6.33	98.42 ± 3.12	56.29 ± 1.75	48.92 ± 1.15	45.90 ± 5.76
			ε"	2067.50 ± 94.80	1396.32 ± 65.38	138.66 ± 2.96	69.21 ± 6.95	39.28 ± 3.75

Whey protein Gel + 1% D-ribose	0%	20	ε'	86.72 ± 4.90	78.67 ± 5.53	57.19 ± 6.42	56.23 ± 7.47	54.11 ± 7.47
			ε''	330.62 ± 58.79	227.66 ± 39.71	27.25 ± 3.14	16.99 ± 1.53	14.66 ± 1.62
		40	ε'	91.90 ± 3.09	82.08 ± 3.95	56.70 ± 4.79	55.33 ± 5.89	53.30 ± 5.88
			ε''	466.17 ± 88.67	319.53 ± 59.72	36.41 ± 4.86	20.87 ± 2.12	15.41 ± 1.66
		60	ε'	96.20 ± 2.85	84.46 ± 3.54	55.54 ± 4.01	53.84 ± 5.03	51.76 ± 5.19
			ε''	610.34 ± 124.56	416.98 ± 83.69	46.08 ± 7.04	25.25 ± 3.19	17.00 ± 2.15
		80	ε'	101.96 ± 2.89	87.57 ± 2.96	54.33 ± 3.38	52.02 ± 4.21	49.83 ± 4.29
			ε''	791.95 ± 140.37	539.59 ± 94.06	58.32 ± 7.76	30.96 ± 3.47	19.47 ± 2.26
		100	ε'	108.92 ± 4.88	91.62 ± 3.53	53.61 ± 2.61	50.53 ± 3.03	48.21 ± 3.26
			ε''	974.74 ± 158.28	663.51 ± 106.17	70.81 ± 8.72	36.96 ± 3.90	22.33 ± 2.49
		120	ε'	118.41 ± 7.50	97.22 ± 5.25	53.37 ± 1.91	50.01 ± 2.34	47.79 ± 2.45
			ε''	1234.27 ± 225.09	839.03 ± 150.45	87.91 ± 11.99	45.97 ± 3.84	26.73 ± 2.38
	0.1%	20	ε'	90.24 ± 3.02	82.40 ± 2.41	61.49 ± 1.77	58.99 ± 2.39	56.91 ± 2.21
			ε''	417.98 ± 33.94	286.05 ± 22.95	33.06 ± 2.75	19.93 ± 1.40	15.85 ± 0.69
		40	ε'	95.14 ± 2.62	85.55 ± 1.63	60.85 ± 1.40	57.96 ± 1.89	55.71 ± 1.62
			ε''	578.00 ± 39.02	394.35 ± 26.36	43.73 ± 3.26	24.37 ± 1.91	17.12 ± 0.90
		60	ε'	100.47 ± 4.00	88.68 ± 1.98	59.96 ± 0.53	56.29 ± 1.52	53.85 ± 1.54
			ε''	777.42 ± 45.34	528.86 ± 30.46	56.91 ± 3.59	30.13 ± 2.29	19.58 ± 0.90
		80	ε'	109.78 ± 9.27	95.14 ± 6.71	60.70 ± 2.48	55.75 ± 0.45	53.26 ± 0.88
			ε''	1023.01 ± 53.17	694.96 ± 35.58	73.01 ± 3.98	37.75 ± 2.44	23.54 ± 0.53
		100	ε'	116.49 ± 10.75	98.51 ± 7.56	59.86 ± 2.16	54.56 ± 0.40	51.34 ± 1.08
			ε''	1307.14 ± 72.26	886.42 ± 47.81	91.48 ± 4.70	46.11 ± 2.45	27.68 ± 0.15
		120	ε'	124.33 ± 12.32	100.99 ± 7.62	57.36 ± 0.10	53.51 ± 1.70	51.33 ± 1.97
			ε''	1790.64 ± 99.94	1211.0 ±65.47	121.55 ± 5.11	61.16 ± 2.79	33.08 ± 0.65
	0.2%	20	ε'	96.36 ± 9.42	86.40 ± 5.80	61.64 ± 3.00	59.74 ± 2.61	56.84 ± 2.43
			ε''	475.04 ± 12.93	325.32 ± 9.08	37.95 ± 1.37	22.11 ± 0.55	16.84 ± 0.58
		40	ε'	103.02 ± 13.22	90.32 ± 7.57	60.19 ± 2.42	58.11 ± 2.17	55.02 ± 1.91
			ε''	669.32 ± 29.27	456.97 ± 20.49	51.41 ± 2.83	28.06 ± 1.02	18.50 ± 0.42
		60	ε'	109.78 ± 17.15	93.80 ± 9.42	58.41 ± 2.53	56.07 ± 2.68	52.80 ± 2.18
			ε''	905.69 ± 20.43	616.47 ± 15.05	67.20 ± 2.75	35.30 ± 1.00	21.38 ± 0.23
		80	ε'	116.38 ± 19.90	97.30 ± 10.61	56.45 ± 2.37	53.35 ± 1.48	49.85 ± 1.80
			ε''	1125.09 ± 36.25	765.27 ± 22.92	82.05 ± 1.79	42.21 ± 0.44	24.58 ± 0.64
		100	ε'	124.51 ± 21.10	101.92 ± 11.00	55.71 ± 1.80	52.16 ± 0.78	48.45 ± 1.41
			ε''	1364.11 ± 101.82	926.69 ± 65.26	98.12 ± 3.75	50.06 ± 1.94	28.28 ± 1.30
		120	ε'	134.91 ± 27.11	107.78 ± 14.60	55.34 ± 1.62	51.26 ± 1.02	47.32 ± 1.94
			ε''	1751.92 ± 259.06	1187.79 ±169.49	122.48 ± 12.52	61.37 ± 5.92	33.62 ± 3.13

