MICROWAVE ASSISTED THERMAL PROCESSING OF
HOMOGENEOUS AND HETEROGENEOUS FOOD
PACKED IN A POLYMERIC CONTAINER

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Consumption of ready-to-eat food has steadily increased over the last decade. This development can be attributed to the fast pace of the modern lifestyles. This trend along with recent recalls caused by outbreaks of microwavable convenience food has forced government regulatory agencies such as the Food and Drugs Administration (FDA) of the United States to pay closer attention and to provide strict regulatory standards to the production of safe ready-to-eat foods. Although major efforts have been made to develop alternative non-thermal processes, heat is still the most efficient and effective means for commercial production of shelf stable foods.

In theory, application of heat destroys or inactivates pathogens and microorganisms. Conventional application of thermal energy from sources such as steam or hot water requires a prolonged time of exposure of the prepackaged food which subsequently results in the destruction of heat sensitive nutrients. Microwave sterilization
is a new and emerging technology that provides faster heat penetration and can significantly reduce the degradation of heat sensitive nutrients.

A four-cavity microwave assisted thermal sterilization (MATS) system was developed at Washington State University (WSU). The system combines traditional hot water heating in pressurized cavities with microwave heating in order to sterilize food packed in polymeric packages. The system is accepted by the FDA for commercial sterilization of homogeneous and heterogeneous foods.

Being a novel technology, several aspects that might have an influence on the overall utilization of the technology still remain unresolved as far as research is concerned. They include: (1) sensitivity of the system on dielectric property of both food and circulating water inside the cavity, (2) overall heat transfer coefficient between food and circulating water inside the cavity, (3) the effect of frequency shift as a result of continuous use and aging microwave generators on stability of heating patterns, and (4) reduction of reflected power as a result of impedance mismatch between microwave generator (source) and microwave cavity (load). These aspects are the focus of this dissertation.

The dissertation is arranged as follows: Chapter 1 and Chapter 2 discuss relevant concept of microwave propagation inside waveguide and cavities and how microwave energy penetrates food materials and is subsequently converted into heat. Fundamentals of Maxwell’s equations, power conversion, and electromagnetic-heat transfer solution through finite-difference time-domain (FDTD) are among the highlights of these two chapters. Chapter 3 outlines the steps and procedure for creating a computer simulation model that would theoretically describe the microwave system. Electromagnetic field
distribution, power dissipation into heat, and the resulting heating patterns in foods were obtained from the computer simulation model. Results were validated experimentally through the chemical marker method. Chapter 4 centers on discussion of the operating frequency of the generators and how it affects the heating patterns in food. In Chapter 4, the computer simulation model created in Chapter 3 was fully utilized. Operating frequencies of the four generators powering the microwave system were evaluated considering the frequencies of generators manufactured by two different companies, repeatability of measured frequencies over time, and dependency of frequencies with power setting on generators over a period of one year. Heating patterns in foods were then simulated considering the Federal Communication Commissions (FCC) allocated frequency bandwidth for industrial, scientific, and medical (ISM) purposes. Chapter 5 discusses efforts to improve the efficiency of the microwave system through impedance matching using a 3-probe tuner along waveguide. The strategy is Chapter 5 was to reduce power reflection by incorporating variable and controllable inductive elements (3-probe tuner) that would balance the impedance mismatch between the generators and the cavities. Chapter 6 which supports Chapter 7 shows how dielectric properties of precooked salmon were established as affected by marinating condition, precooking temperature and precooking time. Chapter 7 discusses the influence of inherent variation in dielectric properties of salmon to heating pattern and location cold spot and its implication on sterilization value calculation. Finally Chapter 8 summarizes and provides an insightful overview of our overall conclusions and recommendations for future study.
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CHAPTER ONE

ELECTROMAGNETIC BASIS OF MICROWAVE HEATING

1. Introduction

Microwave heating of foods results from conversion of electromagnetic energy to thermal energy through increased agitation of water molecules and charged ions when exposed to microwaves. Direct penetration of microwaves into food materials enables us to heat foods much faster than using conventional heating methods that rely on surface heating such as countertop stoves or baking ovens. The convenience brought about by fast microwave heating makes microwave ovens a household necessity in modern society. Microwave heating systems are also commonly used in the food service and processing industry for fast heating applications. But users of microwave ovens or industrial microwave systems also experience various frustrations, in particular non-uniform heating. Factors that influence uneven microwave heating include microwave cavity design, food physical properties, and food geometry. Those factors determine how the microwave field is distributed in ovens and within foods. Chapter one will discuss fundamental principles which underlie the unique characteristics of microwaves in air and in foods, thus laying a foundation for discussions in other chapters of the book.

This chapter includes an introduction to microwave heating in a broad context of electromagnetic (EM) energy and Maxwell equations that govern the fundamental behavior of EM waves in air, in microwave cavities and in foods. Several very important equations derived from Maxwell equations, including wave equations, power equation, and Snell’s law, are presented. Those equations provide insights into microwave heating behavior in domestic and
industrial microwave ovens and in foods. Finally dielectric properties of foods are briefly discussed in connection with microwave heating and heating uniformity.

2. Microwave

Microwaves are electromagnetic waves at frequencies between 300 MHz and 300,000 MHz (DeCareau, 1985), with corresponding wavelengths of 1m to 0.001m, respectively. Microwaves are used in communication systems and radar (Radio Detection and Ranging). Radar systems were first developed during the World War II for detecting enemy aircraft, and is now used for a wide range of remote sensing and motion detection applications including air-traffic control, missile tracking, weather forecasting, and automobile motion sensing. Microwave communication systems include wireless computer networks, global positioning satellite systems, and cellular video systems (Pozar, 1998).

Table 1. Important microwave frequency allocations for industrial, scientific and medical (ISM) use (DeCareau, 1985; Metaxas & Meredith, 1993; Buffler, 1993)

<table>
<thead>
<tr>
<th>Frequency MHz</th>
<th>Frequency tolerance, MHz</th>
<th>Example of applications</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>896</td>
<td>± 10</td>
<td>tempering of frozen products</td>
<td>Great Britain</td>
</tr>
<tr>
<td>915</td>
<td>± 13</td>
<td>Precooking of bacon, tempering of frozen products</td>
<td>North and South America, China</td>
</tr>
<tr>
<td>2375</td>
<td>± 50</td>
<td>Domestic microwave ovens</td>
<td>Albania, Bulgaria, Hungary, Romania, Czechoslovakia, former USSR</td>
</tr>
<tr>
<td>2450</td>
<td>± 50</td>
<td>domestic microwave ovens, industrial precooking of bacon, pasteurization and sterilization of packaged foods</td>
<td>World-wide, except where 2,375 MHz is used</td>
</tr>
</tbody>
</table>
Due to heavy uses for Radar and wireless communication applications, only a limited number of microwave frequency bands are allocated in different countries (in the US by the Federal Communications Commission or FCC) for industrial, scientific, and medical (ISM) applications to avoid interference to Radar and wireless communication. Table 1 lists ISM bands used in different food applications. Industrial equipment for the listed frequency bands is readily available from commercial suppliers.

3. Electromagnetic Waves

Electromagnetic (EM) waves propagate in space at the speed of light ($\sim 3 \times 10^9$ m/s). X-rays, visible light, microwave, radio waves and light are some of the different forms of electromagnetic waves characterized by wavelength and frequency (Figure 1). The microwave portion of the spectrum lies in the frequency range $300$ MHz to $300,000$ MHz and is therefore a non-ionizing form of electromagnetic energy (Schubert et al., 2005).

![Electromagnetic wave spectrum](The National Physical Laboratory, NPL)

Figure 1: Electromagnetic wave spectrum (The National Physical Laboratory, NPL)
EM waves traveling in space without obstruction approximate the behavior of plane waves. Electromagnetic waves have an electric ($\vec{E}$) field component and a magnetic ($\vec{H}$) field component that oscillate in phase and in directions perpendicular to each other. The behavior of each quantity in a specified region in space is described by the wave equations that we will discuss later in this section. For plane waves, also called transverse electromagnetic (TEM) waves, both $\vec{E}$ and $\vec{H}$ components are in transverse planes (perpendicular) to the traveling direction of the electromagnetic wave. In mathematical terms, an electromagnetic wave propagates in the direction of the cross product of two vectors ($\vec{E} \times \vec{H}$). That is, assuming that the direction of the propagation of EM waves is in the z direction as illustrated in Figure 2, the x-z plane contains the electric component $\vec{E}$ with the electric field components directed towards x-axis, while the y-z plane contains the magnetic component $\vec{H}$ with magnetic field components directed towards y-axis.

![Electromagnetic wave propagation](image)

Figure 2: Electromagnetic wave propagation

The amplitude of electromagnetic wave determines the maximum intensity of its field quantities. The amplitude of the electric field ($E_o$) is measured in volts per meter (V/m) and the magnetic field ($H_o$) in amperes per meter (A/m). A peak to peak value covers one complete cycle of a wave (Figure 2). A complete cycle can also be measured from a given point of intersection on an axis up to a second point of intersection. The wavelength ($\lambda$) of an EM wave
is the distance between two peaks of either electric or magnetic field. The number of cycles per second is called temporal frequency ($f$). The unit of temporal frequency is expressed in Hertz (Hz) which is equal to cycle/s. The time required for a wave to complete a cycle is referred as period ($T$, in second), and $T = 1/f$.

Wavelength and temporal frequency are quantities that are inversely proportional. The proportionality constant is the velocity, or speed of propagation ($U_p$) in m/s and is given in the equation as $f = U_p(1/\lambda)$. In free space, the speed of propagation is equal to the speed of light ($c$):

$$c = \lambda f$$  \hspace{1cm} (1)

The speed of light in free space, which is a constant value, is a meter traveled by light at an interval of 1 per 299,792, 548 of a second which is approximately $3 \times 10^8$ m/s (Sullivan, 1983). Angular frequency ($\omega$) is the ratio of one complete cycle ($2\pi$) to the period ($T$) of a sinusoidal EM wave. It is expressed as:

$$\omega = \frac{2\pi}{T}$$  \hspace{1cm} (2)

$$\omega = 2\pi f$$  \hspace{1cm} (3)

4. **General Wave Equations**

4.1. **Maxwell equations**

A set of four Maxwell equations governs the general characteristics of electromagnetic waves traveling in a medium. These equations are:

$$\nabla \cdot \vec{D} = \rho$$  \hspace{1cm} (4)

$$\nabla \cdot \vec{B} = 0$$  \hspace{1cm} (5)

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}$$  \hspace{1cm} (6)

$$\nabla \times \vec{H} = \sigma \vec{E} + \epsilon \frac{\partial \vec{E}}{\partial t}$$  \hspace{1cm} (7)
Table 2. Description of symbols

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Type</th>
<th>Common Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vec{E}$</td>
<td>Electric field Intensity</td>
<td>vector</td>
<td>V/m</td>
</tr>
<tr>
<td>$\vec{D}$</td>
<td>Electric Flux Density</td>
<td>vector</td>
<td>C/m$^2$</td>
</tr>
<tr>
<td>$\vec{H}$</td>
<td>Magnetic field intensity</td>
<td>vector</td>
<td>A/m</td>
</tr>
<tr>
<td>$\vec{B}$</td>
<td>Magnetic flux density</td>
<td>vector</td>
<td>Wb/m$^2$</td>
</tr>
<tr>
<td>$\vec{j}$</td>
<td>Volume current density</td>
<td>vector</td>
<td>A/m$^2$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Volume charge density</td>
<td>scalar</td>
<td>C/m$^3$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Permeability</td>
<td>scalar</td>
<td>H/m</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Permittivity</td>
<td>scalar</td>
<td>F/m</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Conductivity</td>
<td>scalar</td>
<td>S/m</td>
</tr>
<tr>
<td>$T$</td>
<td>Time</td>
<td>scalar</td>
<td>Second</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>Del operator</td>
<td>vector/scalar</td>
<td></td>
</tr>
<tr>
<td>$\cdot$</td>
<td>Dot product</td>
<td>scalar</td>
<td></td>
</tr>
<tr>
<td>$\times$</td>
<td>Cross product</td>
<td>vector</td>
<td></td>
</tr>
</tbody>
</table>

*V = volts, C = Coulomb, A = amperes, Wb = weber, H = henry, F = farad, S = Siemen

For the above equations to be valid, the medium should have a uniform property that is linear, homogeneous and isotropic. Linearity means the electric flux density $\vec{D}$ is directly proportional to the electric field intensity ($\vec{D} = \varepsilon \vec{E}$) and magnetic flux density $\vec{B}$ is directly proportional to the magnetic field intensity ($\vec{B} = \mu \vec{H}$). Homogeneity means that the dielectric properties of the medium (permittivity, permeability, and conductivity) at all points in the path of the EM wave are the same. Isotropicity means permittivity ($\varepsilon$) and permeability ($\mu$) are independent of orientation of the EM wave (Guru and Hiziroglu, 2004).

Equation 4 describes that the source of an electric field is from the charge density in a given volume, while equation 5 denotes that magnetic monopole does not exist. They are collectively known as the Gauss’ Law. Equation 6 or the Faraday’s Law explains that a time varying magnetic field would induce a time varying electric field. Finally, equation 7 or the Ampere’s Circuit Law describes the conservation of charge in terms of magnetic field, current flow and variable electric field. Those laws had been discovered from experimental observations.
40-50 years before James Clerk Maxwell published a unified electromagnetic theory in 1873 (Pozar, 1998).

4.2. Wave equations

Specific wave equations can be derived from Maxwell’s equations. For simplification, the medium in which EM wave travels is assumed to have no charge density and current density (Sadiku, 2006). By applying curl-operation on equations 6 and 7, wave equations in terms of electric field intensity or magnetic field intensity are expressed as (Metaxas, 1996):

\[
\nabla^2 \vec{E} = \mu \sigma \frac{\partial \vec{E}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (8)
\]

\[
\nabla^2 \vec{H} = \mu \sigma \frac{\partial \vec{H}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \quad (9)
\]

The above two equations are not independent, the knowledge of electric field intensity leads to the magnetic field intensity, or vice versa, as indicated in the Maxwell Equations 6 and 7.

For simplicity, we only consider sinusoidal time-varying fields (referred to as time-harmonic fields). Equations 8 and 9 can then be written in the following forms

\[
\nabla^2 \vec{E} = \gamma^2 \vec{E} \quad (10)
\]

\[
\nabla^2 \vec{H} = \gamma^2 \vec{H} \quad (11)
\]

where (\(\gamma\)) is referred to as propagation constant and

\[
\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \quad (12)
\]

In equation 12, \(\omega\) is the angular frequency of the sine wave (\(\omega = 2\pi f\)) and \(j\) denotes imaginary number (\(j = \sqrt{-1}\)). Metaxas (1996) shows detailed derivation of the general Maxwell’s equations to obtain the above two equations for time-harmonic fields.

The propagation constant \(\gamma\) is a complex number. The real part (\(\alpha\)), referred to as the attenuation constant, describes the decrease in the amplitude of the wave (due to absorption and thus generation of heat) as it travels in a certain medium. The imaginary part (\(\beta\)), referred to as
phase constant, and characterizes the propagation of the wave. Both parts are related to the permittivity, permeability and electric conductivity of the medium in question (Sadiku, 2006):

\[
\alpha = 2\pi f \sqrt{\frac{\mu \varepsilon_0 \varepsilon}{2} \left[ \sqrt{1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2} - 1 \right]}
\]

\[
\beta = 2\pi f \sqrt{\frac{\mu \varepsilon_0 \varepsilon}{2} \left[ \sqrt{1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2} + 1 \right]}
\]

The wave velocity is related to the phase constant by:

\[
U_p = \frac{2\pi f}{\beta}
\]

and wave length by

\[
\lambda = \frac{2\pi}{\beta}
\]

The magnitude of the electric field in an EM wave is proportional to that of the magnetic field. The proportionality constant is the intrinsic impedance (\(\eta\)), and is a function of the medium properties \(\mu\) and \(\varepsilon\). The intrinsic impedance is a complex number (consisting of real and imaginary parts) with corresponding magnitude and angle:

\[
\eta = \frac{E}{H} = \frac{j \omega \mu}{\varepsilon} = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \varepsilon}} = |\eta| \angle \theta_\eta
\]

where:

\[
|\eta| = \sqrt{\frac{\mu / \varepsilon}{\left[1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2 \right]^{1/4}}}
\]

\[
tan 2\theta_\eta = \frac{\sigma}{\omega \varepsilon}
\]

With the propagation constants and intrinsic impedance parameters described above, both electric field intensity and magnetic field intensity for the EM wave traveling along the \(z\) axis
(Figure 2) can be expressed in the phasor form (for explanation of phasor notation see Sudiku, 2006)

\[
\begin{align*}
E_x(+z) &= E_{xo} e^{-\alpha z} e^{-j\beta z} \\
H_y(+z) &= \frac{1}{|\eta|} E_{xo} e^{-\alpha z} e^{-j\beta z} e^{-j\theta_\eta} \\
E_x(-z) &= E_{xo} e^{\alpha z} e^{j\beta z} \\
H_y(-z) &= -\frac{1}{|\eta|} E_{xo} e^{\alpha z} e^{j\beta z} e^{-j\theta_\eta}
\end{align*}
\]

where \( E_{xo} \) indicates the amplitude of EM wave at \( z = 0 \), while \( E_x(z) \) and \( H_y(z) \) denote electric field and magnetic fields which propagate in the z-axis while oscillating in the direction of x-axis and y-axis, respectively. \( E_x(+z) \) and \( H_y(+z) \) are forward moving waves, while \( E_x(-z) \) and \( H_y(-z) \) are the backWard moving waves.

The quantity \( e^{-\alpha z} \) and \( e^{\alpha z} \) determines if or how fast the amplitude decays with distance into the medium; the quantity \( e^{-j\beta z} e^{-j\theta_\eta} \) and \( e^{j\beta z} e^{-j\theta_\eta} \) describes the other characteristics of the wave such as phase, wavelength, and velocity.

### 4.3. Energy and power

Microwave carries electromagnetic energy as it travels through a medium. A measure of the microwave power across a unit area is the Poynting vector (in \( \text{w/m}^2 \)) is defined as (Sadiku, 2006):

\[
\vec{P} = \vec{E} \times \vec{H}
\]

It is an instantaneous power density vector in the direction of microwave propagation and is a function of time and location. The Poynting vector for a plane wave traveling in the z direction, as shown in Figure 2, can be expressed as \( \vec{P}(z, t) \). It’s time average value, a more commonly used value to indicate the changes in microwave power with distance, is calculated as:

\[
\bar{P}_{ave}(z) = \frac{1}{T} \int_0^T \vec{P}(z, t) dt
\]
For time-harmonic waves and using Equations 20 to 21, the magnitude of microwave power as a function \( z \) can be written in terms of electric field intensity:

\[
P_{ave}(z) = \frac{1}{2|\eta|} E_{x0}^2 e^{-2az} \cos \theta_\eta
\]  

(26)

Or simply:

\[
P_{ave}(z) = P_{ave}(0)e^{-2az}
\]  

(27)

where \( P_{ave}(0) \) is the microwave power flux intensity (w/m\(^2\)) at \( z = 0 \). Equation 27 resembles the form of the Beer-Lambert law developed empirically for reduction of light intensity as it travels through different materials (Ingle and Crouch, 1988).

5. **Propagation of Microwaves in Different Media**

For convenience, the discussion of EM wave characteristics is made in connection with different media classified into four different general categories (Guru and Hiziroglu, 2004); (1) free space, (2) lossless dielectric, (3) lossy dielectric, and (4) good conductor. As will be seen later, categories 1, 2, and 4 can all be considered as special cases of category 3.