	0.3%	20	ε'	96.47 ± 4.08	86.79 ± 2.06	61.71 ± 2.37	58.84 ± 2.65	56.76 ± 2.44
			ε"	544.43 ± 23.70	371.96 ± 15.41	41.87 ± 1.27	24.26 ± 0.75	18.28 ± 0.45
		40	ε'	101.69 ± 5.77	89.85 ± 2.58	60.17 ± 1.72	56.88 ± 1.71	54.67 ± 1.62
			ε"	739.79 ± 35.12	503.92 ± 22.94	55.02 ± 2.04	29.93 ± 1.15	20.08 ± 0.49
		60	ε'	107.21 ± 8.53	92.76 ± 4.03	58.44 ± 1.27	54.72 ± 1.40	52.19 ± 1.11
			ε"	971.26 ± 35.13	660.25 ± 23.07	70.42 ± 1.91	37.04 ± 1.07	22.82 ± 0.34
		80	ε'	114.25 ± 11.12	96.63 ± 5.44	57.29 ± 1.11	52.89 ± 1.19	49.93 ± 0.82
			ε"	1235.67± 41.03	838.75 ± 26.55	88.07 ± 2.16	45.31 ± 1.34	26.55 ± 0.59
		100	ε'	124.42 ± 16.69	102.50 ± 8.93	56.93 ± 0.75	51.55 ± 1.17	48.28 ± 0.23
			ε"	1542.58 ± 23.55	1045.78 ± 14.81	108.23 ± 1.88	55.04 ± 0.60	31.25 ± 0.33
		120	ε'	138.48 ± 19.13	110.06 ± 10.58	56.57 ± 0.58	50.06 ± 0.35	46.44 ± 1.35
			ε"	1967.25 ± 120.87	1330.85 ± 79.16	135.22 ± 4.66	67.92 ± 2.52	37.68 ± 1.94
	0.4%	20	ε'	100.21 ± 13.82	88.59 ± 10.44	60.55 ± 4.63	57.31 ± 4.35	54.92 ± 3.80
			ε"	583.51 ± 40.83	399.05 ± 28.89	44.55 ± 3.86	25.19 ± 1.99	18.29 ± 1.54
		40	ε'	108.01 ± 16.51	93.28 ± 12.14	59.05 ± 4.89	55.49 ± 4.44	53.03 ± 3.98
			ε"	798.72 ± 23.75	544.83 ± 17.81	59.31 ± 2.54	31.73 ± 1.12	20.40 ± 0.95
		60	ε'	116.32 ± 20.43	98.07 ± 14.59	57.61 ± 4.83	53.44 ± 4.19	51.41 ± 4.22
			ε"	1050.45 ± 35.11	715.42 ± 26.18	76.04 ± 3.51	39.96 ± 2.06	23.89 ± 1.07
		80	ε'	126.37 ± 22.85	103.95 ± 15.60	57.31 ± 3.77	52.37 ± 2.75	49.50 ± 1.94
			ε"	1339.57 ± 15.19	913.11 ± 10.06	95.32 ± 2.80	49.10 ± 0.52	28.38 ± 0.25