5.1. **Free space**

Free space is defined as a perfect vacuum or, at microwave frequencies, air. The permittivity, permeability, and conductivity of a free space have the following values:

\[
\varepsilon_o = \frac{10^{-9}}{36\pi} \text{F/m} \\
\mu_o = 4\pi \times 10^{-7} \text{H/m} \\
\sigma_o = 0 \text{S/m}
\]  

(28)

The permittivity and permeability of all other media are given relative to the dielectric properties of free space

\[
\varepsilon = \varepsilon_r \varepsilon_o \\
\mu = \mu_r \mu_o
\]  

(29) (30)
where, \( \varepsilon_r \) and \( \mu_r \) are dimensionless numbers, referred to as relative permittivity and permeability. For free space, \( \varepsilon_r = 1 \) and \( \mu_r = 1 \). Food materials are generally non-magnetic in nature, the relative permeability approximates a value of one (\( \mu_r = 1 \)).

Using the values provided by Equation 28, the intrinsic impedance of a free space (\( \eta_0 \)) can be calculated from Equation 18:

\[
\eta_0 = \frac{\mu_0}{\varepsilon_0} = 120\pi \approx 377\Omega
\]

The velocity (\( U_p \)) for the EM wave traveling in free space is calculated from Equation 15 as:

\[
U_p = \frac{2\pi f}{\beta} = \frac{2\pi f}{2\pi f \sqrt{\mu_0 \varepsilon_0}} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 299,792,548 \frac{m}{s} \approx 3 \times 10^8 \frac{m}{s}
\]

The above value is indeed the speed of light. Thus, often the more conventionally used symbol \( c \) is used, instead of \( U_p \).

Likewise, the wavelength in free space (and air) is calculated as:

\[
\lambda_0 = \frac{2\pi}{\beta} = \frac{2\pi}{2\pi f \sqrt{\mu_0 \varepsilon_0}} = \frac{1}{f \sqrt{\mu_0 \varepsilon_0}}
\]

5.2. Lossless dielectric media

In a lossless dielectric medium (e.g., plastics, glasses and other electrically non-conductive materials) the conduction current is negligible compared to the displacement current (expressed as the second term on the right hand-side of Equation 7). Thus conductivity can be assumed approximately zero (\( \sigma = 0 \)). The parameters that determine wave propagation, impedance and phase angles expressed in the general Equations 12 and 17 can be simplified into:

\[
\alpha = 0
\]

\[
\beta = 2\pi f \sqrt{\mu_r \varepsilon_r \varepsilon_0}
\]

\[
\eta = \frac{\mu_r \mu_0}{\varepsilon_r \varepsilon_0}
\]

\[
\theta_\eta = 0
\]
The general form for a transverse EM wave (Equations 20 and 21) traveling in a lossless dielectric medium in the direction $z$ can also be simplified into:

\[
\vec{E}_x(+z) = E_{xo}e^{-j\beta z} \\
\vec{H}_y(+z) = \frac{1}{\eta}E_{xo}e^{-j\beta z}
\] (38)  
(39)

The above wave equations suggest no reduction in intensity as EM wave travels in the $z$ direction.

### 5.3. Lossy dielectric media

A lossy dielectric medium is defined as a medium in which the electric conductivity is not equal to zero yet it is not a good conductor. Setting $\sigma \neq 0$ in Equation 12 leads to a non-zero attenuation constant ($\alpha \neq 0$). The general wave equations and the associated parameters expressed in Equations 12 to 27 therefore apply to lossy dielectric media. According to Equations 20 and 21, the amplitude of electric and magnetic fields decreases exponentially with travel distance (Figure 3).

![Figure 3: Reduction in wave amplitude with travel distance.](image)

The changes in the amplitudes are quantified by the attenuation constant ($\alpha$). Microwave power was lost (i.e., converted to heat) according to Equation 27:

\[P_{ave}(z) = P_{ave}(0)e^{-2\alpha z}\] (40)

This is illustrated in Figure 4 as an EM wave enters into a lossy dielectric medium.
Figure 4: Attenuation of EM wave in a lossy dielectric medium and definition of power penetration depth.

The larger the value of the attenuation constant ($\alpha$), the more rapid the EM wave loses its power along the path of transmission. The ability of EM to penetrate a lossy dielectric material is indicated by power penetration depth, commonly (in contrast to the half power depth) defined as the distance over which the EM power decreases to 0.368 ($1/e$) of the original value (Metexas and Meredith, 1993). From this definition, one can derive the expression for the power penetration depth ($d_p$) using Equation 27:

$$P_{ave}(z) = P_{ave}(0)e^{-2\alpha z} = \frac{1}{e}P_{ave}(0)$$  \hspace{1cm} (41)

Using the last two terms in the above equation yields:

$$d_p = \frac{1}{2\alpha}$$  \hspace{1cm} (42)

Substituting in Equation 13 yields:

$$d_p = \frac{1}{2\pi f \sqrt{2\mu \varepsilon_0 \varepsilon \left[1 + \left(\frac{\sigma}{\omega \varepsilon_0}\right)^2\right]}}$$  \hspace{1cm} (43)

The above equation will be used in a later section to discuss microwave power penetration in foods in connection with microwave heating uniformity.
5.4. Good conductor

Good conductors, such as metals, are characterized by extremely large electric conductivities (i.e., $\sigma_{copper} = 6 \times 10^7 \text{ S/m}$). Thus, setting $\sigma = \infty$ in Equations 12 and 17 leads:

$$\alpha = \infty; \quad \beta = \infty; \quad U_p = 0$$

The above values suggest that microwaves do not transmit in good conductors. In reality, all metals are not perfect conductors, and electric conductivity is not infinitely large. Electromagnetic wave does penetrate several microns, depending upon the electric conductivity of the materials. But for practical reasons, we consider all metals to be perfect dielectric conductors (PEC). Metals are used to confine microwave energy in a space (i.e., in a microwave cavity) or to guide microwave (i.e., in a waveguide) to a specific application location.

6. Propagation of Electromagnetic Wave between Two Media

This section provides a brief description of the general characteristics of electromagnetic waves when traveling through two different yet adjacent media (e.g., from medium 1 to medium 2). The wave traveling in medium 1 before encountering medium 2 is called the incident wave. At the interface between medium 1 and 2, a portion of the incident wave will enter medium 2 and be transmitted at a certain angle ($\theta_t$) referred to as the angle of transmission (Figure 5a). This wave is called the transmitted wave. The rest of the incident wave will be reflected back to medium 1 at a certain angle called the angle of reflection ($\theta_r$). This wave is called the reflected wave. If the direction of the incident wave is perpendicular to the interface of the two media ($\theta_i = 0$), the resulting angle of transmission and reflection will be equal zero ($\theta_i = \theta_r = 0$)(Figure 5b). This condition is called normal penetration of EM waves, since the direction of propagation is normal to the interface. In a more general case in which an incident wave travels at a certain
angle to the interface between the two media \( (\theta_i > 0) \), the angle of transmission and reflection will no longer be equal to zero. This condition is called oblique penetration of EM waves.

The portion of an incident wave being transmitted is quantified by the transmission coefficient \( \tau \) defined as the ratio of the amplitude of the transmitted electric field over the amplitude of the incident electric field:

\[
\tau = \frac{E_{xo(\text{transmitted})}}{E_{xo(\text{incident})}} \tag{44}
\]

The portion of an incident wave being reflected is quantified by the reflection coefficient \( q \) defined as the ratio of the amplitude of the reflected electric field over the amplitude of the incident electric field:

\[
q = \frac{E_{xo(\text{reflected})}}{E_{xo(\text{incident})}} \tag{45}
\]
6.1. Normal penetration

For normal penetration of electromagnetic wave, the transmission and reflection coefficients can be expressed in terms of intrinsic impedances of the two media \((\eta_1, \eta_2)\) (Guru and Hiziroglu, 2004):

\[
\begin{align*}
\tau &= \frac{E_{xo(\text{transmitted})}}{E_{xo(\text{incident})}} = \frac{2\eta_2}{\eta_2 + \eta_1} \quad (46) \\
Q &= \frac{E_{xo(\text{reflected})}}{E_{xo(\text{incident})}} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad (47)
\end{align*}
\]

where subscript 1 and 2 denotes the first and second medium, respectively. The above Equations were derived from the assumption that there is no current density at the interface of the two media and that the tangential component of electric and magnetic field are continuous. In an air-dielectric medium interface, the equation of incident, reflected, and transmitted waves are as follows:

\[
\begin{align*}
\vec{E}_x(+z)_{\text{incident}} &= \frac{1}{\eta_1} \vec{E}_{xo(\text{incident})} e^{-j\beta_1 z} \\
\vec{H}_y(+z)_{\text{incident}} &= \frac{1}{\eta_1} \vec{H}_{xo(\text{incident})} e^{-j\beta_1 z} \\
\vec{E}_x(-z)_{\text{reflected}} &= Q \vec{E}_{xo(\text{incident})} e^{j\beta_1 z} \\
\vec{H}_y(-z)_{\text{reflected}} &= -Q \vec{H}_{xo(\text{incident})} e^{j\beta_1 z} \\
\vec{E}_x(+z)_{\text{transmitted}} &= \tau \vec{E}_{xo(\text{incident})} e^{-j\beta_2 z} \\
\vec{H}_y(+z)_{\text{transmitted}} &= \frac{\tau}{\eta_2} \vec{H}_{xo(\text{incident})} e^{-j\beta_2 z}
\end{align*}
\]

Equations 48 and 53 describe the incident wave traveling in medium 1 in the positive direction of \(z\) (towards medium 2). Equations 50 and 51 are for reflected waves traveling in medium 1 in the negative \(z\) direction, away from medium 2. The incident wave is considered to be a forward moving wave and the reflected wave a backWard moving wave. The intrinsic impedance and angular phase for these two waves depend on properties of medium 1 \((\eta_1, \beta_1)\). The transmitted wave described by Equation 52 and 53 is a forward moving wave traveling in medium 2 at
positive z direction. The intrinsic impedance and angular phase in this wave is dependent on medium 2 \((\eta_2, \beta_2)\).

If medium 2 is a good conducting material \((\sigma = \infty)\), the corresponding \(\eta_2\) is approximately 0 (see Equation 17). Using Equations 46 and 47, the transmission coefficient \(\tau\) is then calculated to be zero and the reflection coefficient to be -1. That is, the microwave is totally reflected at the interface.

Microwave oven walls are made of metal sheets with large electric conductivities. Thus, in an enclosed microwave cavity, the microwaves are reflected back and forth between metal surfaces, forming standing wave patterns, which will be discussed in depth in a later section.

6.2. Oblique penetration

Polarization, defined by the direction of the electric field at a given point (Guru and Hiziroglu, 2004), of EM wave does not influence the form of the equations for plane waves traveling normal to the interface of two media. However, for waves traveling oblique to the interface, the expressions for transmission and reflection coefficients depend upon the manner in which the wave is polarized. Therefore discussions of wave equations for oblique penetration are made with respect to polarization of EM waves.

An EM wave can either have parallel or perpendicular polarization relative to the plane of incidence. The plane of incidence is defined by two vectors: the propagation vector (in the direction of wave propagation) and the unit vector normal to the interface of the two media. For the simple case in Figure 5, the x-z plane is the plane of incidence. In parallel polarization the direction of electric field is in the plane of incidence and the direction of magnetic field is perpendicular to the plane of incidence. In perpendicular polarization, on the other hand, the
direction of electric field is perpendicular to the plane of incidence and magnetic field is in the plane of incidence.

By applying continuity on the tangential component of both electric and magnetic fields for the two adjacent media, expressions for the reflection and transmission coefficients can be obtained in terms of intrinsic impedance of the two media. The equations for reflection and transmission coefficients for both parallel and perpendicular polarization are as follows (Sadiku, 2006):

\[
\begin{align*}
Q_\| &= \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_i} \\
\tau_\| &= \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_i} \\
Q_\perp &= \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_t}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t} \\
\tau_\perp &= \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t}
\end{align*}
\]

where subscript (\(\|\) and \(\perp\)) denotes parallel and perpendicular polarization, respectively. The relations between reflection angle \(\theta_r\) and incidence angle \(\theta_i\) and between transmission angle \(\theta_t\) and incidence angle \(\theta_i\) are described by Snell’s law of reflection and refraction, respectively.

Snell’s laws are derived by considering the boundary condition at the interface. For example, at the interface shown in Figure 5a at \(z = 0\), the tangential component of EM field follows a continuity equation (Guru and Hiziroglu, 2004)

\[
\begin{align*}
& e^{-\gamma_1 x \sin \theta_i} + Q_\perp e^{-\gamma_1 x \sin \theta_r} = \tau_\perp e^{-\gamma_2 x \sin \theta_t} \\
& e^{-\gamma_1 x \sin \theta_i} + Q_\| e^{-\gamma_1 x \sin \theta_r} = \frac{\eta_1}{\eta_2} \tau_\perp e^{-\gamma_2 x \sin \theta_t}
\end{align*}
\]

for perpendicular and parallel polarizations, respectively. In perpendicular polarization (Equation 58), both reflected and transmitted waves are proportional to the reflection and transmission coefficient, respectively. These coefficients will sum to one assuming a perfectly conserved EM wave. The expression can be obtained by setting \(x\) equal to zero in Equation 58.

\[
1 + Q_\perp = \tau_\perp
\]
In parallel polarization (Equation 59), however, the transmitted wave is proportional to the product of transmission coefficient and the ratio of the intrinsic impedance at medium 1 and intrinsic impedance at medium 2:

\[ 1 + \vartheta_\parallel = \frac{\eta_1}{\eta_2} \tau_\parallel \]  

(61)

Equating Equation 58 with Equation 60 and Equation 59 with Equation 61 simultaneously for all values of \( x \) would give an equation of:

\[ \gamma_1 \sin \theta_i = \gamma_1 \sin \theta_r = \gamma_2 \sin \theta_t \]  

(62)

The relationship would result into three terms of equality. The first and second terms are the basis of Snell’s law of reflection (Equation 63) which states that the incident angle (\( \theta_i \)) is equal to the reflection angle (\( \theta_r \)). Thus, it is convenient to assign both to \( \theta_1 \) as they are in medium 1. Equating the third term of Equation 62 to either first or second terms yields Snell’s law of refraction (Equation 64) which states that the product of propagation constant of the first medium (\( \gamma_1 \)) and the sine of the angle in the first medium (\( \theta_1 \)) is equal to the product of propagation constant of the second medium (\( \gamma_2 \)) and the sine of the transmission angle (\( \theta_t \)). As \( \theta_i \) is for the second medium, we use symbol \( \theta_2 \) instead. In summary:

\[ \theta_1 = \theta_i = \theta_r \]

\( \theta_2 = \sin^{-1}\left(\frac{\gamma_1 \sin \theta_1}{\gamma_2}\right) \Rightarrow \gamma_1 \sin \theta_1 = \gamma_2 \sin \theta_2 \)  

(63)

(64)

If interfacing media are dielectric-dielectric or free space-dielectric, the ratio of propagation constant would become (assuming non-magnetic media with \( \mu = 1 \)):

\[ \frac{\gamma_1}{\gamma_2} = \frac{j \beta_1}{j \beta_2} = \frac{\varepsilon_{r_1}}{\varepsilon_{r_2}} \]

(65)

where \( \varepsilon_{r_1} \) and \( \varepsilon_{r_2} \) are the relative permittivity of the first and second medium, respectively.

Snell’s law of refraction can be written in a simplified form:
\[ \theta_2 = \sin^{-1}\left(\sqrt{\frac{\epsilon_r}{\epsilon_r}} \sin \theta_1\right) \]  

(66)

Snell’s law is useful in understanding the unique microwave heating patterns within certain size spherical and cylindrical shaped foods. Detailed discussion of this subject can be found in Buffler (1993).

7. Standing Waves

Consider a simple condition wherein a transverse EM wave (Figure 2) travels in the air in a direction normal to a good conducting surface, such as a metal wall, at \( z = 0 \). As discussed earlier in Section 6, the wave will be completely reflected back. To satisfy the boundary condition that the tangential electric field intensity at the metal wall is zero, the reflected wave is 180° out of phase with the incident wave at the reflection surface. The reflected wave and the incident wave, traveling with equal amplitude but in opposite directions, form a field pattern that appears to be stationary (referred to as a standing wave) with fixed locations of zero intensity, where the two waves are 180° out of phase, and maximum intensity, where the two waves are in phase. The locations for the maximum and zero intensity are adjacent to each other and separated by 1/4 wavelength with a zero intensity location at the metal wall (see Figure 6). The field intensity of the standing wave at the maximum is twice that of a single traveling wave.

Figure 6: Illustration of a standing wave oscillating with amplitude that changes with location in space. The right hand minimum point is at the metal wall.
An intuitive way to describe a standing wave is to imagine a flexible string with one end attached to a fixed wall (Figure 7). Waves can be introduced by swinging the other end of the string. When the first full wave encounters the fixed point, it is reflected back in the opposite direction. Reflection happens because wave from the string cannot travel beyond the wall. The point of the attachment causes a momentum change, shifting the phase angle by 180°. The first full wave now traveling back Ward encounters the second full wave traveling forward. The first and second waves interfere and form a standing wave pattern with node (minimum amplitude) and anti-node (maximum amplitude) at fixed locations. The standing waves in microwave cavities create cold and hot spots, which is one of the main reasons for uneven heating.

Figure 7: Illustration of a standing wave with a flexible string, the location of nodes (minimum amplitude) and anti-nodes (maximum amplitude) are fixed in space, depending on wavelength.

7.1. Voltage Standing Wave Ratio

In a general case where a reflective surface is not a highly conductive material, only a portion of incident wave is reflected. The amplitude of the reflected wave is less than that of the incident wave as quantified by the reflection coefficient (\( \phi \)) (Equation 47). The standing wave
formed by the incident and reflected waves has maximum and minimum amplitude at the locations of 0 and 180 phase difference (Figure 8(a) and 8(b), respectively):

\[
\begin{align*}
E_{\text{max}(\text{standing})} &= E_0(\text{incident}) + E_0(\text{reflected}) \\
E_{\text{min}(\text{standing})} &= E_0(\text{incident}) - E_0(\text{reflected})
\end{align*}
\]

(67)  
(68)

Figure 8: Voltage standing wave ratio: (a) incident wave in phase with partially reflected wave; (b) incident wave 180° out of phase with partially reflected wave; (c) incident wave in phase with completely reflected wave; (d) incident wave 180° out of phase with completely reflected wave.

Voltage standing wave ratio (VSWR) is a value used to quantify the maximum and minimum amplitudes of a standing wave. It calculated as the ratio between the absolute value of the maximum and minimum amplitude of a standing wave:

\[
\text{VSWR} = \frac{|E_{\text{max}}|}{|E_{\text{min}}|}
\]

(69)
VSWR has a value between 1 and infinity. The VSWR value for the standing wave formed by an incident and completely reflected waves discussed earlier is equal to infinity (refer to Figure 8(c) and 8(d)). When there is no reflection, as in the case where a wave travels from a waveguide into a matching load, no standing wave will be formed. Therefore, $E_{\text{min}} = E_{\text{max}}$ and VSWR is equal to one ($\text{VSWR} = 1$).

8. Waveguide

A waveguide is a hollow metallic channel that has either rectangular or cylindrical cross-sections. The main purpose of a waveguide is to direct electromagnetic wave from a microwave source (e.g., a magnetron) to a microwave applicator (e.g., an oven cavity). Although different shapes of waveguide are designed for different purposes, a rectangular shape waveguide (Figure 9) is commonly used in industrial microwave heating and solely in domestic microwave ovens.

![Rectangular waveguide](image)

Figure 9: Rectangular waveguide

When confined in a waveguide, electromagnetic wave travels with certain patterns (modes) governed by the Maxwell equations under the boundary conditions defined by the conducting waveguide walls. Thus, transverse electromagnetic waves (TEM) will not propagate in a waveguide. Propagation is either by transverse electric modes ($TE_{mn}^Z$) or transverse magnetic modes ($TM_{mn}^Z$). In $TE_{mn}^Z$ modes, the electric field is transverse to the direction of wave...
propagation along the waveguide (i.e., the z direction in Figure 9), thus $E_z = 0$. In $TM_{mn}^z$ modes, the magnetic field component is transverse to the direction of wave propagation, and $H_z = 0$. Each mode is characterized by a discrete field pattern quantified by integers, $m$ and $n$ (i.e., 0, 1, 2…), which represent the number of half wave variations in field patterns along x and y direction, respectively (Sadiku, 2006). In TE modes both $m$ and $n$ cannot be zero at the same time; in TM modes $m$ and $n$ cannot be equal to zero which means the lowest value is 1. The type of modes, each having a discrete pattern inside the waveguide, depends on waveguide dimensions, the medium inside, and the operating frequency of the electromagnetic wave (Guru and Hiziroglu, 2004).

Figure 10 illustrates the electric field and magnetic field for $TE_{10}^z$ (a) mode and $TM_{11}^z$ (b) mode seen from different cross sections of a waveguide. The solid lines show the direction of the electric field; the dashed lines show the direction of the magnetic field. The density of the lines indicates field intensity. Since the tangential electric field at a good conductive surface is zero, in the proximity of metal walls the electric field lines are always perpendicular to wall surfaces, accordingly the magnetic field lines are parallel to the wall surfaces.

From the transverse cross sectional view (top graph of Figure 10 (a)), the electric field pattern for the $TE_{10}^z$ mode has one half wave variation along the x axis, with zero field intensity along both vertical walls of the waveguide (in y direction). For the $TM_{11}^z$ mode, the magnetic field has one half wave variation in both x and y directions (top graph of Figure 10 (b)). Figure 11 illustrates 3 dimensional field patterns for $TE_{10}^z$ mode and $TM_{11}^z$. 
The general equation of electromagnetic wave traveling inside a waveguide can be obtained by deriving the Maxwell’s equations and applying the boundary conditions on four corners of the metal surface of the waveguide. The following are the wave equations for electric and magnetic fields in different directions ($E_x$, $E_y$, $E_z$, $H_x$, $H_y$, and $H_z$) for both $TE$ and $TM$ modes propagating along the $z$ axis.
Figure 11: Field pattern of $TE_{10}^{z}$ and $TM_{11}^{z}$ (Jefferies, 1996)

For $TE_{mn}^{z}$ mode:

\[
E_x = \frac{j\omega \mu H_o}{(j\beta z)^2 + \omega^2 \mu e} \cos(Mx)\sin(Ny)e^{-j\beta z}
\]
\[
E_y = \frac{-j\omega \mu H_o}{(j\beta z)^2 + \omega^2 \mu e} \sin(Mx)\cos(Ny)e^{-j\beta z}
\]
\[
E_z = 0
\]
\[
H_x = \frac{j\beta M H_o}{(j\beta z)^2 + \omega^2 \mu e} \sin(Mx)\cos(Ny)e^{-j\beta z}
\]
\[
H_y = \frac{j\beta N H_o}{(j\beta z)^2 + \omega^2 \mu e} \cos(Mx)\sin(Ny)e^{-j\beta z}
\]
\[
H_z = H_o \cos(Mx)\cos(Ny)e^{-j\beta z}
\]

For $TM_{mn}^{z}$ mode:

\[
E_x = \frac{-j\beta \mu E_o}{(j\beta z)^2 + \omega^2 \mu e} \cos(Mx)\sin(Ny)e^{-j\beta z}
\]
\[
E_y = \frac{-j\beta \mu E_o}{(j\beta z)^2 + \omega^2 \mu e} \sin(Mx)\cos(Ny)e^{-j\beta z}
\]
\[
E_z = E_o \sin(Mx)\sin(Ny)e^{-j\beta z}
\]
\[
H_x = \frac{j\omega \epsilon E_o}{(j\beta z)^2 + \omega^2 \mu e} \sin(Mx)\cos(Ny)e^{-j\beta z}
\]
\[
H_y = \frac{-j\omega \epsilon E_o}{(j\beta z)^2 + \omega^2 \mu e} \cos(Mx)\sin(Ny)e^{-j\beta z}
\]
\[
H_z = 0
\]

$E_o$ and $H_o$ is the maximum amplitude of electric field and magnetic field, respectively. $M$ and $N$ are the half wave representation of waves. For a rectangular waveguide (Figure 9) $M$ and $N$ is equal to
Cutoff Frequency \( (f_{c_{mn}}) \) is the lowest frequency that allows propagation of EM wave. For electromagnetic waves to propagate along a waveguide, the operating frequency \( (f_{mn}) \) should be greater than the cutoff frequency for a given mode. Consider the propagation constant of EM wave inside the waveguide \( (\gamma_{mn}) \) which is a complex number (Equation 84). If the operating frequency is greater than the cutoff frequency \( (f_{mn} > f_{c_{mn}}) \), \( \gamma_{mn} \) will become an imaginary number \( (\gamma_{mn} = \beta_{mn}) \), indicating purely propagation of waves. The equation of the cutoff frequency (Equation 85) can be derived by equating \( \gamma_{mn} \) to zero and using the expression \( \omega = 2\pi f \).

\[
\gamma_{mn} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} - \omega^2 \mu e = \alpha_{mn} + \beta_{mn} \tag{84}
\]

\[
f_{c_{mn}} = \frac{1}{2\pi\sqrt{\mu e}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \tag{85}
\]

However, if the operating frequency is less than the cutoff frequency, \( \gamma_{mn} \) is a real number \( (\gamma_{mn} = \alpha_{mn}) \), indicating purely attenuating waves. Under this condition, EM wave will exponentially attenuate along z direction (Harrington, 1961).

It is possible that multiple modes may co-exist inside a waveguide. For a waveguide that has a dimension \( a = 2b \), the value of the cutoff frequency for given \( m \) and \( n \) integers are in the following increasing order; \( f_{c_{10}} < f_{c_{01}} < f_{c_{11}} \). If the excitation frequency is between \( f_{c_{10}} \) and \( f_{c_{01}} \) (i.e., \( f_{c_{10}} < f_{mn} < f_{c_{01}} \)), only one mode will predominate which is the TE mode. This is called single mode operation. However, if the excitation frequency is greater than \( f_{c_{11}} \) (i.e., \( f_{c_{11}} < f_{mn} \)), both TE and TM modes may coexist. This is called a multimode operation. The field pattern and behavior of the wave is easier to characterize for a single mode compared to multimode.

Most rectangular waveguide are designed to carry \( TE_{10} \) mode. For example, in a domestic microwave oven operating at 2.45 GHz, a WR340 waveguide which has a dimension of
and is commonly used (Guru and Hiziroglu, 2004). The cutoff frequency of $TE_{10}^Z$ and $TE_{01}^Z$ mode is 1.74 GHz and 3.49 GHz, respectively, hence a 2.45 GHz operating frequency is within the range and would propagate in the $TE_{10}^Z$ mode.

9. Field Patterns in Single-mode and Multimode Cavities

During microwave heating, materials are enclosed in spaces surrounded by metal walls. Those specially designed spaces are commonly referred to as microwave cavities. A microwave cavity can be categorized as single-mode or multimode. A single-mode cavity has dimensions which allow only one possible field pattern. This field pattern is created by the standing wave between the walls of the cavity. Figure 12 shows the example of a single-mode cavity. It consists of a $TE_{10}^Z$ waveguide, a small cavity (or resonator), and a coupling aperture to maximize the power coupled into the cavity. The size of the cavity is comparable to or slightly larger than that of the waveguide, and the excitation frequency from the source of microwave power is provided within a narrow frequency band to maintain the necessary coupling (Metaxas and Meredith, 1993).

![Figure 12: TM_{010} cavity resonator (Schubert and Riegel, 2005)](image)

Inside the cavity shown in Figure 12, the position of the maximum electric field is at the center. The food material is loaded to a position that has a maximum electric field for optimum
absorption of energy for microwave heating. This is a major advantage of a single mode cavity. A disadvantage of a single mode cavity is the relatively small zone in which food material can be effectively heated. This design can be used for heating small samples in analytical laboratories, or for heating liquid or other pumpable materials in industrial applications.

Multimode cavities are most commonly used in microwave heating applications. A typical domestic microwave oven is a multimode cavity. The size of a multimode cavity is much larger than that of a single mode for the same operating microwave frequency. Typically the dimensions of a multimode cavity are several times the free space wavelength of the microwave generated by the magnetron.

In a multimode cavity, several different field patterns are possible over a narrow frequency range, with each field pattern representing a given mode. Calculation of cutoff frequency of modes inside a microwave cavity is different from that of the waveguide. This is because waveguide is open ended while microwave cavity is enclosed. The equation of cutoff frequency for microwave cavity is:

$$f_{cmnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$  \hspace{1cm} (86)

where $m$, $n$, and $p$ are integer numbers that represent the discrete pattern of the half wave variation of field with corresponding length of $a$, $b$ and $l$ along $x$, $y$, and $z$ axis respectively (Figure 13).
Modes that exist in an empty microwave cavity are characterized by the discreet pattern of $m$, $n$ and $p$, representing $x$, $y$ and $z$ directions. Specifically, they are designated as $TE_{mnp}$ and $TM_{mnp}$ for transverse electric and transverse magnetic, respectively. In $TM$ modes, the lowest possible value of $p$ is zero (0). In $TE$ modes the lowest possible value of $p$ is one (1). Several $TE$ and $TM$ modes may co-exist for the same frequency bounded by its corresponding cutoff frequency. These modes are referred to as degenerate modes. But two different modes ($TE$ and $TM$) will only exist at a same frequency if their indices ($m$, $n$, and $p$) are non-zero or two sides of cavity ($xy$, $xz$, $yz$) are equal in length. Although different modes may exist for the exactly the same frequency, their corresponding field pattern is not the same. The possible modes that may exist in a microwave cavity can be estimated using the Equation 87.

$$2\pi f_{mnp}\sqrt{\mu\epsilon} = \sqrt{\left(\frac{mn}{a}\right)^2 + \left(\frac{nn}{b}\right)^2 + \left(\frac{pn}{l}\right)^2}$$

(87)

For an empty microwave cavity that has a cubical shape ($a = b = l = \text{length}$), Equation 87 can be simplified to.

$$4\left(\frac{\text{length}}{\lambda}\right)^2 = m^2 + n^2 + p^2$$

(88)

Evaluating the left hand side of Equation 87 using the corresponding operating frequency range ($f_{mnp}$) and the dimension ($a$, $b$, and $l$) of microwave oven gives possible modes and its
corresponding indices \((m, n, p)\). This can be done by substituting a trial and error value of \(m\), \(n\) and \(p\) to the right hand side while considering the restriction for a TE and TM mode. A combination of \(m\), \(n\) and \(p\) that gives a value within the range of the left hand side of Equation 87 is a valid index. Listed below are the possible modes and its corresponding indices for an empty non-cubical microwave oven operating in a frequency range of 2.425 to 2.475 GHz.

Table 3. Possible modes for an empty non-cubical microwave oven (Chan and Reader, 2000)

<table>
<thead>
<tr>
<th>Indices</th>
<th>Modes</th>
<th>Frequency / GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 5 2</td>
<td>TE</td>
<td>2.4320</td>
</tr>
<tr>
<td>0 4 3</td>
<td>TE</td>
<td>2.4343</td>
</tr>
<tr>
<td>4 1 3</td>
<td>TE, TM</td>
<td>2.4390</td>
</tr>
<tr>
<td>5 3 0</td>
<td>TM</td>
<td>2.4464</td>
</tr>
<tr>
<td>2 0 4</td>
<td>TE</td>
<td>2.4518</td>
</tr>
<tr>
<td>4 4 1</td>
<td>TE, TM</td>
<td>2.4578</td>
</tr>
<tr>
<td>0 2 4</td>
<td>TE</td>
<td>2.4600</td>
</tr>
<tr>
<td>1 5 2</td>
<td>TE, TM</td>
<td>2.4674</td>
</tr>
<tr>
<td>1 4 3</td>
<td>TE, TM</td>
<td>2.4697</td>
</tr>
<tr>
<td>3 5 0</td>
<td>TM</td>
<td>2.4750</td>
</tr>
</tbody>
</table>

Microwaves are introduced to the cavity via a waveguide. Figures 14 (a) and (b) show the electric field patterns in an empty cavity when the excitation frequency is at 2.4750 GHz and 2.4518 GHz, respectively. When 2.4750 GHz is excited, the mode will be transverse magnetic, specifically \(TM_{350}\) (Figure 14 (a)). On the other hand, when 2.4518 GHz is excited, the mode will be transverse electric specifically \(TE_{204}\) (Figure 14 (b)).
In reality, the above two and several other field patterns may simultaneously be excited in a multimode cavity, because a magnetron does not operate at a single frequency, rather over a certain frequency band width (Schubert and Riegel, 2005). An example of the microwave spectrum generated by a 2.45GHz magnetron is shown in Figure 15. The microwave energy covers a frequency band width of about 50 MHz. A 915 MHz magnetron may have a bandwidth of 15 MHz with operating frequency range of 900 MHz to 915 MHz (Chan and Reader, 2000).

When a load such as food is placed inside a microwave cavity, the resulting field distribution becomes even more complicated. It is not possible to use Equations 87 and 88 to accurately identify the modes inside a loaded cavity. This is because a presence of load can shift modes and can also split or merge degenerate modes (Chan and Reader, 2000). Illustrated below is a computer simulated electric field distribution in a loaded microwave cavity excited at 2.4295 GHz.
Figure 15: Frequency Spectrum of 2.45 GHz magnetron (Chan and Reader, 2000)

Figure 16: Electric field pattern for a loaded microwave cavity at 2.4295 GHz (Chan and Reader, 2000)
Changes in the field pattern, relative to empty microwave cavity, depend on the complexity of the load. An arbitrary shaped load results in a field distribution that is more complex than a geometrically simple load. Similarly, field patterns in a cavity with multiple loads are more complex than with a single load. EM field distribution in a loaded cavity is totally different from the field distribution suggested by a certain mode or combination of modes in an empty cavity. There are, however, appropriate experimental methods to help determine field distributions in a loaded cavity. These methods primarily relate the proportionality of temperature distribution to electric field distribution. For example, Dibbens and Metaxas (1996) and Pathak et al. (2003) used infrared thermal camera to capture the temperature distribution inside a loaded cavity. Grellinger and Janney (1993) used fiber optic and infrared temperature sensors to compare temperature distribution within a loaded cavity. More recently, Pandit et al. (2007) and Chen et al. (2008) used chemical markers, resulting from Maillard reactions between amino acids and reducing sugars in low acid model foods (e.g., whey protein gels or mashed potato), to study heating patterns in microwave systems designed for high temperature processing of packaged foods.

By far the most effective means to visualize the electromagnetic field patterns inside a microwave cavity is to numerically solve Maxwell equations for space and heated loads in the cavity using high power computer simulation. Among the numerical methods that can be applied to solve electromagnetic problems are Finite Element Method (FEM), Finite Difference Time Domain (FDTD) Method, and Method of Moment (MoM). Commercial software such as QuickWave™ and Ansoft™ are available for this purpose. QuickWave™ software works using FDTD while Ansoft™ uses FEM. The accuracy of numerical simulation for electromagnetic applications depends on mesh sizes used for cavity and the heated object. A smaller mesh or
element normally provides more accurate results (refer to ‘Modeling microwave heating in foods’ by Celuck and Kopyt in Chapter 14 for proper mesh sizing discussion). But, the time it would take to simulate an EM problem increases sharply with reduction in mesh size (Chen et al., 2007). In this regards, it is always a balance between accuracy and computing power of computer that runs the software. The field patterns shown in Figures 14 and 16 were generated with computer simulation.

10. Remarks

While microwave heating has brought much convenience to daily lives of modern society, the physical phenomena involved in this heating method are complicated, much more than other traditional heating methods. This provides significant challenges for technical people in the food industry charged with responsibilities to develop microwaveable foods and prepare appropriate cooking instructions for general consumers. Equal challenges are faced by engineers and scientists working on new industrial microwave heating applications. This chapter attempts to provide basic principles that describe how microwave propagate in air and cavities, and interact with foods which will provide the foundation for understanding concept discussed in succeeding chapters.

11. References


CHAPTER TWO

MICROWAVE THERMAL PROCESSING

Abstract

A comprehensive review of the use of microwave energy in thermal processing of food is presented in this paper. The main objective is to report the current status of microwave for commercial sterilization and the field of research associated with it. Discussion of the origin and various important concepts in thermal processing and the disadvantages/limitations of using conventional heating method resolved with the use of microwave energy are among the highlights of this paper. Related topics such as (1) microwave cavity mode of operation and frequency (2) packaging materials and food containers for microwave processing, (3) methods for determining and verifying location of cold spot, and (4) procedure for establishing and verifying process schedule in microwave sterilization system are discussed in detail. In addition, this paper aims to inform public about the first Food and Drug Administration (FDA) approved microwave sterilization processes for low acid foods in the United States and ultimately, it aims to gain support for both research and commercialization of the system.

1. Commercial thermal processing of food

Thermal processing of food is an effective preservation method that utilizes heat to deactivate microorganisms of public health significance and, microorganisms that can cause food spoilage. A French gentleman and businessman Nicolas Appert introduced the concept in 1809. In his demonstration, he used meat stuffed in a glass bottle, sealed, and heated in boiling water for an extended period (Wiley, 1994). His observations showed that thermally treated meat in
glass bottles had a longer shelf life as compared to those that have not been thermally treated. Although the experiment was indeed an ingenious way of food preservation, it was not clear during Appert’s time how heat prevented food from spoiling. After nearly six decades, in 1862, the swan-neck flask experiment of his countryman Louis Pasteur provided an insightful explanation. This simple experiment demonstrated that something from air and dust can contaminate food and can subsequently lead to spoilage (Debré & Forster, 1998). Inherent microbial contaminations on hermetically sealed food attain sterility upon subsequent application of heat, thereby attaining a longer shelf life.

The traditional source of heat for industrial thermal processing of canned food is either steam or hot water applied in a pressurized environment. The mode of heat penetration from the source to the food is through a series of convection outside the can (i.e., from steam to the surface of the can) and conduction and/or convection inside the can (i.e., from outer to inner surface of the can then to the bulk of the food). The predominant mode of heat transfer inside the can depends if food solid, semi-solid, or liquid. A canned food is considered commercially sterile if the amount of heat absorbed, which contributes to the lethality of the process, summed up to an equivalent sterilization value known as $F$ value. By definition, $F$ value represent the equivalent heating time at a chosen reference temperature which will bring about the desired reduction of target microorganism and its spores (i.e., represented in thermal death time curve TDT). Since $F$ value is dependent on a chosen reference temperature, the relationship which represents the change in resistance of microorganism or its spores with change in temperature is the $z$ value (Equation 1) (Stumbo C. R., 1973).

$$F = t \times 10^{\frac{T-T_{ref}}{z}}$$

(1)

where $F$ – sterilization value
\[ t - \text{TDT at temperature } T \]

\[ T_{ref} - \text{reference temperature (standard value equal to 250°F or 121.1°C)} \]

If thermal processing is carried out using standard reference temperature (i.e., 250°F or 121.1°C), \( F \) value is denoted as \( F_o \). The logarithmic survivor curve of target microorganism and its spores is characterized by the death rate constant (i.e., decimal reduction time, \( D \) value). \( D \) value is defined as the time required to reduce the initial number of microorganisms and its spores by ten-fold at a given temperature (i.e., \( D_o \) if temperature is standard temperature). One of the current techniques for measuring \( D \) value is through multiple-point method, which uses capillary tube (internal diameter = 1.8 mm, outer diameter = 3 mm) containing cell/spore suspension subjected to a certain temperature (Mah, Kang, & Tang, 2009). The desired \( F \) value is a multiple of \( D \) value known as sterilizing value (SV). Typically, thermal processing of low acid food requires a sterilizing value of 12 therefore known as 12\( D \) process.

Evaluation of \( F \) value depends on the rate of heat penetration at the slowest heating point in food known as the cold spot. Heat penetration is quantified by measuring temperature history at the cold spot. As an assumption, when cold spot receives enough lethality such that the accumulated \( F \) value is equal to or greater than the desired \( F \) value, it follows that the all other region in the food has an accumulated \( F \) value greater than the target \( F \) value or has received more than enough lethality. Accumulated \( F \) value is the integral of lethal rate (LR) contribution from the start of heating up to the end of cooling (Equation 2).

\[
F = \int_0^{t_{total}} LR \, dt
\]  

(2)

where \( LR \) – lethal rate (\( LR = 10^{\frac{T-T_{ref}}{z}} \))

\( t_{total} \) – total heating time from start of heating up to end of cooling

\( T \) – instantaneous temperature at a given time

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Equation 2 is the basis for the two most popular, and industrially accepted, process calculation method - (1) General/Graphical method (Stumbo C. R., 1953) and, (2) Formula Method (Ball & Olson, 1957). Another reliable process calculation method is through microbial enumeration developed by Stumbo (1973). This method relies on number and identification of surviving microorganism, after trial and error exposure of food to a certain temperature at a certain time.