		100	ε'	139.30 ± 25.35	111.61 ± 16.37	57.09 ± 3.12	50.93 ± 2.85	47.22 ± 1.65
			ε"	1639.51 ± 93.59	1113.58 ± 64.44	115.63 ± 6.88	58.31 ± 2.63	32.96 ± 1.31
		120	ε'	154.89 ± 29.63	121.30 ± 18.72	56.21 ± 2.35	48.63 ± 3.24	45.63 ± 2.60
			ε"	1981.33 ± 134.05	1344.14 ± 92.19	137.79 ± 10.42	69.74 ± 4.99	38.72 ± 2.20
	0.5%	20	ε'	102.62 ± 6.33	90.19 ± 3.30	61.47 ± 3.70	58.37 ± 3.25	56.10 ± 3.71
			ε"	687.12 ± 69.41	468.32 ± 45.44	51.21 ± 3.10	28.83± 2.01	20.43 ± 1.57
		40	ε'	109.37 ± 10.29	93.86 ± 5.65	59.40 ± 2.54	55.81 ± 2.06	53.44 ± 2.59
			ε"	898.72 ± 39.74	611.48 ± 25.13	65.91 ± 1.04	35.55 ± 0.65	22.62 ± 0.58
		60	ε'	116.33 ± 15.57	97.32 ± 9.08	57.42 ± 2.23	53.32 ± 1.53	50.84 ± 1.78
			ε"	1166.00 ± 54.99	792.34 ± 35.96	83.60 ± 2.97	43.77 ± 1.57	26.13 ± 1.23
		80	ε'	126.30 ± 20.45	102.69 ± 11.90	56.65 ± 2.19	52.01 ± 1.38	49.37 ± 1.39
			ε"	1481.97 ± 55.41	1005.44 ± 35.91	104.36 ± 2.91	53.73 ± 1.49	30.96 ± 1.24
		100	ε'	140.64 ± 25.62	110.37 ± 13.62	56.54 ± 1.92	50.38 ± 2.32	48.25 ± 1.38
			ε"	1894.32 ± 94.26	1281.90 ± 62.15	129.81 ± 5.98	66.47 ± 2.59	37.72 ± 1.79
		120	ε'	165.25 ± 35.35	122.90 ± 17.66	56.49 ± 2.18	49.21 ± 4.27	47.92 ± 0.48
			ε"	2425.33 ± 125.76	1644.26 ± 88.25	163.60 ± 11.71	83.26 ± 2.66	46.59 ± 1.18
Whey Protein Gel +1.5% D-ribose	0.3%	20	ε'	90.52 ± 3.72	83.29 ± 3.38	61.31 ± 1.80	58.46 ± 2.01	56.01 ± 2.06
			ε"	517.78 ± 20.63	353.24 ± 14.09	40.10 ± 1.76	23.29 ± 1.30	17.85 ± 0.39
		40	ε'	93.41 ± 4.23	84.84 ± 3.64	59.27 ± 1.94	56.24 ± 2.18	54.38 ± 2.29
			ε"	723.33 ± 33.44	491.67 ± 22.71	53.32 ± 2.56	29.19 ± 1.89	19.25 ± 0.45