The slow rate at which heat penetrates the cold spot through combined action of convection and conduction impose major fundamental challenge in obtaining high quality food. Several attempts have been made to optimize food quality (i.e., nutrient content retention, texture preservation, and sensory acceptability) by adjusting processing time and retort temperature combination. However, since the primary concern to attain commercial sterility is microbial stability, a considerable decrease in quality is inevitable. In general, microorganisms and its spores is less heat resistant (that is D value is relatively low) and more sensitive to temperature (that is z value is relatively low) compared to heat resistant and temperature sensitivity of most quality factors. Therefore, the most practical solution to optimize quality is through “High Temperature Short Time” (HTST) process. For liquid food and mixture of solid and liquid wherein natural convection, which partially agitate and hasten heat penetration, is the dominant mode of heat transfer, high temperature short time (HTST) process can be adopted to optimize quality. However, for solid and relatively viscous food, wherein conduction heat transfer predominates (i.e., rate of heat transfer is relatively lower), HTST is not a solution since portion of food near the surface exposed to high temperature would result into overall decrease in quality (Heldman & Lund, 2007).
From a detailed study conducted by Feliciotti & Esselen (1957) on the optimization of retention of thiamine (vitamin B1), it was reported that to attain an $F_o = 6$ min, a decrease of thiamine of up to 30% is expected when pureed meat and vegetables is processed to a temperature of 230°F (110°C) for about 80-90 min. Furthermore, the highest temperature and shortest time combination for HTST processing allowable on a pureed meat and vegetables containing vitamin B1 is 280°F (138°C) and 0.1 min resulting to a decrease of less than 1%. This study justifies the validity of HTST in quality optimization; however, the major constraint is that food should be pumpable (i.e., convection heat transfer predominates over conduction) wherein every volume element in the container receives approximately similar lethality (Lund, 1977). This is not the case for conduction heating. Teixeira et al. (1969B) reported that in conduction heating the mode of heat transfer and not the reaction kinetics is controlling the process. In this specific study, optimization of nutrients on conduction heating shows that Low-Temperature Long-Time (LTLT) is the appropriate process for nutrient with a low $z$ value (15°C) and for nutrients with a high $z$ value (30°C), processing below 90 min and above 121°C or above 90 min and below 121°C will sharply reduce nutrient (specifically thiamine). Furthermore, it was concluded that in thermal processing of food controlled by conduction heating, the only possible avenue for nutrient optimization is through modification of the geometry of the food container (Teixeira, Dixon, Zahradnik, & Zinsmeister, 1969B).

Recent studies on the retention of ascorbic acid (vitamin C) on thermal processing of fruits show a similar trend. Ascorbic acid (Vitamin C) from different fruit has a $z$ values ranging between 19 - 49.3°C and $D_{75°C}$ ranging between of 24,110 - 771 min (Saguy, Kopelman, & Mizrah, 1978); (Alvarado & Viteri, 1989); (Johnson, Braddock, & Chen, 1995). Processing the fruit to 121°C would reduce the $D$ value to a range of 1 to 3 fold, far lower compared to the time
needed to achieve a $6D$ to $12D$ process required for low acid food. Therefore, a low-acid food containing Vitamin C after undergoing thermal process treatment to achieve $6D$ or $12D$ at $121°C$ would result in complete degradation of ascorbic acid to dehydro-ascorbic acid (Vieira, Teixeira, & Silva, 2000). For a typical 211x400 size can containing corned beef, the length of thermal processing necessary to achieved $12D$ process is estimated to be 3-6 hrs at 121.1°C. Essential amino acids such as tryptophan, tyrosine and phenylalanine begin to become unstable at temperature higher than $60°C$ (Gatellier, et al., 2009). In a related experiment, bovine meat of specific size, containing three different amino acids were cooked at temperature of $60°C$, $100°C$, and $140°C$ for 30 min followed by 15 min cooling. Summarized in Table 1 is the percent-decrease in amino acid content.

Table 1. Percent decrease in amino acid content of bovine meat cooked at different temperature

<table>
<thead>
<tr>
<th>Type of amino acid</th>
<th>Percent reduction for a given cooking temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$60°C$</td>
</tr>
<tr>
<td>tryptophan</td>
<td>5%</td>
</tr>
<tr>
<td>tyrosine</td>
<td>16%</td>
</tr>
<tr>
<td>phenylalanine</td>
<td>9%</td>
</tr>
</tbody>
</table>

Source: (Gatellier, et al., 2009)

Another notable study on optimization is reported by Terajima & Nonaka (1996) in which $C$ value $\left( C = \int_{0}^{t} 10^{T-100°C/\Delta t} \right)$ for both surface and volume was minimized, while achieving a sufficient $F$ value. $C$ value indicates the sensory and nutritional value of food and is proportional to the rate of quality change (Ohlsson T. , 1980b). In the optimization procedure, however, a minute reduction of $12D$ process means a tenfold reduction on safety margin.

Besides quality retention, another disadvantage of using traditional source of heat is the efficiency of the process. Simpson et al., (2006) reported that a standard steam retort loses 15-
25% total energy through retort walls and pipes alone, and that bulk of the total energy is used to bring the system to the desired operating temperature in batch canning systems. A very high-energy requirement for reaching the operating temperature (*i.e.*, >75% of total energy input) is due to the accompanying venting process for removing residual air in batch canning systems.

The following limitation of conventional heating processes led research effort to developing advanced thermal processes (Fellows, 2000). A forecast in 1996 from *Food Engineering* magazine (Morris, 1996) identified microwave as one of the leading advanced food processing technologies for both sterilization and pasteurization that would dominate the twenty-first century. Electromagnetic energy as heat source, at a microwave length and frequency specified by the Federal Communications Commission (FCC), carries instantaneous power at the direction of propagation. Food materials, considered as lossy dielectric, upon encountering incident microwave electromagnetic field partially store electric energy and converted into heat. Conversion of heat is volumetric and is far more rapid compared to the surface conduction/convection heat transfer using a traditional heat source. Volumetric heating is a proportional dissipation of heat in all infinitesimal volume of elements representing the totality of the material leading to rapid increase in temperature (Metaxas & Meredith, 1993). The amount of energy-to-heat conversion is dependent on the dielectric properties (*i.e.*, relative dielectric constant and relative dielectric loss factor) of the food. Dielectric property of foods also dictates the microwave penetrating depth (Tang & Resurreccion, 2009). The mechanism of heat generation depends on the amount of dipole rotation and electric conduction within the food material. The dielectric properties of food is a function of the operating frequency of microwave, temperature, electric conductivity, moisture content, and molecular size of polar molecules of the food material (Tang J., 2005).
In a comparative study of Ohlsson (1987) on conventional heating process and microwave heating process, the processing times of carrot packed in can and retortable foil pouch using conventional heat source were 45 and 13 min respectively, to achieve a $F_o = 6$ min. However, for carrots packed in a polymeric tray processed in microwave, the same $F_o$ was achieved after reaching a temperature of 128°C in just 3 min, producing superior quality (i.e., appearance, texture, and taste) after being evaluated after 6 months of storage at a temperature of 25°C. Literature on several microwave systems used for pasteurization (e.g. Berstorff systems) and sterilization (e.g., OMAC system) of prepared meals were also reported to produce superior quality products (Harlfinger, 1992). In a similar study, Gerard (2004) reported that the pH, titratable acidity, and sensory characteristic of cider extracted from untreated apple mash were not significantly different from the cider extracted from microwave treated apple-mash. In addition, the amount of extracted juice increased with increasing time of exposure of apple mash to microwave before extraction. In general, a short duration of high temperature during microwave heating should result in a low $C$ value. This should lead to a high retention of heat sensitive components such as vitamins and essential amino acids. Furthermore, considering the length of processing time, the total energy input used microwave processing is lower compared to conventional heating processes.

2. Factors to consider in commercial sterilization

The design of thermal process treatment takes into account different factors-- the type and size of food packages, heat resistance of microorganisms of concern, pH and water activity of the food, the manner by which heat is applied, and the physical state and property of food (Fellows, 2000). In addition, since process calculation is based on lethality at the slowest heating
point (i.e., cold spot), accurate determination of cold spot is an important factor to consider when designing a thermal process treatment.

2.1. Packaging material

Due to Appert’s choice of container, glass bottles or jars were the first packaging material used for thermal processing of food. However, because of low resistance to thermal shock and fragility to other physical stresses, especially during transportation; tin cans gradually replaced glass bottle containers. Peter Durand introduced the tin can, and the concept was patented in 1810 (Wagenknecht, 1982). Being more rigid, cheaper and relatively easier to mass produce, standard cylindrical tin cans of various sizes became associated with thermal processing of canned food.

Despite the advantages of tin cans over glass containers, problems related to lead poisoning soon emerged. Lead, used for soldering tin-cans cover to the lid of the cylindrical body, can leach into the food and subsequently cause poisoning when ingested. Historical fact confirms numerous lead poisoning incidents related to the use of tin-cans. With the development of double seam method for both three pieces and the recently two pieces tin-cans and aluminum-cans assembly, there has been a significant reduction on the use of lead in canned food. Food and Drug Administration (FDA) banned the use of lead soldered tin-cans in 1990 (Michael & Kashtock, 2008).

Although it is unlikely that modern day consumers will suffer from lead poisoning from eating canned food, manufacturers cannot ignore the fact that container such as tin cans can undergo corrosion which increases the metal content of the canned food. Metal accumulation depends on the period and condition of storage. The body of tin cans is an alloy of steel coated with tin on the side exposed to food. Tin has a lesser tendency to react with food. However, if the
food stored inside the can contains a considerable amount of dissolved oxygen, acidic components, and antioxidant, the tin will corrode. The first 4 to 15 days of storage, depending on the content of food, is the time where tin corrosion is high (Robertson, 2006). Depleted tin exposes alloys of steel to food, which will then react and produce H₂ gas. Further corrosion of steel will make food unfit for consumption due to high metal content. Cans that are coated with enamels, are not exempt from undergoing corrosion and in some cases, depending on the type of food contained within the enamel-coated cans, enamels can even cause accelerated corrosion by acting as catalyst (Robertson, 2006).

As far as corrosion is concerned, the perfect containers for food are those made up of polymeric materials. Different material formulation and laminates of polymers can give the desired barrier properties, physical strength, and thermal resistance. From the producer’s point of view, polymeric packaging materials are relatively cheaper to mass-produce, compared to glass bottle or jars, and metallic can containers (i.e., tin-cans and aluminum-cans). From the consumer’s point of view, which is centered on convenience, polymeric packaging materials offer easy-to-open lids on ready-to-serve containers that can be heated directly in a microwave oven.

Although study reported by Galotto et al., (2008) shows that the physical and mechanical properties of some polymeric laminates are altered upon exposure to elevated temperature, the overall percent change is below 25%, which is still within the acceptable industrial standard (Lambert, Demazeau, & Largeteau, 2000). The specific polymeric laminates that were considered in Galotto’s study were: (a) polyethylene/ethylene vinyl alcohol/ polyethylene (PE/EVOH/PE); (b) metallized polyester/polyethylene (PETmet/PE); (c) polyester/ polyethylene (PET/PE); (c) polypropylene SiOx (PPSiOx). Tempering effect on polymeric material is not an
issue when thermal processing utilized microwave as heat source. Microwave energy delivered volumetrically can significantly reduce processing time, which makes the tempering effect on polymeric material fall within the acceptable range. A study conducted by MokWena (2009) on EVOH film processed using (a) standard steam retort, and (b) microwave sterilization system at Washington State University (WSU) shows that oxygen barrier property is better on the latter and within the set standard. Both heat source (i.e., steam and microwave) are tested at condition equivalent to $F_o = 3$ min and $F_o = 6$ min.

2.2. Heat resistance of microorganisms

The main consideration in designing commercial sterilization processes for low acid canned food with anaerobic condition inside the cans is the possible occurrence of botulism if; (1) not sufficiently processed and/or (2) can seam is faulty which will lead to external contamination. The cause of botulism is the botulin toxins produce by *Clostridium botulinum*. Throughout the history, there were numerous cases of botulism related to canned food, including the incidents in canned tuna fish in 1963, and the 1978 outbreak in New Mexico (CDC, 2008). Recently in 2007, a company producing canned meat was force to recall most of their product line (i.e., both canned food and canned pet food) for possible *C. botulinum* contamination (CDC, 2008). Due to the severity and the long term effect of the toxin to botulism patients (Mann, Martin, Hoffman, & Marrazzo, 1981), *Clostridium botulinum* was identified as microorganism of public health significance and that thermal processing should be designed on the basis of completely deactivating this bacteria (Richards, 2001).

Since *C. botulinum* is difficult to handle due to risk of contamination, a surrogate microorganism of similar characteristic is usually used to validate new thermal processes for low acid food. According to Ocio et al., (1994), *Clostridium sporogenes* (PA 3679) is the perfect
surrogate for *Clostridium botulinum* (type A&B) in thermal processing study due to the following reasons; (1) thermal resistance of PA 3679 is relatively higher compared to *C. botulinum*, (2) PA 3679 are spore formers, and (3) PA 3679 is non-pathogenic. Another desirable characteristic of *Clostridium sporogenes* is that a wide range of temperatures do not affect its viability. A related study suggests that spores of PA 3679 are best stored in refrigerated conditions to maintain its viability and heat resistance (Mah, Kang, & Tang, 2009). The $D_{121^\circ C}$ of *Clostridium sporogenes* stored at refrigerated condition is in the range of 0.70 to 0.81 min (Mah, Kang, & Tang, 2008) while the typical $D_{121^\circ C}$ of *Clostridium botulinum* is 0.2 min (Brennan, Butters, Cowell, & Lilly, 1969). The relatively high thermal resistance of PA 3679 is advantageous, especially in inoculated pack studies, since a lesser number of spores of PA 3679 is needed to inoculate food samples under study to make an equivalent thermal resistance with that of *Clostridium botulinum*.

### 2.3. pH and water activity of food

The pH and water activity of the food plays a significant role in determining the severity of thermal process treatment specifically the number of log reduction (*i.e.*, sterilizing value). For instance, low-acid food, with pH greater than 4.6 and water activity greater than 0.85, requires stringent heat treatments among other food groups since pH and water activity at this level are favorable to both aerobic and anaerobic micro-flora (USFDA, 2009). Usually for low-acid foods, the equivalent process ($F_o$) should be within $6D$ to $12D$ depending on the component of food and storage condition (Richards, 2001). Regulatory agencies in the United States imposed a strict regulation in commercial production of shelf-stable low acid foods.Outlined in 21 CFR 113 (Thermally Processed Low-Acid Food) of the U.S. Food and Drug Administration (USFDA) are the rules and regulations associated with processing low-acid food. Although CFR 113 is for
processing low-acid food in general, patterns of protocol are specific to equipment that uses steam and hot water. There is no published provision for process based on different source of heat, such as microwave.

2.4. Physical state of food

Generally, liquid food and liquid-solid mixtures require less processing time compared to solid food packed in containers with the same geometry and size. The fluid inside the container typically undergoes natural convection, partly agitating the food and thus accelerating the heat transfer. A comparative study by Teixeira et al., (1999) using a model food system (i.e., 5% bentonite suspension for solid and pure water for liquid) packed in same can size shows that a solid food requires a longer processing time compared to liquid food to achieve comparable $F_o$ values. When liquid food solidifies during exposure to heat, this is considered a more complex scenario. Components such as starch undergoes gelatinization and protein coagulation (Elgadir, et al., 2009) at a temperature lower than the usual thermal processing temperature. Changes in the food’s physical state (e.g., from liquid to solid or from solid to liquid) shifts the position of the cold spot. The assumption for the lethality at the slowest heating point method will not hold if there is a shift in cold spot since heat penetration data at this scenario is not a representation of the food’s true cold spot.

In 1957, Ball & Olson outlined a procedure for calculating sterilization value when a change in phase occurs. Commonly referred to as broken heating method, it is a modification to Ball’s Formula method, in reference to the two congruent lines that resemble a broken line in the plot of lethal rate and time on semi-logarithmic scale (Ball & Olson, 1957). Despite the limitation of Balls’ formula method (i.e., method applicable only when there is no more than two congruent lines in the semi-logarithmic plot), it can be used to estimate, with relative precision,
the processing schedule of a certain food packed in different can size using only one representative heat penetration data. Factors related to heat transfer characteristics incorporated in Ball’s formula method are interchangeable to accommodate changes in process condition, such as changes in retort temperature and initial temperature of food, without necessarily repeating the heat penetration tests (Stumbo C. R., 1973). In thermal processing that utilizes microwave, changes in physical state are less likely to occur because the food is exposed to a high temperature for a shorter period.

2.5. Cold point determination

The earliest records describing the procedures to identify the cold spot in different containers were developed by the National Canners Association (NCA, 1968). The procedure is based on the study conducted by Pflug and Nicholas (1961) which determined the cold spot in glass jar with liquid food (i.e., convection heating in packages). Ecklund (1956) demonstrated the proper insertion of pre-selected thermocouple wire in a tin-can containing pea puree (i.e., combined conduction and convection). Sensors base on thermoelectric effect (e.g., thermocouples, thermistors and resistance temperature detectors-RTD) are applicable only for monitoring temperature in conventional heating processes. For microwave heating, such sensors will disrupt electromagnetic (EM) field distribution and hence are not suited. Fiber optic sensors, having non-metallic material, are commonly used for both microwave and radio frequency heating since it has minimum interaction with EM field distribution (Cable & Saaski, 1990).

Identification of the cold spot using temperature sensors is categorized as invasive method; there is however a non-invasive way to identify the cold spot. Study conducted by Pandit et al., (2006) utilized a chemical marker to determine the cold spot in model food systems. Chemical markers M-1 and M-2 are produced through a non-enzymatic reaction (Maillard
Reaction) between reducing sugars and amino acid (Kato, Nakayama, Sugimoto, & Hayase, 1982) within the temperature range of 100°C - 130°C. If the specific sugar reactant is glucose, M-1 will be produced, and if ribose is present, M-2 will be produced. Figure 1 illustrates the pathways of the reactions. The amount of M-1 and M-2 produced is proportional to temperature and heating time. The microwave sterilization group of Washington State University (WSU) developed a system to capture the color intensity of the marker at a certain plane within the food, using a color-temperature matching software to a large color scale from blue to red. The only limitation of the method is that it works only for solid and semi-solid food. Furthermore, Maillard reaction is an irreversible reaction, which means the intensity of brown color (i.e., the amount of M-1 or M-2 produce) on a given area in food will not change even if there is a subsequent decrease in temperature.

![Maillard reaction pathways](image)

Figure 1: Maillard reaction pathways of (a) D-glucose leading to M-1 and (b) D-ribose leading to M-2 (Kim, Taub, Choi, & Prakash, 1996)

Oftentimes, the temperature sensor used for invasive cold spot determination is also the sensor used in obtaining time-temperature data at the cold spot during heat penetration tests. This
becomes a hurdle especially in continuous operations such as agitated type retorts. Modern temperature sensors addressed the issue by incorporating an independent power source and memory unit to the sensor in one stand-alone assembly usually categorized as mobile data tracers. Once activated, mobile data tracers will start logging temperature data indefinitely until power supply runs out or the tracer has been manually terminated. These unique characteristic of mobile data tracers allows the placement of the unit right in the cold spot within the food sealed in a packaging container. The microwave sterilization group of Washington State University utilized the chemical marker when locating cold spots and mobile data tracers for monitoring temperature at the cold spots during research related to microwave.

3. Microwave thermal processing of food

Electromagnetic waves at microwave frequency were originally used for military communication and aircraft detection. It was accidentally discovered for having unique characteristic for heating materials (Chan & Reader, 2000). Since the introduction of the first commercially available microwave oven operating at 2.45 MHz by Raytheon™ in 1947, the microwave oven has established itself as an indispensable household appliance. In the survey conducted by Witters (1984), domestic microwave oven exceeded the popularity of the standard kitchen stove in the United States. One of the main reasons for its popularity is the rapid volumetric heating (Clark & Sutton, 1996) allowing only a few seconds to heat food at a desired temperature.

Several studies suggest two modes of microbial inactivation in microwave heating: (1) non-thermal effect on microorganism below lethal temperature and (2) thermal effect on microorganism at lethal temperature (i.e., thermal effect similar to traditional heating). Non-thermal effect on microorganism is the interaction of cell membrane to microwave energy.
Interaction may result in alteration of cell membrane permeability (Liburdy & Vanek, 1985), or cell membrane damage due to preferential heating of sub-cellular component (Khalil & Villota, 1988). However, it is not conclusive if non-thermal effect can indeed cause a substantial inactivation of microorganism (Datta & Ananantheswaran, Handbook of Microwave Technology for Food Applications, 2004). In fact, Ponne et al. (1996) concluded that a radio frequency (RF) field would have no substantial effect in the deactivation of Erwinia caratovora cells. Similarly, according to Tang et al. (2007) wavelength of both RF and microwave are relatively long compared to the size of microorganism and therefore, preferential heating of sub-cellular component is unlikely to happen.

Since the only conclusive mode of microbial inactivation is through thermal effect at lethal temperature, inactivation kinetics of target microorganism (e.g., Clostridium botulinum for low acid food) is similar to conventional heating using steam or hot water. Therefore, thermal parameters of microorganism such as $F$ value, $D$ value and $Z$ value obtained from the TDT curve (i.e., based from the first order inactivation kinetics of target microorganism) are used in developing microwave sterilization processes. This means that calculation of thermal process schedules for microwave heating is similar to the described procedure for conventional canning operation. That is evaluating the lethality at the slowest heating point requires cold point determination and heat penetration studies. The only difference is that a rapid increase in temperature at the cold spot would result in reaching target $F$ value at a shorter processing time.
4. Factors to consider in microwave heating

4.1. Dielectric property of material

Dielectric property of material consists of permittivity ($\varepsilon$) and permeability ($\mu$) which relates to the macroscopic interaction between the material and the electric field and magnetic field respectively. For an isotropic media, the permittivity of a material is equal to the product of permittivity constant ($\varepsilon_o = \frac{10^{-9}}{36\pi}$) [F/m] for air and relative permittivity of the material ($\varepsilon_r$), and the permeability is equal to the product of permeability constant ($\mu_o = 4\pi \times 10^{-7}$) [H/m] for air and relative permeability of the material ($\mu_r$).

Since food is non-magnetic in nature, permeability has no contribution to heating. When a static or quasi-static (i.e., frequency = 0) electric field is applied to a polar material or a mixture of material containing polar molecules such as water, the material acts like a capacitor. The charge storage ability of the material is called static permittivity ($\varepsilon_s$) (Balanis, Advanced Engineering Electromagnetics, 1989). However in an alternating field at a certain frequency, permittivity becomes a complex term ($\varepsilon = \varepsilon' - j\varepsilon''$) consisting of real part, called dielectric constant ($\varepsilon'$), and imaginary part, called loss factor ($\varepsilon''$). Complex permittivity in alternating field is described by Debye equation (i.e., commonly known as the Debye relaxation equation):

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j2\pi f \tau}$$

where $\varepsilon_\infty$: a fictitious permittivity at very high frequency ($f \rightarrow \infty$)

$\varepsilon_s$: static permittivity

$f$: frequency

$\tau$: relaxation time
Complex permittivity describes the ability of the material to transmit (i.e., either store or convert into heat), and reflect alternating electromagnetic field at a certain frequency. To demonstrate this concept, consider Maxwell-Ampere equation (Equation 4) which describes propagation of electromagnetic field:

\[ \nabla \times \vec{H} = \vec{J}_c + j \omega \varepsilon \vec{E} \]  

(4)

Plugging in the expression of permittivity, Equation 4 becomes,

\[ \nabla \times \vec{H} = \sigma_s \vec{E} + j \omega (\varepsilon' - j \varepsilon'') \vec{E} \]  

(5)

Where \( J_c = \sigma_s E \)  

electric conduction current density

\( \sigma_s \)  
Static conductivity due to presence of free ions

Simplifying Equation 5 yields:

\[ \nabla \times \vec{H} = (\sigma_s + \omega \varepsilon'') \vec{E} + j \omega \varepsilon' \vec{E} \]

\[ \nabla \times \vec{H} = (\sigma_s + \sigma_a) \vec{E} + j \omega \varepsilon' \vec{E} \]

\[ \nabla \times \vec{H} = \sigma_e \vec{E} + j \omega \varepsilon' \vec{E} = (\sigma_e + j \omega \varepsilon') \vec{E} \]

\[ \nabla \times \vec{H} = \vec{J}_{ce} + \vec{J}_{de} \]  

(6)

where \( \sigma_a = \) Conductivity due to alternating field

\( \sigma_e = \sigma_s + \sigma_a \)  
Effective conductivity

\( \vec{J}_{ce} = \sigma_e \vec{E} \)  
Effective electric conduction current density

\( \vec{J}_{de} = j \omega \varepsilon' \vec{E} \)  
Effective displacement electric current density

From Equation 6, displacement of current density is dependent only on the dielectric constant, while effective electric conduction current density is dependent on both static conductivity and conductivity due to alternating field.
Material can be categorized as good dielectric and good conductor by assessing the effective electric loss tangent ($\tan \delta_e$):

$$\tan \delta_e = \frac{\sigma_e}{\omega \varepsilon_i}$$  \hspace{1cm} (7)

A material is a good dielectric if loss tangent is $\ll 1$. This means that the conduction current density is very small compared to the displacement current density (e.g., air). For a good conductor, loss tangent is $\gg 1$, which means the conduction current density is much greater than displacement current density (e.g., metals). Anything in between is considered lossy dielectric material such as food, which is capable of converting conduction current density into heat. In microwave heating, the amount of heat dissipated is proportional to the effective conductivity ($\sigma_e$). Effective conductivity is a contribution of both dipole relaxation of polar molecules and free ions present in the lossy material.

### 4.2. Microwave heating

Poynting theorem describes conservation of energy in a presence of electromagnetic field. Poynting theorem states that the power density in electromagnetic field is equal to the curl of electric field with magnetic field (Equation 8):

$$\vec{P} = \vec{E} \times \vec{H}$$  \hspace{1cm} (8)

Considering a volume bounded by closed surface in a presence of electromagnetic field according to Gauss’s divergence theorem, the power flow ($\varphi$) in or out of the given volume is equal to the surface integral of the curl of electric field and magnetic field that flows in or out of the surface that bounds the volume. Therefore, conservation of energy in terms of power flow can be written as:

$$\varphi = - \oint \oint \vec{E} \times \vec{H} \cdot dS$$  \hspace{1cm} (9)
Considering average power flow, and applying Gauss’s divergence theorem to Equation 9:

$$\varrho = -\frac{1}{2} \iiint \nabla \cdot (\vec{E} \times \vec{H}^*) \, dv$$  \hspace{1cm} (10)$$

where $\vec{H}^*$ is the complex conjugate of $\vec{H}$, and the negative terms denotes for the direction of power flow. Expanding Equation 10, and applying Maxwell-Ampere equation (Equation 4) and Maxwell-Faraday equation:

$$\varrho = \frac{1}{2} \iiint \sigma |\vec{E}|^2 \, dv + \frac{1}{2} j \omega \iiint \left[ \varepsilon |\vec{E}|^2 + \mu |\vec{H}|^2 \right] \, dv$$ \hspace{1cm} (11)$$

The first term in Equation 11 is the dissipated real power in watts as heat. The second and third terms are the increase in stored energy due to electric and magnetic field, respectively.

In microwave heating, the first term in Equation 11 is most important since the dissipated power is the one that causes volumetric heating. Considering a given volume, and assuming that the electric field distribution is uniform in that volume, volumetric heating in watts per unit volume can be expressed as:

$$P = \sigma_e |\vec{E}|^2 = \omega \varepsilon_e^* |\vec{E}|^2 = 2\pi f \varepsilon_e^* |\vec{E}|^2$$ \hspace{1cm} (12)$$

where $\varepsilon_e^*$ is the effective loss factor, which reflects the contribution of both water dipole relaxation and free ions.

Tabulated below are some of the dielectric properties of selected foods and the corresponding power penetration depth ($d_p$) of microwave at 915 MHz and 2450 MHz. One important concept shown in Table 2 is the dependency of penetration depth to operating frequency. In general, the power penetration depth of 915 MHz microwave (except for ice) is greater than that of 2450 MHz.
Table 2. Dielectric properties and power penetration depth of selected foods (Tang J., Dielectric properties of foods, 2005)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>915 MHz</th>
<th>2450 MHz</th>
<th>915 MHz</th>
<th>2450 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distilled/deionized</td>
<td>20</td>
<td>79.5</td>
<td>3.8</td>
<td>122.4</td>
<td>78.2</td>
</tr>
<tr>
<td>0.5% salt</td>
<td>23</td>
<td>77.2</td>
<td>20.8</td>
<td>22.2</td>
<td>75.8</td>
</tr>
<tr>
<td>ice</td>
<td>-12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.2</td>
</tr>
<tr>
<td>corn oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>apples</td>
<td>22</td>
<td>60</td>
<td>9.5</td>
<td>42.6</td>
<td>57</td>
</tr>
<tr>
<td>potato</td>
<td>25</td>
<td>65</td>
<td>20</td>
<td>21.3</td>
<td>54</td>
</tr>
<tr>
<td>asparagus</td>
<td>21</td>
<td>74</td>
<td>21</td>
<td>21.5</td>
<td>71</td>
</tr>
<tr>
<td>Red Delicious</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dehydrated apples*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>87.5% MC</td>
<td>22</td>
<td>56</td>
<td>8</td>
<td>48.9</td>
<td>54.5</td>
</tr>
<tr>
<td>30.3% MC</td>
<td>22</td>
<td>14.4</td>
<td>6</td>
<td>33.7</td>
<td>10.7</td>
</tr>
<tr>
<td>9.2% MC</td>
<td>22</td>
<td>2.2</td>
<td>0.2</td>
<td>387</td>
<td>2.2</td>
</tr>
<tr>
<td>High Protein products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yoghurt (pre-mixed)</td>
<td>22</td>
<td>71</td>
<td>21</td>
<td>21.2</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>61</td>
<td>96</td>
<td>5.1</td>
<td>60</td>
</tr>
<tr>
<td>cooked ham**</td>
<td>50</td>
<td>50</td>
<td>140</td>
<td>3.7</td>
<td>53</td>
</tr>
<tr>
<td>cooked beef***</td>
<td>25</td>
<td>76</td>
<td>36</td>
<td>13</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>72</td>
<td>49</td>
<td>9.5</td>
<td>68</td>
</tr>
</tbody>
</table>

* (Feng, Tang, & Cavalieri, Dielectric properties of dehydrated apples as affected by moisture and temperature, 2002)
** (Mudgett R. E., 1986)
*** (Bircan & Barringer, 2002)

Considering a certain location in food, within the power penetration depth ($\delta_p$) dissipated power (i.e., described by Equation 12) as heat will cause temperature increase at that location. Since temperature increase is due to coupled heat transfer-electromagnetic field effect, it can be
assumed that dissipated power from microwave is an internal heat source. Adding dissipated power from microwave (Equation 13) as internal heat source to the governing partial differential equation (PDE) for heat transfer (Equation 14):

\[
\rho \varepsilon C_p \frac{\partial T}{\partial t} = 2 \pi f \varepsilon \varepsilon_0 |\vec{E}|^2
\]

\[
\nabla^2 T - \frac{\rho \varepsilon C_p}{k} \frac{\partial T}{\partial t} = 0
\]

will give the spatial change in temperature considering the coupled heat transfer-electromagnetic field effect (Equation 15):

\[
\nabla^2 T - \frac{\rho \varepsilon C_p}{k} \frac{\partial T}{\partial t} + \frac{1}{k} 2 \pi f \varepsilon \varepsilon_0 |\vec{E}|^2 = 0
\]

The first term in Equation 15 describes the spatial change in temperature, the second term is the change in the stored energy, and the third term is the dissipated power from microwave. The solution for Equation 21 can be solved numerically using: (a) finite difference method, (b) finite element method, or (c) boundary element methods.

5. Application and Advantages of Microwave heating

5.1. Domestic application

The most common application of domestic microwave ovens (operating at 2450 MHz) is for cooking or heating/reheating food. Nowadays, the microwave ovens have gained favor over conventional stoves and ovens because there are minimal loss in essential nutrients and flavor in food heated using domestic microwave ovens. In a comparative study between microwave oven and conventional roasting oven in the retention of thiamine and Vitamin B6 on animal muscle, meat cooked in a microwave oven retained 85.6% to 88% and 59.9% to 64.2% of its thiamine and vitamin B6 content respectively (Uherova, Hozova, & Smirnov, 1993). These values are
much higher compared to 48% and 21.6% for both thiamin and vitamin B6 retention on a conventional roasting oven. Also, loss of volatile food components such as aldehydes, ketones, and esters, which affects flavor, is not significant in a microwave oven heating compared to conventional heating (Stanford & McGorrin, 1994).

Other benefits of domestic microwave heating in comparison to conventional stove or oven include accelerated reduction in viable vegetative cell count of common food pathogen. Among common food pathogens that can be deactivated by domestic microwave ovens are: (1) *Bacillus cereus* in soybean curd (Tanaka, Motoi, & Hara-Kudo, 2005), (2) *Listeria monocytogenes* in chicken skin (Coote, Holyoak, & Cole, 1991) and in milk (Choi, Marth, & Vasavada, 1993), and (3) *Salmonella* species on milk and beef broth (Heddleson & Doores, 1994).

Studies also show that domestic microwave ovens used in deep fat frying can greatly improve the quality food and lesser degradation of frying oil (Gharachorloo, Ghavami, Mahdiani, & Azizinezhad, 2010) as compared to conventional deep fat frying.

### 5.2. Industrial application

The two common operating frequencies of an industrial microwave system is 2450 MHz or 915 MHz. The earliest record of an industrial microwave system was detailed in the review article by Osepchuk (1984). Raytheon Company, Litton Industry, Microdry Company, and DCA Industries were among the pioneers in manufacturing microwave systems for industrial purposes (Edgar & Osepchuk, 2001). An example of early industrial microwave systems was the competing designs of Raytheon Co., and Litton Ind. Both companies developed a microwave system operating at 915 MHz with a serpentine applicator configuration that can deliver a
maximum of 50 kW power (Osepchuk, 1984). The Frito-Lay Company commissioned the design for the purpose of drying mass produced potato chips.

There is a wide application of microwave heating in the food industry nowadays. Some of these are; (a) precooking of food, (b) food drying, and (c) tempering of frozen meat. Several studies associated to application of microwave in drying operations were conducted for different commodities such as; (1) wood (Leiker & Adamska, 2004) (Zhao, Turner, & Torgovnikov, 1998) and the treatment effect on wettability as compare to other drying method (Wang, Zhang, & Xing, 2007.), (2) grain product which includes wheat, corn, and grain derivatives such as flour (Manickavasagan, Jayas, & White, 2006) (Vadivambal, Jayas, & White, 2008), and (3) fruit such as apples (Nindo, Sun, Wang, Tang, & Powers, 2003) (Feng, Tang, & Cavalieri, 2002). Besides removal of moisture in microwave drying, microwave treatment on grain also serves as insecticidal. Despite the non-uniform temperature distribution on the surface of the grain (Manickavasagan, Jayas, & White, 2006), bench top experiment conducted by Vadivambal et al., (2007) & (2008) concluded that microwave treatment eliminates 100% of insect in stored grains. Zhang et al. (2006) published a comprehensive review on the applications of microwave in the drying of fruits and vegetables. The study focused on the advantages of combinational drying technology (i.e., microwave and conventional drying) and disadvantages related to the cost of equipment and recommendations for the improvement of the process (Zhang, Tang, Mujumdar, & Wang, 2006). Recent applications of industrial microwave systems are popular in the pre-treatment of raw material to aid other physical operations such as distillation of essential oils (Miletic, Grujic, & Marjanovic-Balaban, 2009), and extraction of tea phenols (Spigno & De Faveri, 2009).
6. Limitations of microwave heating

6.1. Domestic application

Since there is a considerable reduction in heating time when a domestic microwave oven is used, changes in volatile components and most temperature dependent chemical reactions in food decrease as well. On one end, this is desirable as far as retaining the natural flavor and untreatedness of the food is concerned. However, it is undesirable in creating new flavor, which most consumers perceived as cooked food. A relevant example is the browning at the surface of bread during baking, which is unlikely to occur when a microwave oven is used. Browning of a bread’s surface is an important quality index parameter brought about by the combined caramelization and Maillard reaction (Fennema O. R., 1996). Both reactions are time and temperature dependent, and the reduction of baking time (i.e., as in the case of using microwave oven) significantly reduced browning at the surface of the bread. There is, however, a smart packaging material for microwave food products that incorporates heat susceptor. Heat susceptors, in contact with the surface of the food, converts microwave into thermal heat thereby promoting regular heating allowing the surface of the food to undergo the necessary browning. Although heat susceptor in microwave heating is an effective way to imitate the heating condition at the surface of the food during conventional heating, it is worth mentioning that the rate of caramelisation and Maillard reaction is relatively slower with heat susceptors compared to microwave volumetric heating. Therefore, baking time in a microwave oven may not be sufficient to produce the necessary browning and crispiness at the surface.

Because of the limitation of domestic microwave ovens in creating the flavor of a regularly cooked food, its application is leaning towards reheating previously cooked food or food that is partially cooked rather than complete cooked.
6.2. Industrial applications

Despite the potential of microwave for commercial sterilization as energy source in thermal processing, most applications, such as drying and thawing, serve as an intermediate step for the conditioning of raw materials to aid main sequential processing steps. Notable examples include microwave-assisted dried spices for food flavorings (Bertelli, Plessi, & Miglietta, 2004) and microwave-thawed and tempered frozen food product (Akkari, Chevallier, & Boillereaux, 2006); (Taher & Farid, 2001); (Chamchong & Datta, 1999). Although there are existing industrial microwave setups for commercial sterilization and pasteurization of food (e.g., OMAC and Berstorff system (Harlfinger, 1992) and (Schlegel, 1992), microwave sterilization at Otsuka Chemical Company (Otsuka, Japan), and microwave sterilization at TOP’s Food (Olen, Belgium), no microwave sterilization processes were accepted by the FDA in the United States prior to the work at Washington State University (WSU). Reasons include: (1) unpredictability of heating pattern and (2) lack of reliable procedure for validating safety to meet FDA standards (Tang & Chow Ting Chan, 2007). Furthermore, cavities of existing microwave setup are multimode operating at frequency similar to that of domestic microwave oven (i.e., 2450 MHz). A multimode cavity operating at 2450 MHz will result in unpredictable heating pattern and low depth of microwave penetration.

7. Challenges for Industrial application of Microwave

Several studies from earlier years (i.e., 1970’s the era where the microwave oven became a famous household appliance) highlighted the non-uniformity of temperature distribution in foods processed in microwave systems (Bengtsson & Lycke, 1969); (Watanabe, Suzuki, & Sugimoto, 1971); (Kashyap & Wyslouzil, 1977); (Ohlsson & Risman, 1978). Among the factors that contribute to the uneven temperature distribution in food samples are: (a) the size and
geometry of the load (Chamchong & Datta, 1999); (Zhang & Datta, 2005), (b) the power level output of the magnetron (Chamchong & Datta, 1999), and (c) the dielectric property of food (Ayappa, Davis, Davis, & Gordon, 1991); (Peyre, Datta, & Seyler, 1997); (Ryynanen, Risman, & Ohlsson, 2004).