	60	ε'	96.80 ± 4.18	86.56 ± 3.41	57.58 ± 1.60	54.09 ± 1.86	52.02 ± 1.87
		ε"	970.46 ± 37.38	658.16 ± 25.75	69.57 ± 2.85	36.50 ± 1.94	22.19 ± 0.54
	80	ε'	100.87 ± 4.36	88.63 ± 3.23	56.10 ± 1.78	51.68 ± 2.03	50.48 ± 2.11
		ε"	1245.44 ± 38.9	843.35 ± 26.40	86.99 ± 3.70	45.63 ± 3.12	26.49 ± 1.04
	100	ε'	106.81 ± 4.41	91.92 ± 2.86	55.14 ± 2.50	50.18 ± 1.53	49.24 ± 2.73
		ε"	1556.12 ± 13.7	1052.28 ± 8.93	107.05 ± 0.62	55.54 ± 2.61	31.01 ± 0.72
	120	ε'	115.32 ± 5.00	97.25 ± 2.46	53.91 ± 3.26	47.41 ± 1.29	47.57 ± 3.40
		ε"	1943.72 ± 89.67	1311.82 ± 60.11	130.76 ± 2.96	68.28 ± 2.63	37.07 ± 2.03
Pink salmon fillet	20	ε'	104.71 ± 6.16	91.82 ± 4.49	63.34 ± 2.6	59.45 ± 2.24	55.67 ± 2.27
		ε"	524.03 ± 20.70	358.34 ± 14.37	42.24 ± 1.15	25.56 ± 0.74	19.21 ± 0.64
	40	ε'	113.85 ± 6.87	97.51 ± 3.63	63.45 ± 1.73	59.17 ± 1.95	55.59 ± 1.97
		ε"	687.10 ± 39.87	469.25 ± 26.95	53.56 ± 2.82	30.76 ± 1.37	21.13 ± 0.64
	60	ε'	128.52 ± 7.31	107.17 ± 3.49	62.68 ± 2.20	57.82 ± 2.51	54.01 ± 2.64
		ε"	876.84 ± 56.27	598.97 ± 37.62	67.10 ± 3.31	36.95 ± 1.60	23.71 ± 1.00
	80	ε'	146.29 ± 9.74	119.37 ± 5.06	61.53 ± 2.06	55.59 ± 2.59	51.47 ± 2.84
		ε"	1058.35 ± 69.81	724.25 ± 46.71	81.25 ± 3.62	43.63 ± 1.79	26.64 ± 1.07
	100	ε'	157.38 ± 7.49	126.66 ± 3.87	59.75 ± 1.43	52.93 ± 2.13	48.57 ± 2.49
		ε"	1216.17 ± 81.30	832.26 ± 53.98	93.40 ± 3.86	49.43 ± 1.80	29.27 ± 0.94
	120	ε'	168.88 ± 8.62	133.60 ± 4.15	59.54 ± 0.70	51.66 ± 1.84	46.99 ± 2.48
		ε"	1450.54 ± 120.10	990.60 ± 80.08	109.29 ± 6.07	57.00 ± 2.69	32.87 ± 1.45

[a] ε' is the dielectric constant and ε'' is the dielectric loss factor.

[b] Results of each position of pink salmon fillet are the mean values based on at least three independent trials.

Penetration Depth

Penetration depth of electromagnetic waves is a function of the composition of the food material and is generally used to predict whether microwave or RF radiation will penetrate through a particular thickness of food so that a relatively uniform heating could be achieved during dielectric heating processes. It is important in this study to predict whether the penetration depth in whey protein gel is similar to salmon. If this does hold true, then it will provide greater confidence that models for heating using whey protein gel will be valid for salmon. The equation used to determine the penetration depth is (Equation 1):

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \tag{1}$$

where d_p is the power penetration depth (cm); ε' is the dielectric constant and ε'' is the dielectric loss factor; c is the speed of light in free space (3.00×10^8 m/s) and f is the frequency of the microwaves or the radio frequency waves (Hz).

Penetration depths for salmon were about 66 mm at 27 MHz and 18 mm at 915 MHz at 20 °C, respectively. The penetration depth reduced to 36 mm at 27 MHz and 7.5 mm at 915 MHz at 120 °C (Table 3). Penetration depths for whey protein with added 1% D-ribose and 0.3% NaCl were about 58.49 mm at 27 MHz and 16.62 mm at 915 MHz at 20 °C, respectively. The penetration depth reduced to 29.18 mm at 27 MHz and 6.29 mm at 915 MHz at 120 °C. Penetration depths for whey protein with added 1% D-ribose and 0.2% NaCl were about 63.41 mm at 27 MHz and 18.53 mm at 915 MHz at 20 °C. The penetration depth reduced to 31.03 mm at 27 MHz and 6.88 mm at 915 MHz at 120 °C. The results indicate that penetration depths for whey protein with added 1% D-ribose and 0.2% NaCl are close to the penetration depths of salmon at microwave and RF frequencies range.

Table 3- Penetration depth (mean value [a], mm) for whey protein gel and pink salmon fillet

Sample	T (°C)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
Pink salmon fillet	20	60.28	50.58	21.79	16.08	10.44
	40	51.77	43.17	17.61	13.45	9.51
	60	45.40	37.67	14.43	11.22	8.40
	80	41.15	34.02	12.26	9.50	7.36
	100	38.22	31.54	10.90	8.35	6.57
	120	34.77	28.66	9.67	7.34	5.83
Whey protein gel+ 0.5% D-ribose +0.3%NaCl	20	58.43	49.14	21.99	16.93	11.48
	40	49.17	41.11	17.16	13.76	10.42
	60	42.17	35.10	13.72	11.09	8.77
	80	36.95	30.67	11.37	9.06	7.49
	100	32.61	27.01	9.65	7.48	6.07
	120	28.29	23.38	8.06	6.16	4.92
Whey protein gel + 1% D-ribose + 0.3%NaCl	20	58.49	49.10	21.73	16.82	11.06
	40	49.20	41.06	16.86	13.56	9.92
	60	42.37	35.21	13.55	10.94	8.58
	80	37.23	30.85	11.27	9.01	7.29
	100	33.12	27.39	9.64	7.55	6.17
	120	29.18	24.10	8.21	6.29	5.13
Whey protein gel + 1.5% D-ribose + 0.3%NaCl	20	59.91	50.44	22.54	17.44	11.25
	40	49.55	41.45	17.23	13.82	10.31
	60	42.16	35.11	13.62	11.04	8.80
	80	36.87	30.61	11.32	8.88	7.34
	100	32.78	27.16	9.64	7.42	6.26
	120	29.20	24.17	8.33	6.17	5.25
Whey protein gel + 1% D-ribose + 0.1%NaCl	20	68.03	57.49	27.01	20.37	12.74
	40	56.41	47.30	20.76	16.63	11.69
	60	47.80	39.87	16.35	13.41	10.09
	80	41.22	34.26	13.32	10.84	8.41
	100	36.14	29.95	11.08	8.98	7.09
	120	30.57	25.27	8.88	7.00	6.01
Whey protein gel + 1% D-ribose + 0.2%NaCl	20	63.41	53.32	23.77	18.53	12.00
	40	52.15	43.53	17.89	14.55	10.77
	60	44.11	36.65	14.08	11.55	9.18
	80	39.23	32.49	11.86	9.62	7.83
	100	35.41	29.27	10.31	8.22	6.78
	120	31.03	25.61	8.76	6.88	5.72

a. Results are the mean values of at least three independent trials.