After introducing the microwave oven in the 1950’s, there have been numerous innovations on the design of microwave cavities to address the issue of uneven distribution of heat (Kashyap & Wyslouzil, 1977). Incorporation of metal stirrer at the end of feeding waveguide (i.e., mode stirrer) (Plaza-Gonzalez, Monzó-Cabrera, Catalá-Civera, & Sánchez-Hernández, 2005), and rotating turntable has been integrated in the design of microwave oven in an attempt to even out the distribution of heat. Other efforts to minimize uneven heat distribution includes; (a) having a multiple feeds (Pitarch, Canós, Peñaranda-Foix, Catalá-Civera, & Balbastre, 2003), (b) moving load (i.e., food) into different locations other than plain rotation (Pedreño-Molina, Monzó-Cabrera, & Catalá-Civera, 2007), and (c) covering load with dielectric material (Monzó-Cabrera, Diaz-Morcillo, & Domínguez-Tortajada, 2007).

All the above mentioned efforts in minimizing uneven heat distribution were geared towards improving microwave multimode cavities rather than designing single mode cavities. Cavities operating in multimode would most likely bring uneven heat distribution in food. Furthermore, most of these efforts use microwave generators operating at 2450 MHz, a frequency that carries less energy, and has a relatively shorter microwave penetration depth in food as compared to 915 MHz frequency.

Another issue that needs to be addressed is the problem brought about by corner and edge effect in microwave heating. Boundary conditions for refraction and reflection of field in sharp edges such as corner and edge of the food, (i.e., for food packed in a container that has sharp
edges like slab shape container) give rise to a relatively more concentrated E field as compared to a flat or smooth surface region. High E field amplitude results in a high volumetric power density, therefore the heating rates at the locality of the corner and edge of the food are much higher compared to that at the flat surfaces and the rest of the food volume. Oftentimes, the heating rate at the corner and edge of the food is high enough to burn the food volume in that locality producing unpleasant appearance and burnt flavor. For industrial microwave applications this phenomena is most likely to occur and the thermal characteristic of air medium in most microwave-air-filled-cavities (e.g. microwave sterilization at TOP’s Food (Olen, Belgium) is not appropriate in preventing corner and edge effects.

Finally, in most industrial scale microwave systems, complex configuration of waveguide system is necessary to direct flow of microwave energy from the source (i.e., microwave generator) to load (i.e., microwave cavities that contains the food being heated). In addition to the intrinsic mismatch between the source and the load, waveguide parts such as bends, splitters, and adaptors tend to worsen mismatch, resulting in a much higher microwave reflection. Higher reflection means lower total energy efficiency since only a portion of incident microwave power (i.e., the transmitted microwave energy) is utilized in food heating. To this end, one of the challenges for industrial application of microwave is the implementation of a tuning system to minimize microwave reflection.

8. Research and development needs for developing industrial microwave thermal processing system

Certain areas that need further concentration in studies related to development of industrial scale microwave system for thermal processing are as follows:
8.1. Computer simulation of electromagnetic field distribution

This aspect is very important especially in designing and/or retrofitting any components or parts in a microwave system. As mentioned in the challenges for industrial application of microwave, the common objective of the design of a microwave system for thermal processing is to address the issue of uneven heat distribution and to optimize the energy efficiency by minimizing reflected power. However, even minute changes in sizes, geometry, insertion of parts, and even orientation of any part in a microwave system can result in total alteration of field distribution. Since the risk and cost is too high for the construction of a physical design and experimentation of the outcome, there is a need to predict a reasonable outcome of a design even before it is physically constructed. Coupled electromagnetic field and heat transfer simulation is a convenient tool to satisfy this need. Through computer simulation, using model representation of actual microwave systems and the food inside them, electromagnetic field distribution and the resulting heat transfer can be determined. Electromagnetic simulation software (e.g., QuickWave QW-3D by QWED), configured to implement numerical methods (e.g., Finite-Difference Time-Domain or FDTD), are available for this purpose. The challenge for researcher lies in developing a geometrically acceptable model to represent the microwave system design and identifying all the possible conditions or parameters that may influence the result of the simulation. These parameters should conform to the expected conditions should the design be implemented. Proper meshing and discretization of the modeled domain within the computing power of the hardware resources should also be considered to obtain an accurate electromagnetic field distribution, power density, heating pattern in food, microwave reflection, and other output parameter related to electromagnetic propagation. In addition, since electromagnetic field distribution is greatly affected by the dielectric property of the non-metallic part of the microwave system (e.g., food
under consideration), it is important to incorporate in the simulation model accurately measured dielectric property data. Several factors should be considered in measuring dielectric property of a food system, these are (a) temperature (Ayappa, Davis, Davis, & Gordon, 1991), (b) operating frequency of microwave, (c) moisture content (Guo, Tiwari, Tang, & Wang, 2008), and (d) fiber orientation especially for meat (Basaran-Akgul, Basaran, & Rasco, 2008). Finally, most computer simulations on microwave heating of food is under the assumption of food being homogenous (i.e., using one data for dielectric property to represent food as a bulk). Effort on computer simulation studies should consider designating dielectric property as a function of space for heterogeneous foods.

8.2. Heat pattern verification

Although computer simulation provides predicted heating patterns in food based on the parallelism among field distribution, power density, and temperature profile, there should be an effective means to verify the results. This is especially true when simulation results are used to identify the location of the cold spot in foods. A computer vision method (Pandit R. B., Tang, Liu, & Mikhaylenko, 2007) which utilizes high-resolution imaging to detect color difference in chemical marker (M-1 or M-2) in a model food system (i.e., whey protein gel) is a good qualitative verification. However, whey protein gel as model food is only accurate for representing the volume of homogeneous solid and semi-solid food. Research should gear towards identifying a medium from which chemical marker can be applied that can be used to model liquid food. In addition, a reliable standard of color for chemical marker should be established. Another approach to verify heating pattern is through real time quantitative measurement of temperature on a selected spot in food sample (i.e., the cold spot and hot spot location as suggested by the simulation result and computer vision method). Temperature profile
output from simulation can be compared to the temperature profile extracted from actual temperature sensor. The challenge in real time temperature measurement lies in the choice of the sensors and their possible effect on electromagnetic field distribution. Several researches compared the accuracy among thermocouple, fiber optic, and infrared sensor (Grellinger & Janney, 1993) and thermal camera as described by Dibbens and Metaxas (1996). However, these sensors are limited in terms of mobility due to their physical attachment on their corresponding data logging device. Since industrial microwave thermal processing would most likely be carried out in a continuous operation, research should focus on developing a wireless temperature sensor for real time temperature logging.

8.3. Microbial Validation

Following the standard set forth by the FDA, new products belonging to category of low acid food should undergo microbial validation, to check the effectiveness of applied thermal treatment. As described by Mah et al., (2009), a careful selection, characterization, and storage study of surrogate microorganism is necessary to ensure that sterilization process based on the surrogate is equivalent to sterilization based on Clostridium botulinum.

8.4. Packaging material study

Unlike the conventional heating method, the container / packaging materials for food, processed using microwave, should not be metallic or should have low electric conductivity. Among the desirable characteristics of packaging materials used for microwave processing are high moisture and oxygen barrier properties before and after microwave processing. However, a study shows that water upon migration to polymeric plastic reduces its oxygen barrier property (Mokwena, Tang, Dunne, Yang, & Chow, 2009). Research on packaging materials related to
microwave should focus on developing laminates of polymeric films that has a minimal changes in oxygen barrier characteristic even after exposure to microwave. Several combinations of polymers of different thicknesses and proportions such as ethylene vinyl alcohol (EVOH), polyethylene terephthalate (PET), polypropylene (PP), and polyvinylidene chloride (PVDC) can be tested to come up with stable packaging materials. Incorporation of microwave heat susceptors for specific types of food groups is also a researchable area that needs attention in industrial microwave thermal processing. Other considerations for packaging are the shelf-life study taking to account possible polymer leaching, mechanical strength of the packaging, and cost.

9. Current state of industrial microwave thermal sterilization system development in United States

In 1996, Dr. Juming Tang of Washington State University (WSU) started research utilizing microwave energy at 915 MHz on a single-mode cavity. The objective of the research was to provide a blueprint in developing a continuous microwave sterilization systems for commercial sterilization of food packed in polymeric containers. This technology would bridge the gap in making high-temperature-short-time (HTST) sterilization process possible for optimizing nutrient retention in food controlled by conduction type heating. In October of 2009, after meticulous review by the FDA of the submitted process schedule, engineering data, and microbial validation data pertaining to commercial sterilization of mashed potato (i.e., considered as low acid food) packed in polymeric trays, a microwave sterilization process has been accepted for homogeneous food -mashed potato. Conforming to all standards set forth by the regulatory agency, it was identified as the first FDA approved microwave process for commercial sterilization of low acid food in the United States.
The current microwave system in WSU includes four massive single mode cavity applicators connected, through a standard WR975 waveguide configuration, to four magnetron generators operating at 915 MHz. The maximum power delivered is up to 40 kW. The earlier stage of the design of the microwave system was based on the result of electromagnetic simulation studies conducted by Pathak *et al.*, (2003). Results of the study suggest that a single-mode cavity design of the system can produce a predictable heating pattern on food. The 915 MHz microwave have a power penetration depth of up to 3 cm hence can deliver a larger power density efficiently. Computer simulated heating patterns were verified using whey protein gel (WPG) containing ribose to form chemical marker M-2 (Wang, Lau, Tang, & Mao, 2004). Results of verification studies shows that the temperature distribution on WPG after microwave treatment is comparable to the predicted temperature distribution based on computer simulated electromagnetic field distribution.

In filing for FDA acceptance using a mashed potato packed in 300g Rexam™ containers, different process schedules that would give a $F_\text{o}$ equal to 3.0 min, 4.4 min, 6.0 min, and 8.0 min were established. Process schedule includes different power settings for each of the four cavities, initial temperature of the food, temperature of the water at different section of the microwave system, and speed of the belt carrying the food as it goes through the cavities. A general method was used in the process calculation of $F_\text{o}$, which is based on the time-temperature profile at the predetermined cold spot. A mobile data tracer was placed at the cold spot to log time-temperature profile. Identification of cold spot in mashed potato tray follows the procedure described by Pandit *et al.* (2007) (Figure 2a) which uses chemical marker M-2. Cold spot location was verified by implementing FDTD simulation on the model of microwave system developed by Chen *et al* (2008) (Figure 2b) and through actual temperature measurement using
mobile Ellab data tracer (Ellab Inc., 6551 South Revere ParkWay, Suite 145 Centennial CO 80111, USA) (Figure 2c).

![Figure 2: Cold spot identification and verification: (a) Computer vision method, (b) FDTD simulation method, (c) temperature measurement using fiber optic sensor]

Verification of lethality of the established process schedule was through microbial validation. This method is possible since the inactivation kinetics of microbial spore for both microwave processing and conventional heating follows first order rate of reaction (Datta & Ananantheswaran, Handbook of Micrwave Technology for Food Applications, 2004). Using Clostridium sporogenes as surrogate to Clostridium botulinum, an ample amount of spores were inoculated in mashed potato within the area of the cold spot. Trays of mashed potato were sorted then processed to its designated processing schedule (i.e., $F_o$ of 4.4, 5.0, and 8.0 min). After sufficient incubation period, trays processed in $F_o$ 3.0 and 4.4 min shows growth and no growth for both 5.0 min and 8.0 min. Results are in accordance to what is expected (i.e., similar result if processed using conventional heating method) since $F_o$ of 3.0 and 4.4 min is not sufficient to deactivate all spores as compare to 5.0 and 8.0 min.
The described procedure for establishing processes schedule on the microwave system at WSU, and the method for verifying factors which are considered by the FDA as critical are the primary key for gaining acceptance. In summary the following factors and verification procedure are as follows;

(1) Electromagnetic field distribution- claimed to be single mode; cavity modeled using FDTD simulation and verified using heating pattern on whey protein gel with chemical marker.

(2) Cold point determination- identified using mashed potato with chemical marker M-2, verified using FDTD simulation and actual measurement of temperature using fiber optic sensors and mobile data tracers.

(3) Processed schedule- established using General method, and lethality verified through inoculated packed study using Clostridium sporogenes as surrogate.

10. Conclusion

Since the acceptance by the FDA of the first microwave sterilization process in United State for compliance in processing low acid food, there is an immediate need to commercialize the technology. The benefits of using microwave for thermal processing includes better food quality, reduction of processing time, and efficient energy utilization. To this end, it is very crucial that food industries be informed that such technology already exists.
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CHAPTER THREE

DEVELOPMENT OF A MICROWAVE ASSISTED THERMAL STERILIZATION COMPUTER SIMULATION MODEL (MATS-CSM) FOR PROCESSING FOOD USING THE MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEM

Abstract

A Microwave Assisted Thermal Sterilization Computer Simulation Model (MATS-CSM) was developed to aid verification of heating pattern, location of cold spot, and other thermodynamic parameters related to foods processed by Microwave Assisted Thermal Sterilization (MATS) system. MATS-CSM also provides a theoretical platform for continuous design improvement of MATS, ensuring proper propagation of its electromagnetic fields. MATS-CSM provides the numerical solution for the complex, coupled, electromagnetic-heat transfer phenomena related to processing homogeneous and heterogeneous foods in MATS. Using similar cell grid and discretization, both electromagnetic and heat transfer solutions were solved using the Finite-Difference Time-Domain numerical method. MATS-CSM is an improved version of the simulation model created by Chen et al. (2008) which was based upon the single mode applicator design of Pathak et al. (2003). This paper summarizes the procedure for creating MATS-CSM with special attention to the flexibility of the simulation model, ease of interface use, and the accuracy and verifiability of the results.
1. Introduction

1.1. Rationale for creating the microwave assisted thermal sterilization computer simulation model (MATS-CSM)

A significant attribute of MATS is the improved quality of the food produced due to reducing processing time by as much as ten times when compared to conventional heating methods (Brody, 2011); (Tang, Feng, & Lau, 2002). Figure 1 illustrates a comparison of the temperature history for food (i.e., 162 g of salmon in 65 g of Alfredo sauce packed in an 237 mL. 160 × 110 × 16 mm rectangular flexible pouches) using MATS and a typical thermal sterilization process for packaged food using conventional horizontal retort. In this illustration, with the aid of microwave energy, sterilization temperature was reached 40 min earlier when compared to pure heat from steam or hot water alone.

Although the advantages of using microwave energy are obvious, several challenges must be overcome to ensure smooth integration of the microwave concept into a feasible technology, one of which is the problem of uniformity in the electromagnetic (EM) field distribution (Metaxas & Meredith, 1993). The fundamental physics of the system demand that the design and operating frequency of the microwave cavity as well as the shape, size, placement, and dielectric properties of food can influence uniformity of EM field distribution (Kashyap & Wyslouzil, 1977; Ryynanen & Ohlsson, 1996; Romano, Marra, & Tammaro, 2005; Geedipalli, Rakesh, & Datta, 2007). Another notable challenge in using microwave energy is the edge overheating effect in food which is a non-resonant phenomena caused by the electric field parallel to the edge of the food (Risman, 2009).
Figure 1: Temperature history at the cold spot in salmon processed in traditional horizontal retort and MATS

Challenges in using microwave energy can be addressed by proper design of microwave applicators and cavities. In MATS, cavities (*i.e.*, geometry and configuration) are single-mode with or without load (*i.e.*, food) (Pathak, Liu, & Tang, 2003). A single-mode cavity operates with only one resonant mode in a small well defined volume (Metaxas & Meredith, 1993; Decareau, 1985). Therefore, the EM field pattern inside a single-mode cavity is always consistent and predictable. Furthermore, a single-mode cavity is advantageous in providing predictable and stable heating pattern and location of the cold spots in foods. Since the edge overheating effect is almost always present either in domestic or commercial scale design of microwave ovens when food is heated in air (*i.e.*, a MATS system is no exception), to lessen the effect of overheating, water can be circulated inside the cavities of MATS together with the food being processed. The circulating water has three purposes: (1) it acts as a heat sink to reduce the edge overheating effect in food during microwave heating, (2) it maintains the temperature of the food once it
reaches sterilization temperature (Tang, Liu, Pathak, & Eves, 2006), and (3) it acts as a matching medium resulting in a relatively even power deposition profile at the surface of the food (Pathak, Liu, & Tang, 2003).

Computer simulation is a widely accepted tool that aids engineers in designing microwave ovens (Sundberg, Risman, Kildal, & Ohlson, 1996; Celuch & Kopyt, 2009; Hossan, Byun, & Dutta, 2010; Celuch, Soltysiak, & Erle, 2011). In developing MATS, computer simulation was an indispensable tool in examining the theoretical basis for the design of the system. Pathak et al (2003) used the Finite-Difference Time-Domain numerical method for computer simulation to characterize microwave field distribution inside the cavities of MATS. It was demonstrated that the water in the cavities helps in leveling out the power distribution within food. Following the work of Pathak et al. (2003), Chen et al. (2008) developed a computer simulation model using the same FDTD numerical method that included both microwave propagation and heat transfer to simulate the continuous operation of MATS with the purpose of describing the heating pattern and location of the cold spot in food as it went through the four microwave cavities of MATS. The computer simulation model by Chen et al. (2008) was created only for a certain scenario and has no provision for modification. Thus there is an urgent need to completely revise the tool. Furthermore, considering that MATS is in its commercialization phase, scale up will undoubtedly require several changes to the original configuration necessitating adjustments in the computer simulation.

1.2. Description of microwave assisted thermal sterilization (MATS) system

The microwave assisted thermal sterilization (MATS) being modeled for numerical simulation in this study is a product of 15 years of research by the microwave sterilization group at Washington State University (WSU). The MATS (Figure 2) is a closed system consisting of
four sections—preheating, heating, holding and cooling—arranged in series representing the four sequential processing steps. Each section has a separate water circulation system that consists of a pressurized tank and plate heat exchangers to control water flow at a pre-set temperature. A custom designed transition section between two adjacent sections allows food packages to move through each section in single file while restricting the exchange of circulating water. In a typical operation, the water temperature in the preheating, heating, holding and cooling sections was maintained at 72°C, 122°C, 122°C, and 20°C, respectively. A pocketed mesh conveyor belt made of non-metallic material extending from one end of the preheating section to the other end of the cooling section conveys food trays or pouches across different sections of MATS. The manner by which food is loaded categorizes the first generation MATS operating in a semi-continuous mode. In operation, each batch consisting of not more than 48 food trays or pouches moves along the sections of MATS.

The preheating section is for equilibrating the temperature of the food to a uniform initial temperature (IT) (i.e., target IT set at 70 to 72°C). The temperature of the water circulating inside the preheating section is monitored by an RTD sensor connected to a control system that regulates injection of steam in the plate heat exchanger attached between the preheating section and the pressurized tank. For physical monitoring, the temperature inside the preheating section is displayed in an Anderson™ Digital Reference Thermometer (DART) (Anderson Instrument Co., Inc., 156 Auriesville Rd., Fultonville, NY 12072).

As food trays or pouches loaded on the conveyor belt traverse the microwave (MW) heating section of MATS, food is heated by the combined action of thermal energy from hot water (i.e., 122°C and 234.4 kPa) circulating in the MW heating section and the microwave energy emitted from the four applicators attached to the MW heating section. The measured
flow-rate of hot water circulating inside the heating section is approximately 50-55 L/min. The nominal operating frequency of the microwave generators (i.e., magnetron type generator) is at 915 MHz with the setting described in Table 3. Similar to the preheating section, the water temperature in the MW heating section is controlled using an RTD sensor, and displayed using DART.