Regression Analysis

Predictive equations for pink salmon and whey protein gel are presented in Table 4. Polynomial relationships were chosen to develop the regression equations at 27 and 915MHz. The regression equations in this study indicate that both temperature and salt content plays an important role in the dielectric characteristics of whey protein gel.

The regression equations and all the predictors in the equations had a significance of $P<0.001$, and the adjusted coefficients of the equation R^2 values greater than 0.97 in all cases, which suggested that the equations can fit in very well with the dielectric properties data and could be used to predict the dielectric properties information for whey protein gel and pink salmon fillet during dielectric heating processes.

For whey protein gel at the same frequencies range (*e.g.*, 915 MHz), the coefficients of the equations for addition of 0.2% or 0.3% salt were very close to each other in both of the dielectric constant and dielectric loss factors, and both cases were well match the coefficients of the equations for pink salmon fillet, gel with added 0.2% salt matches a little bit better. On the other hand, when gel with same amount of salt concentration (*e.g.*, 0.3%), the significant differences of the correlation of the determination coefficients for two frequencies (27 and 915 MHz) was observed from the equations, which shown good agreement with conclusions in Chapter 2, that frequency greatly effects the dielectric behavior of these food products. Briefly, these equations highly support the idea of the use of model food during dielectric heating processes and could be used to obtain the temperature dependent dielectric properties for real food systems within a temperature range 20-120 °C, if the compositions of samples are close to those in this study.

Table 4- Predictive equations for the dielectric constant [a] and the loss factor [b] of whey protein gel and pink salmon as a function of Temperature at 27 and 915 MHz

			Regression Equations	**R^2**
27 MHz	Pink salmon fillet		$\varepsilon' = -0.248E-03T^2 + 0.7201T + 87.643$	0.992
			$\varepsilon'' = 7.792E-03\ T^2 + 8.0477T + 356.936$	0.999
	Whey protein gel +1% D-ribose	0.3% NaCl	$\varepsilon' = 2.791E-03T^2 - 0.01177T + 97.472$	0.993
			$\varepsilon'' = 66.073E-03T^2 + 4.6617T + 455.717$	0.997
		0.2% NaCl	$\varepsilon' = 2.009E-03T^2 + 0.1841T + 90.987$	0.999
			$\varepsilon'' = 66.104E-03T^2 + 4.3728T + 367.841$	0.996
		0.1% NaCl	$\varepsilon' = 3.257E-03T^2 + 0.04833T + 87.271$	0.996
			$\varepsilon'' = 69.532E-03T^2 + 2.4364T + 356.491$	0.997
915 MHz	Pink salmon fillet		$\varepsilon' = -0.440E-03T^2 - 0.02844T + 60.782$	0.979
			$\varepsilon'' = 0.443E-03T^2 + 0.2544T + 20.036$	0.999
	Whey protein gel + 1% D-ribose	0.3% NaCl	$\varepsilon' = 0.338E-03T^2 - 0.1405T + 63.039$	0.999
			$\varepsilon'' = 2.067E-03T^2 + 0.1406T + 21.479$	0.998
		0.2% NaCl	$\varepsilon' = 0.166E-03T^2 - 0.09365T + 60.080$	0.994
			$\varepsilon'' = 2.011E-03T^2 + 0.1437T + 19.190$	0.998
		0.1% NaCl	$\varepsilon' = 0.182E-03T^2 - 0.08359T + 60.122$	0.994
			$\varepsilon'' = 2.276E-03T^2 + 0.05376T + 18.221$	0.997