The holding section is an extension of the MW heating section. Circulating water in the holding section at 122°C and 234.4 kPa maintains the temperature of the food, or acts as a heat sink if the temperature of the food rises above 122°C until the food reaches the desired sterilization value ($F_o$). The holding section is also equipped with an RTD sensor and DART. Inside the holding section, the belt that carries food trays or pouches is continuously moving. The effect of the holding section provides additional residence time for trays or pouches at the sterilization temperature. The last section is the cooling section, which lowers the temperature of the food to room temperature.
Figure 2: Microwave assisted thermal sterilization (MATS) system showing various sections: preheating, heating, holding and cooling.
Figure 3: Cavity 3 assembly consists of (a) single mode cavity, (b) UltemTM window at top and bottom of the cavity, (c) horn, and (d) Tee waveguide junction. Waveguide assembly for connecting cavity 3 to generator consists of (e) 90° H-bend waveguide elbow, and (f) 90° E-bend waveguide elbow.
This study is primarily concerned with the microwave heating section of the MATS. The MW heating section consists of four connected rectangular microwave cavities (i.e., cavity 1, cavity 2, cavity 3, and cavity 4). Each of the four cavities is connected to a separate corresponding microwave generator (generator 1, generator 2, generator 3, and generator 4).

The details of cavity 3, for example, are illustrated in Figure 3. The dimensions of the inner cross-section of the microwave cavity are 247.7 mm by 81.0 mm with a total length of 773.2 mm (Figure 3a). This configuration allows the cavities to operate in a single mode (i.e., only one pattern of electromagnetic field distribution predominates regardless of the presence of load at 915 MHz). Each cavity has two windows on the top and on the bottom made of Ultem® polymer Ultem-1000 by Plastic International (7600 Anagram Drive, Eden Prairie, MN 55344) of size 557.2 mm by 185.7 mm (Figure 3b). Cavity 3 is connected to an applicator consisting of two (2) horns for top and bottom injection of microwaves, four-(4) 90° E-bend waveguide elbows, and a tee junction of symmetrical dimension. The horn is a tapered shape parallelogram with inner cross sectional dimension at the narrow and wide end similar to the cross sectional dimension of a standard WR975 waveguide (i.e., the inner cross section is 247.7 mm by 123.8 mm) and the cavity windows, respectively (Figure 3c). The wide end of the top and bottom horn is attached to the two windows of the cavity. The applicator resembles a circular shaped (donut-like) assembly, to which microwave energy is injected at one end, bifurcated at the tee junction (Figure 3d) such that a portion will travel in the upper part of the semi-circle and another portion will travel in the lower part merging on the loaded cavity (i.e., circulating hot water at 122°C with food trays or pouches as the load of the cavity). Considering the configuration of the tee junction, the phase difference between the wave traveling on the upper part and the lower part
would be 90°. To ensure a 0° phase shift at the center of the cavity, a half wavelength waveguide was added to the upper part.

1.3. Study gap

In this study, the new computer simulation model is referred to as MATS-CSM (Microwave Assisted Thermal Sterilization Computer Simulation Model). The MATS-CSM employs a similar numerical approach as described by Chen et al. (2008) but also addresses the limitations of the previous version. Listed below are the critical limitations of Chen et al.’s (2008) computer simulation model with the revisions done in the MATS-CSM:

- In the simulation model of Chen et al. (2008), the food packages were monitored as if they were equally spaced as they traveled through the four heating cavities. This means that, considering the length of one cavity (i.e., 773.2 mm), each food package will travel only six discrete steps per cavity. For the MATS system with its four cavities, this would translate into twenty four discrete steps. Six discrete steps was the limit of Chen et al.’s (2008) model because they assumed a pseudo-moving package, whereas there are actually six food packages per cavity in the simulation model. After obtaining the solution of coupled EM-heat transfer, they applied it to the first food package, and then initialized the heating pattern of the second food package using the information from the first food package. This loop continues until it completes the calculation for the final sixth food package. Following this scheme would limit the number of discrete steps since it would not allow overlapping of food packages. In Section 5.3 of this study, it is proven that fewer than 32 discrete steps results in inaccurate heating patterns. In this study the MATS-CSM model simulates moving food by replacing the media parameter of the volume that will be occupied by the food on its next discrete step to the media parameter of the food. The initial heating pattern of the next
discrete step is equal to the final heating pattern of the previous discrete step. Replacing volume in the computational domain with the media parameters of the food allows overlapping of food package positions; therefore, there is no limit to the number of discrete steps. The higher the number of discrete steps, the more accurate the simulation result.

- The paper of Chen et al. (2008) describes a two-cavity system; however in the simulation model there is only one cavity. This means simulation was executed twice (i.e., first simulation for the first cavity and second simulation for the second cavity) and that the heating pattern from the sixth food package from the first simulation was the initial condition of the first food package in the second simulation. In the simulation model of Chen et al. (2008), the grid for the finite difference calculation was terminated using a perfect electric conductor (PEC) (Chen, Tang, & Liu, Couples simulation of an electromagnetic heating process using the finite difference time domain method, 2007). This would result in almost a 2% error in EM field calculation. If the simulation is executed twice, the error in EM field also multiplies. The MATS-CSM includes four cavities in one model eliminating the need for multiple simulations. Furthermore, the right end of the first cavity and the left end of the fourth cavity of the MATS-CSM are extended such that the PEC termination is far from the bulk of the computational domain. Doing so reduces the error due to the PEC termination down to 0.5% or less. Although the computational domain of the MATS-CSM is much larger (approximately five times) than that of Chen et al.'s (2008) simulation model, this is compensated for by using a more powerful workstation.

- The simulation in Chen et al. (2008) requires node transformation, since the node for EM in QuickWave QW3D is not the same as the temperature node for heat transfer adopted by Kopyt and Celuch (2003). Using the new version of QuickWave (version 7.5) to create the
MATS-CSM, thermal FDTD uses the same mesh as with EM FDTD (Celuch, Soltysiak, & Erle, 2011), thereby eliminating the need for node transformation and avoiding numerical diffusion error (Kopyt & Celuch, 2004). Furthermore, the simulation model in Chen et al. (2008) was created using an older version of QuickWave (version 5.0) wherein the heat flow module (HFM) was not available. The MATS-CSM utilizes the HFM to facilitate synchronization of the thermal and EM solutions.

- The heat transfer equation in Chen et al.’s (2008) simulation model is very specific to the node defined in the model. If there is a change in meshing, modification in the geometry of the cavity, or change in size, shape and composition of food package geometry, the heat transfer equation of Chen et al. (2008) will no longer work. In the MATS-CSM, for flexibility, all components are defined in an individual object with variable parameters (e.g., dimension, number of discrete steps, components of food, size and shape of food, etc.). These variables can be changed depending on the objective of the user, and the mesh automatically readjusts to accommodate changes in the parameters. Furthermore, the new model takes advantage of the HFM. The heat transfer equation in HFM automatically adjusts to the mesh of the computational domain, allowing flexibility in modifying dimensions. This is especially useful since MATS is currently in the commercialization phase wherein scale up will require several changes in the dimensions from the original system simulation.

1.4. Objective

The general objective of this study is to create a new computer simulation model for the microwave assisted thermal sterilization (MATS) system (which will be known as the MATS-CSM) that considers the coupled solution of electromagnetic field and heat transfer phenomena
in food packages moving in multiple microwave cavities. The specific objectives of this study are:

- To create a flexible computer simulation model that is able to accommodate future modification in the MATS system as well as the food being processed in the MATS. The MATS-CSM should be able to consider a wide range of food materials and package geometries, including both homogeneous and heterogeneous types of food.
- To describe electromagnetic field distribution inside microwave cavities with and without food packages.
- To determine the acceptable discrete number of time steps for the movement of food.
- To compare heating patterns in certain food packages considering EM-only solution versus EM-heat transfer solution.
- To validate the heating pattern output of the MATS-CSM through the chemical marker method.

2. Related concepts

2.1. Finite-difference time-domain (FDTD) numerical method

2.1.1. FDTD governing equation

The set of four Maxwell equations that govern the general characteristics of electromagnetic waves traveling in a certain medium are (QWED, 2009) (refer to Chapter 1, Table 2 for definitions of variables):

\[
\nabla \cdot \vec{D} = \rho \\
\n\nabla \cdot \vec{B} = 0
\]
\[ \nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \]  
(3)

\[ \nabla \times \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \]  
(4)

By applying curl-operation on Equations 3 and 4, wave equations in terms of electric field intensity or magnetic field intensity are obtained (Metaxas & Meredith, 1993):

\[ \nabla^2 \vec{E} = \mu \sigma \frac{\partial \vec{E}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \]  
(5)

\[ \nabla^2 \vec{H} = \mu \sigma \frac{\partial \vec{H}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \]  
(6)

Considering the equation of propagation constant \( [\gamma^2 = j \omega \mu (\sigma + j \omega \varepsilon)] \), and a time harmonic field wherein curl of electric and magnetic was equated (\( \nabla^2 \vec{E} = \gamma^2 \vec{E} \), and \( \nabla^2 \vec{H} = \gamma^2 \vec{H} \)), Equations 5 and 6 was simplified into (Guru & Hiziroglu, 2004):

\[ \nabla^2 \vec{E} = \gamma^2 \vec{E} = j \omega \mu \sigma \vec{E} - \omega^2 \mu \varepsilon \vec{E} \]  
(7)

\[ \nabla^2 \vec{H} = \gamma^2 \vec{H} = j \omega \mu \sigma \vec{H} - \omega^2 \mu \varepsilon \vec{H} \]  
(8)

Solving the derived Maxwell’s equation presented in Equations 7 and 8 on a regular geometry (i.e., slab, cylinder, and sphere) is straightforward (Balanis, 1989). However, for irregular or complex geometry, there is no closed-form solution to Maxwell’s equation so that the most appropriate approach is to solve Maxwell’s equation numerically. The numerical approach works by discretizing the irregular or complex geometry (known as the computational volume) into cells or regular geometries. This allows reduction of complex differential equations into a simple linear or polynomial set of equations (Burden & Faires, 2005).

Finite-difference time-domain (FDTD) is a common numerical method for electromagnetic problems designed specifically to solve the time differentiated Maxwell’s curl equations (equation 7 and 8). FDTD is a modification of the finite difference method (FDM)
initially introduced by Thom & Apelt (1961). The geometry of the cells used to discretize the computational volume in FDTD is based on Yee’s cell unit which is basically a slab (Figure 4).

Since the first introduction of FDTD by Yee, 1966 it became widely used in research involving both analysis and design of devices and systems for electromagnetic wave phenomena. Taflove (1975) is one of the many researchers who used the concept of Yee and applied it extensively in the analysis of two and three-dimensional scattering problems (Shlager & Schneider, 1995; Taflove & Brodwin, 1975). According to Taflove (1975), the FDTD method is a time-marching procedure that simulates the continuous electromagnetic waves in a finite spatial region while time-stepping continues until a desired simulation time is achieved or a stable field pattern is established. The FDTD method is favored over other methods that employ object discretization because of its computational efficiency and straightforward implementation of Maxwell’s equation (Sheen, Ali, Abouzahra, & Kong, 1990).

A standard Yee’s unit cell is illustrated in Figure 4 for numerical computation. The electric field, $E$, in Figure 4 is represented by arrows along the edge of the cell and the magnetic field, $H$, by arrows tangential to the face of the cell. The dimensions of the cell along the $x$, $y$, and $z$ axes are $\Delta x$, $\Delta y$, and $\Delta z$, respectively. Although Yee’s standard unit cell is a cube (i.e., $\Delta x = \Delta y = \Delta z = \delta$), it is possible to have non-equal edges as long as the structures conform with the stability of numerical computation determined through evaluation of the stability factor (Pereda, Garcia, Vegas, & Prieto, 1998).
A three-dimensional volume was discretized by stacking cubic or rectangular unit cells to fill a larger domain that mimics the desired computational volume in a staircase or conformal FDTD setting (Yee, Chen, & Chang, 1992). A conformal FDTD is a modified staircase FDTD wherein the top and bottom plane of the unit cells are allowed to be in the shape of other polygons (i.e., other than square or rectangle), but with an equal number of vertices. (QWED, 2009). This allows for precise modeling of an object that has a curved or inclined boundary. A computational volume in reality can extend to infinity; however, the actual object can only be represented by a finite computational grid. Therefore, it is necessary to terminate the grid with the assumption that all of the out-going waves at the terminal faces propagate into infinity with negligible reflections. The grid can be terminated with either an absorbing boundary condition (ABC) representing a perfectly matched layer (PML) (Teixeira, Hwang, Chew, & Jin, 2001), a perfect electric conductor (PEC), or a perfect magnetic conductor (PMC) (Chen, Tang, & Liu, 2007).
2.1.2. FDTD cell stability factor

According to Taflove (1988), proper cell discretization can be obtained from the second order dispersion relations of Yee’s FDTD grid. In one dimension (i.e. propagation is aligned in the grid), the dispersion equation is,

\[ \sin^2\left(\frac{\omega \Delta t}{2}\right) = \left(\frac{c \Delta t}{\delta}\right)^2 \sin^2\left(\frac{k \delta}{2}\right) \]  

(9)

where

- \(\omega\) angular frequency \((\omega = 2\pi f)\);
- \(f\) frequency \((f = c/\lambda)\);
- \(c\) speed of light;
- \(\lambda\) wavelength;
- \(\Delta t\) temporal step size;
- \(\delta\) spatial step size;
- \(\tilde{k}\) numeric wave number.

Taking the square root of equation 9 and letting \(N_\lambda = \lambda / \delta\) as points per wavelength in free-space, and \(S = c \Delta t / \delta\) as the Courant number or stability factor yields

\[ \tilde{k} \delta = 2 \sin^{-1}\left[\frac{1}{S} \sin\left(\frac{\pi}{N_\lambda} S\right)\right] \]  

(10)

Although Equation 10 describes propagation in one-dimension, it also represents propagation along principal axes in higher dimensions (e.g., 2 dimensions or 3 dimensions). In two and three dimensions, for stability of the numerical solution, the Courant number \((S)\) should be less than one (i.e., for two dimensions \(S = 1/\sqrt{2}\), and for three dimensions \(S = 1/\sqrt{3}\)). In this scenario, the argument inside the arc sine operation in Equation 10 would have a value \(\leq 1\), for as long as the number of points per wavelength \((N_\lambda)\) is given a large value, resulting in a real wave

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number ($\tilde{k}$). However, as $N_\lambda$ value decreases (i.e., cell discretization becomes course) such that \( \sin(S\pi/N_\lambda) > S \), the resulting wave number ($\tilde{k}$) becomes complex. For a complex wave number, phase velocity increases with grid coarseness, resulting in a phase velocity greater than the speed of light. The spectral component in this condition is termed as superluminal (Schneider & Wagner, 1999).

Considering that $N_\lambda$ is related to the free-space wavelength, the highest frequency that can be coupled into the FDTD grid is $f_{max} = 1/(2\Delta t)$ corresponding to the minimum wavelength of $\lambda_{min} = c/f_{max} = 2c\Delta t$. The minimum points per wavelength would then be the minimum wavelength divided by spatial step size—that is $N_{\lambda_{min}} = \lambda_{min}/\delta = 2c\Delta t/\delta = 2S$. In a three dimensional FDTD, where the Courant number is equal to $1/\sqrt{3}$, $N_\lambda$ should be at least $2/\sqrt{3} \approx 1.155$ points per wavelength. This means that the maximum spatial step should be $0.866\lambda$ (Schneider and Wagner, 1999).

In general, the maximum temporal step size (Equation 11) is limited by the Courant number (Sheen, Ali, Abouzahra, & Kong, 1990):

$$\Delta t \leq \frac{1}{\nu_{max} \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}}$$

(11)

Considering the entire computational volume, the maximum velocity ($\nu_{max}$) is equal to the speed of light ($c$) unless the whole volume is occupied by a certain dielectric. Equation 11 can be rewritten as Equation 12, the stability of the numerical solution described by Taflove (1988) if $\Delta x = \Delta y = \Delta z = \delta$, that is the Courant number ($S = c\Delta t/\delta$) is equal to $1/\sqrt{3}$ for a three-dimensional volume.

$$c\Delta t \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}} \leq 1$$

(12)
If the dimension of the unit cells that make up the entire computational volume are not equal \((i.e., \Delta x \neq \Delta y \neq \Delta z)\), it is practical to non-dimensionalize Equation 12 by setting the spatial step size \(\delta\) arbitrarily equal to one of the dimensions in the unit cell. In this study, \(\Delta x\) is chosen to be equal to \(\delta\), and the ratio of the other two dimensions with respect to \(\Delta x\) are; \(r_y = \Delta y/\Delta x\); and \(r_z = \Delta z/\Delta x\). Following the notation described, Equation 12 becomes:

\[
S = \frac{c\Delta t}{\delta} \leq \frac{1}{\sqrt{1 + \frac{1}{r_y^2} + \frac{1}{r_z^2}}}
\]  

(13)

In cases where the computational volume is composed of different dielectric materials, the overall stability of the calculation is still determined using Equation 13. However, the wavelength is shorter when travelling in a dielectric material as compared to when travelling in free space, \(N_{\lambda_{\text{dielectric}}} \gg N_{\lambda_{\text{min}}}.\) As a rule of thumb, 10 points per wavelength within the dielectric material has been suggested (Pathak, Liu, & Tang, 2003). Tang (2005) gives the equation for calculating wavelength within the dielectric material as a function of dielectric properties:

\[
\lambda_{\text{dielectric}} = \frac{\lambda_o}{\sqrt{\varepsilon'_r \left[\frac{\varepsilon''_r}{\varepsilon'_r} + 1\right]}}
\]  

(14)

where

- \(\lambda_o\) wavelength in free space;
- \(\varepsilon'_r\) dielectric constant;
- \(\varepsilon''_r\) dielectric loss factor.
2.1.3. FDTD governing equation

The algorithms for solving three-dimensional (3D) FDTD computational volume were derived from the Maxwell equations, Equations 3 and 4, considering the components of the electric and magnetic field (Guru & Hiziroglu, 2004):

\[
\nabla \times \vec{E} = \begin{bmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{bmatrix} = -\mu \frac{\partial \vec{H}}{\partial t}
\]

(15)

\[
\nabla \times \vec{H} = \begin{bmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{bmatrix} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t}
\]

(16)

Considering its components in the \(x\), \(y\), and \(z\) dimensions, the equations of the EM-fields becomes (Taflove & Hagness, 2005):

\[
\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right)
\]

(15)

\[
\frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right)
\]

(16)

\[
\frac{\partial H_z}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right)
\]

(17)

\[
\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x \right)
\]

(18)

\[
\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right)
\]

(19)

\[
\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \right)
\]

(20)

Referring to the configuration of Yee’s cell in Figure 4, the size of one of Yee’s cells is equal to \(\Delta x\), \(\Delta y\), and \(\Delta z\) in the \(x\), \(y\), and \(z\) direction, respectively, at a given time step \(\Delta t\). Considering the coordinate of Yee’s cell as grid point \((m, n, p)\), the \(x\), \(y\), and \(z\) distance of any grid point would be \(x = m\Delta x\), \(y = n\Delta y\), and \(z = p\Delta z\). Discretization of time follows in the
same manner wherein a certain point in time \( q \) at the grid corresponds to a certain time by considering a time step \( \Delta t \) (i.e., \( t = q \Delta t \)).