[a] ε' is dielectric constant

[b] ε'' is dielectric loss factor

CONCLUSION

The dielectric properties of pink salmon fillet and whey protein gel with added D-ribose (0.5%, 1%, and 1.5%, wb) were measured at 0, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% salt concentration, within the frequency range 1-1800 MHz and temperatures range 20-120 ° C. The following significant conclusions may be obtained from this study:

1. The dielectric constant for pink salmon fillet and whey protein gel both sharply increased with temperature at 27 and 40 MHz and moderately decreased at 433, 915 and 1800 MHz. The dielectric loss factor was increased with increasing of temperature at 915 MHz.
2. Salt (sodium chloride) greatly effects on the dielectric loss factor of whey protein gel. With the same amount of D-ribose (1%, wet weight basis), the results show significant differences in the dielectric loss caused by adding salt. The higher salt content the greater the dielectric loss factor.
3. Addition of salt to whey protein gel can adjust its dielectric properties, thus provides flexibility for its use as a model food for microwave sterilization processes to simulate real food systems.
4. Testing of the dielectric properties of several whey protein gel formulations suggested that addition of 0.2% or 0.3% salt content provides a close match to the dielectric properties of frozen and thawed female pink salmon (*O. gorbuscha*) fillet. These gel formulations could be used in place of salmon for process development. Any process would then have to be validated using tests with the real food.
5. The prediction equations for dielectric properties using whey protein gel showed good agreement with experimental results. These equations could be incorporated into computer simulations to simulate heating pattern of salmon during microwave sterilization processes.

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CHAPTER FOUR

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

Food safety is one of the most important issues facing the commercialization of microwave sterilization processes. Many studies have been dedicated to understanding the behavior of food materials during dielectric heating to ensure adequate sterility for shelf-stable foods. However, very few guidelines can be found in the literature for developing microwave sterilization processes, and studies which have quantified the factors affecting the temperature distribution are very rare.

In this study, attention was paid to some factors affecting the dielectric properties, namely composition (salt or ash, fat, and moisture content, *etc*.). Whey protein gel was selected as a model food to simulate real food systems; whey protein gel of varying composition was used as a model to predict the behavior of salmon determine the location of cold and hot spots in packaged foods and the function of design effective thermal process to ensure food safety for shelf-stable foods. Testing of dielectric properties of several concentration whey protein gel formulations suggested that addition of 0.2% NaCl and 1% D-ribose provided a close match to the dielectric properties of salmon.

Validation with real food systems (for example, salmon) indicates that whey protein gels can be used for process development in order to predict the cold spot in real food systems. The predict equations for dielectric properties of whey protein gel has good agreement with the experimental results. This way, computer simulations can be developed using dielectric properties data to simulate heating pattern of salmon during microwave sterilization processes. Further research is needed into several areas:

1. The results of this thesis show that model foods can be developed for salmon, and potentially other muscle foods using a whey protein gel base. These model foods will be useful for developing dielectric heating processes; the only restriction is that they should be developed in tandem with the target food product.

2. Water is the major chemical constituent of foods, and it greatly influences the dielectric behavior of foods. Salt content is critically important. It will be important to design experiments and collect the dielectric properties data for whey protein gel formulations at several moisture levels and salt levels if the concentrations of these constituents vary significantly in the target food. The same caveat applies to other model foods such as mashed potatoes. It is important that the water and salt content of a gel be adjusted to closely match the target food, particularly for foods with higher moisture contents.

3. The current research should, therefore, open the way to a series of studies, such as, charting the variation in dielectric parameters in different sections within a heterogeneous food product. For example, it may be possible to design a whey protein gel material that has regions with varying moisture, salt or lipid content that would more closely resemble whole tissue (*e.g.,* lipid distribution in a fish fillet or cut of beef). Studies should also be conducted to determine the most suitable ingredients for incorporation into model foods.

4. Further developments are necessary to achieve a more uniform temperature distribution in foods during microwave sterilization. This study can be very useful for food scientists and other researchers when developing higher quality microwaveable foods.