In FDTD, the linear equation representation of a partial equation with respect to time is given by:

\[
\frac{\partial H_{i}}{\partial t} = \frac{H_{i}^{q+1/2}(m,n,p) - H_{i}^{q-1/2}(m,n,p)}{\Delta t}
\]

\[
\frac{\partial E_{i}}{\partial t} = \frac{E_{i}^{q+1}(m,n,p) - E_{i}^{q}(m,n,p)}{\Delta t}
\]

(21)

and the linear equation representation of the partial equation with respect to position considering central difference is given by:

\[
\frac{\partial F_{i}}{\partial x} = \frac{F_{i}^{q+1}(m+1,n,p) - F_{i}^{q}(m,n,p)}{\Delta x}
\]

\[
\frac{\partial F_{i}}{\partial y} = \frac{F_{i}^{q}(m,n+1,p) - F_{i}^{q}(m,n,p)}{\Delta y}
\]

\[
\frac{\partial F_{i}}{\partial z} = \frac{F_{i}^{q}(m,n,p+1) - F_{i}^{q}(m,n,p)}{\Delta z}
\]

(22)

where \( F \) is either electric, \( E \), or magnetic \( H \) field component. Considering the \( xy \), \( xz \), and \( yz \) plane of Yee’s cell in Figure 4, each plane has a magnetic field in a direction perpendicular to the plane. That is the \( H_{x}(m+1/2,n+1/2,p) \), \( H_{y}(m+1/2,n,p+1/2) \), and \( H_{z}(m,n+1/2,p+1/2) \) magnetic field component are perpendicular to \( yz \), \( xz \), and \( xy \), respectively. The corresponding electric field component to the magnetic field perpendicular to the \( yz \), \( xz \), and \( xy \) planes at a certain point in time, \( q \), at the grid, are those that are along the grid edges. Specifically:

\[
H_{x}(m,n+1/2,p+1/2): \begin{cases} 
E_{y}(m,n+1/2,p+1,q) \\
E_{x}(m,n+1,p+1/2,q) \\
E_{z}(m,n,p+1/2,q) \\
E_{x}(m,n,p+1,q)
\end{cases}
\]

(23)
\[ H_y(m + \frac{1}{2}, n, p + \frac{1}{2}); \begin{cases} E_x(m + \frac{1}{2}, n, p + 1, q) & E_x(m + \frac{1}{2}, n, p, q) \\ E_z(m + 1, n, p + \frac{1}{2}, q) & E_z(m, n, p + \frac{1}{2}, q) \end{cases} \] (24)

\[ H_z(m + \frac{1}{2}, n + \frac{1}{2}, p); \begin{cases} E_x(m + \frac{1}{2}, n + 1, p, q) & E_x(m + \frac{1}{2}, n, p, q) \\ E_y(m + 1, n + \frac{1}{2}, p, q) & E_y(m, n + \frac{1}{2}, p, q) \end{cases} \] (25)

Considering the field along the x, y, and z axes of Yee’s cell in Figure 4, the three electric field components would have a corresponding magnetic field at a certain point in time \( q + \frac{1}{2} \) located on the plane perpendicular to the axis. Specifically, these fields are:

\[ E_x(m + \frac{1}{2}, n, p); \begin{cases} H_y(m + \frac{1}{2}, n, p + \frac{1}{2}, q + \frac{1}{2}) & H_y(m + \frac{1}{2}, n, p - \frac{1}{2}, q + \frac{1}{2}) \\ H_z(m + \frac{1}{2}, n + \frac{1}{2}, p, q + \frac{1}{2}) & H_z(m + \frac{1}{2}, n - \frac{1}{2}, p, q + \frac{1}{2}) \end{cases} \] (26)

\[ E_y(m, n + \frac{1}{2}, p); \begin{cases} H_x(m + \frac{1}{2}, n + \frac{1}{2}, p - \frac{1}{2}, q + \frac{1}{2}) & H_x(m + \frac{1}{2}, n + \frac{1}{2}, p + \frac{1}{2}, q + \frac{1}{2}) \\ H_z(m + \frac{1}{2}, n + \frac{1}{2}, p, q + \frac{1}{2}) & H_z(m - \frac{1}{2}, n + \frac{1}{2}, p, q + \frac{1}{2}) \end{cases} \] (27)

\[ E_z(m, n, p + \frac{1}{2}); \begin{cases} H_x(m + \frac{1}{2}, n, p + \frac{1}{2}, q + \frac{1}{2}) & H_x(m + \frac{1}{2}, n, p - \frac{1}{2}, q + \frac{1}{2}) \\ H_y(m + \frac{1}{2}, n, p + \frac{1}{2}, q + \frac{1}{2}) & H_y(m - \frac{1}{2}, n, p + \frac{1}{2}, q + \frac{1}{2}) \end{cases} \] (28)

The time step in Equations 26 up to 28 is the next time step on the grid \((q + 1/2)\). The electric field described in Equations 26 up to 28 is dependent on the updated magnetic field \(H_i^{q+1/2}\). Then for the next time step on the grid, the magnetic field described in Equations 23 up to 25 would be dependent on the updated electric field \(E_i^{q+1}\). The routine of updating fields mimics a time-marching procedure of a simulating electromagnetic fields as described by Taflove (2005). To determine the equation of the update of the field on the next time step, Equation 21 was substituted into Equations 15 to 20, while considering the electromagnetic field counterpart described in Equations 23 to 28, and the central difference described in Equation 22:
\[
H_x^{q^+\frac{1}{2}}(m, n + \frac{1}{2}, p + \frac{1}{2}) = H_x^{q-\frac{1}{2}}(m, n + \frac{1}{2}, p + \frac{1}{2}) + \left\{ \frac{\Delta t}{\mu \Delta y} \left[ E_y^{q}(m, n + \frac{1}{2}, p + 1) - E_y^{q}(m, n + \frac{1}{2}, p) \right] \right\}
\]
\[
E_y^{q}(m, n + \frac{1}{2}, p) - \frac{\Delta t}{\mu \Delta y} \left[ E_x^{q}(m, n + 1, p + \frac{1}{2}) - E_x^{q}(m, n, p + \frac{1}{2}) \right] \right\}
\]
\[
H_y^{q^+\frac{1}{2}}(m + \frac{1}{2}, n, p + \frac{1}{2}) = H_y^{q-\frac{1}{2}}(m + \frac{1}{2}, n, p + \frac{1}{2}) + \left\{ \frac{\Delta t}{\mu \Delta x} \left[ E_z^{q}(m + 1, n, p + \frac{1}{2}) - E_z^{q}(m, n, p + \frac{1}{2}) \right] \right\}
\]
\[
E_z^{q}(m, n, p + \frac{1}{2}) - \frac{\Delta t}{\mu \Delta x} \left[ E_x^{q}(m + \frac{1}{2}, n, p + 1) - E_x^{q}(m + \frac{1}{2}, n, p) \right] \right\}
\]
\[
H_z^{q^+\frac{1}{2}}(m + \frac{1}{2}, n + \frac{1}{2}, p) = H_z^{q-\frac{1}{2}}(m + \frac{1}{2}, n + \frac{1}{2}, p) + \left\{ \frac{\Delta t}{\varepsilon \Delta y} \left[ E_y^{q}(m + 1, n + \frac{1}{2}, p) - E_y^{q}(m, n + \frac{1}{2}, p) \right] \right\}
\]
\[
E_y^{q+1}(m + \frac{1}{2}, n, p) = \frac{1 - \sigma \Delta t}{1 + \sigma \Delta t} E_x^{q}(m + \frac{1}{2}, n, p) + \frac{1}{1 + \sigma \Delta t} \left\{ \frac{\Delta t}{\varepsilon \Delta x} \left[ H_x^{q^+\frac{1}{2}}(m + \frac{1}{2}, n + \frac{1}{2}, p) - H_x^{q^+\frac{1}{2}}(m + \frac{1}{2}, n - \frac{1}{2}, p) \right] \right\}
\]
\[
E_y^{q+1}(m, n + \frac{1}{2}, p) = \frac{1 - \sigma \Delta t}{1 + \sigma \Delta t} E_y^{q}(m, n + \frac{1}{2}, p) + \frac{1}{1 + \sigma \Delta t} \left\{ \frac{\Delta t}{\varepsilon \Delta x} \left[ H_x^{q^+\frac{1}{2}}(m, n + \frac{1}{2}, p + \frac{1}{2}) - H_x^{q^+\frac{1}{2}}(m + \frac{1}{2}, n + \frac{1}{2}, p) \right] \right\}
\]
\[
H_x^{q^+\frac{1}{2}}(m, n + \frac{1}{2}, p - \frac{1}{2}) - \frac{\Delta t}{\varepsilon \Delta x} \left[ H_x^{q^+\frac{1}{2}}(m + \frac{1}{2}, n + \frac{1}{2}, p) - H_y^{q^+\frac{1}{2}}(m, n + \frac{1}{2}, p) \right] \right\}
\]
\[
E_x^{q+1}(m, n, p + \frac{1}{2}) = \frac{1 - \sigma \Delta t}{1 + \sigma \Delta t} E_x^{q}(m, n, p + \frac{1}{2}) + \frac{1}{1 + \sigma \Delta t} \left\{ \frac{\Delta t}{\varepsilon \Delta x} \left[ H_y^{q^+\frac{1}{2}}(m + \frac{1}{2}, n, p + \frac{1}{2}) - H_y^{q^+\frac{1}{2}}(m, n, p + \frac{1}{2}) \right] \right\}
\]
\[
H_y^{q^+\frac{1}{2}}(m - \frac{1}{2}, n, p + \frac{1}{2}) - \frac{\Delta t}{\varepsilon \Delta y} \left[ H_x^{q^+\frac{1}{2}}(m, n + \frac{1}{2}, p + \frac{1}{2}) - H_x^{q^+\frac{1}{2}}(m, n, p + \frac{1}{2}) \right] \right\}
\]
2.1.4. Power calculation

Using FDTD to solve the electromagnetic equations on microwave heating requires definition of a microwave source, and characterization of how microwave power from the microwave source is being dissipated as heat in the load (i.e., the food). For the source of microwaves, typically, an input port is defined at a location within the computational volume. An input port covers an area in the computational volume, wherein the electric and magnetic field at a selected frequency is triggered at a known amplitude and excitation waveform (QWED, 2009). From the initial value of the electromagnetic field at the input port, the rest of the EM field at every cell comprising the entire computational volume was solved using Equations 29 to 34.

The equivalent power injected at the input port is dependent on the amplitude of the electric fields. Given the actual time-averaged power available from a microwave source (i.e., magnetron), the amplitude at the input port should be equal to the square root of the time-maximum power available to the source to ensure the correct level of dissipated power in the load (QWED, 2009).

\[ A = \sqrt{2P} \]  
where \( A \) is the amplitude of the electric field in the input port, \( P \) is the time-average power available from the source, and \( 2P \) is the time-maximum power available from the source.

Poynting’s Theorem (Equation 36) describes the amount of dissipation of microwave energy into heat (Balanis, Advanced Engineering Electromagnetics, 1989). Considering a time-average power flow \( (P) \) from the source:

\[ P = \frac{1}{2} \Re(\vec{E} \times \vec{H}^*) \]  
where \( P \) is the time-average power and the real part of the cross product of the electric field \( (\vec{E}) \) and the conjugate of magnetic field \( (\vec{H}^*) \) is the time-maximum power.
Derivation of dissipated power will consider the closed surface of the volume to which power will be dissipated (e.g., the surface of the food):

$$P = \frac{1}{2} \oint \vec{E} \times \vec{H}^* \cdot ds$$  \hspace{1cm} (37)

Applying the divergence theorem on Equation 37 yields:

$$P = \frac{1}{2} \iiint \nabla \cdot (\vec{E} \times \vec{H}^*) \, dv$$  \hspace{1cm} (38)

Applying product vector identity to Equation 38 yields:

$$P = \frac{1}{2} \iiint [\vec{E} \cdot (\nabla \times \vec{H}^*) + \vec{H}^* \cdot (\nabla \times \vec{E})] \, dv$$  \hspace{1cm} (39)

Applying Maxwell’s equation described in Equation 1 to 4 and assuming a power input (-P):

$$-P = \frac{1}{2} \iiint \left[ -\vec{E} \cdot \left( \sigma \vec{E}^* + \varepsilon \frac{\partial \vec{E}^*}{\partial t} \right) + \vec{H}^* \cdot \left( -\mu \frac{\partial \vec{H}}{\partial t} \right) \right] \, dv$$

$$P = \frac{1}{2} \iiint [\sigma \vec{E} \cdot \vec{E}^* + \omega \varepsilon \vec{E} \cdot \vec{E}^* + \omega \mu \vec{H} \cdot \vec{H}^*] \, dv$$  \hspace{1cm} (40)

The first term in Equation 40 represents heat dissipated ohmically, the second term represents the energy stored due to the electric field (i.e., portion is dissipated as heat), and finally the third term represents the energy stored due to the magnetic field. Since biological materials are not magnetic in nature, dissipation of microwave energy is related only to the electric field. Therefore, in Equation 40 only the first and second terms contribute to heating (Wappling-Raaholt, 2009).

Expressing Equation 40 in terms of permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$), and considering effective conductivity as a contribution of both static conductivity ($\sigma$) and alternating field conductivity ($\omega \varepsilon''$), (Balanis, 1989) yields:

$$\sigma_e = \sigma + \omega \varepsilon''$$  \hspace{1cm} (41)

Thus, the final expression for dissipated power is:

$$P = \frac{1}{2} \iiint [\sigma_e \vec{E} \cdot \vec{E}^* + \omega \varepsilon' \vec{E} \cdot \vec{E}^* + \omega \mu \vec{H} \cdot \vec{H}^*] \, dv$$  \hspace{1cm} (42)
The second and third terms in Equation 42 are purely stored electric and magnetic fields that have no contribution to heating. Therefore, the final equation of microwave power dissipated as heat is:

\[ \varphi = \frac{1}{2} \iiint [\sigma_e \vec{E} \cdot \vec{E}] \, dv \]  \hspace{1cm} (43)

then notice that the effective conductivity is a combination of both a non-frequency dependent (\(\sigma\)) and a frequency dependent (\(\omega \varepsilon''\)) term. Therefore, effective conductivity becomes a frequency dependent property (Risman P., 2009) and can be expressed in terms of the loss factor as (\(\sigma_e = 2\pi f \varepsilon_o \varepsilon''\)). Considering a unit volume and a simple plane wave, the time-average power per unit volume and the time-maximum power per unit volume dissipated as heat is simplified into equation 44 and 45 respectively:

\[ \varphi = \frac{1}{2} [2\pi f \varepsilon_o \varepsilon'' |E|^2] \]  \hspace{1cm} (44)

\[ \varphi_o = 2\pi f \varepsilon_o \varepsilon'' |E|^2 \]  \hspace{1cm} (45)

2.2. Finite difference method (FDM for heat transfer)

2.2.1. Heat flow

QuickWave™ software (QWED, Warszawa, NIP Poland 1132173057) was used to solve the electromagnetic field distribution through FDTD first, and then the dissipated power in the food was calculated using Equation 44. In general, the specific heat of food changes with temperature. This finding was incorporated into the model to calculate the appropriate increase in temperature corresponding to the microwave dissipated power at a specific time increment. Given the fact that the electric field is not uniform within the food from an initial temperature (\(T_o\)), food after exposure to microwaves had an uneven temperature distribution giving rise to a temperature gradient for heat transfer. In fact even at the start of the microwave heating in
MATS, there exists a temperature gradient between the boundary of the food (typically at an initial temperature of 72°C) and circulating water (typically at an initial temperature of 121~122°C) inside the MATS. Although the rate of dissipation of microwave energy into heat is much faster compared to heat transfer due to the temperature gradient (Celuch, Soltysiak, & Erle, 2011), for a more accurate simulation result, the heat flow due to the temperature gradient was considered in the MATS-CSM simulation model.

In this study, the derivation of the update equation for change in temperature due to temperature gradient follows the discretization of computational volume described by Yee’s cell as illustrated in Figure 4. The temperature and heat designation within the cell are illustrated in Figure 5.

![Figure 5: Cells for finite-difference heat transfer](image)

The governing equation for conductive heat transfer used in the model is (Incropera, DeWitt, Bergman, & Lavine, 2007):

\[ \nabla^2 T - \frac{c_p}{k} \frac{\partial T}{\partial t} = 0 \]  

\[ (46) \]
where $T$ is the temperature, $c$ is specific heat, $\rho$ is density, and $k$ is thermal conductivity. These parameters are temperature dependent and the values are stored in the MATS-CSM. Considering $j$ as the discretization of heating time, $\Delta \tau$ as the heating time step, and $t$ as the total heating time ($t = j\Delta \tau$), the updated equation of temperature for the next time step is given in Equation 47 [adopted from (QWED, 2009), with modification as noted in indices]. Note that the heating time step ($\Delta \tau$) is different from the FDTD time step ($\Delta t$).

\[
T^{j+1}(m, n, p) = T^j(m, n, p) \Delta \tau \frac{\rho c}{V} \left[ \frac{k^j(m + 0.5, n, p) + k^j(m - 0.5, n, p)}{k^j(m, n + 0.5, p) + k^j(m, n - 0.5, p)} + \frac{k^j(m, n, p + 0.5) + k^j(m, n, p - 0.5)}{k^j(m, n + 1, p) + k^j(m, n - 1, p)} \right]
\]

In equation 47, $V$ is the volume of one cell which is equal to $V = \Delta x \Delta y \Delta z$.

### 2.2.2. Heat transfer boundary condition

In this study, a slab of whey protein gel (WPG) in Alfredo sauce packaged in a 160 $\times$ 110 $\times$ 16 mm flexible pouch was used as the food sample (see Section 4.2). It was assumed that the Alfredo sauce was viscous enough to cause insignificant movement during processing. Therefore, although WPG and Alfredo sauce each have unique dielectric and thermal properties as a function of temperature (Table 5 and Table 6, respectively), both were considered as one solid food as far as heat transfer is concerned. Therefore, heat transfer within the food follows a straightforward conduction (updated equation for temperature described in equation 47 applies). However, at the boundary between the food and circulating water, heat flux ($\psi$) is governed by
convective heat transfer (Incropera, DeWitt, Bergman, & Lavine, 2007; Zhou, Puri, Anantheswaran, & Yeh, 1995):

\[ \psi = -h(T - T_s) \]  

(48)

where \( T \) is the temperature of the food at the boundary, \( T_s \) is the temperature of the circulating water, and \( h \) is the heat transfer coefficient. The updated equation for change in temperature at the boundary depends on the number of faces of Yee’s cell exposed to \( T_s \). Let \( l \) equal the number of faces exposed to \( T_s \) (i.e., \( l \leq 6 \)):

\[ T^{j+1}(m, n, p) = T^j(m, n, p) - T^j(m, n, p) \left[ \frac{\Delta r}{v_{pc}(m,n,p)} \left( h \Delta x + \sum_{i=1}^{6-l} k_i \right) \right] + \frac{\Delta r}{v_{pc}(m,n,p)} \left[ \frac{h \Delta x}{\sum_{i=1}^{l} k_i} T + \sum_{i=1}^{6-l} k_i T \right] \]

(49)

where \( h \) is the heat transfer coefficient, \( \Delta x \) is the shortest length of the face of the cell exposed to \( T_s \), \( \sum_{i=1}^{6-l} k_i \) is the sum of thermal conductivity at cell grid not exposed to \( T_s \), \( \sum_{i=1}^{l} k_i \) is the sum of thermal conductivity at cell grid exposed to \( T_s \), and \( \sum_{i=1}^{6-l} k_i T \) is the sum of the product of thermal conductivity and temperature at the grid of the cell not exposed to \( T_s \).

### 2.2.3. Heat transfer coefficient

In a classical expression of the convective heat transfer coefficient \( h \), it is imbedded in a dimensionless number known as the Nusselt number \( (Nu) \):

\[ Nu = \frac{hL}{k_f} = f(Re, Pr) \]

(50)

where \( h \) is the convective heat transfer coefficient, \( L \) is the characteristic length (i.e., length of flat plate), \( k_f \) is the thermal conductivity of fluid, \( Re \) is the Reynold’s number, and \( Pr \) is the Prandtl number.
The Reynold’s number is the ratio of inertial and viscous force while the Prandtl number is the ratio of momentum and thermal diffusivities (Incropera, DeWitt, Bergman, & Lavine, 2007):

\[ Re = \frac{\rho VL}{\mu} \]  
\[ Pr = \frac{c_p \mu}{k_f} \] (51) (52)

where \( \rho \) is the density of the fluid, \( V \) is the velocity of the fluid, \( \mu \) is the viscosity of the fluid, and \( c_p \) is the specific heat of the fluid.

For turbulent and local flow \((Re \leq 10^8)\) with a Prandtl number range of \((0.6 \leq Pr \leq 60)\), the empirical equation for approximation of the Nusselt number is (Incropera, DeWitt, Bergman, & Lavine, 2007):

\[ Nu = \frac{hL}{k_f} = 0.0296Re^{\frac{4}{3}}Pr^{\frac{1}{3}} \] (53)

Deriving the equation for convective heat transfer coefficient gives:

\[ h = \frac{0.0296Re^{\frac{4}{3}}Pr^{\frac{1}{3}}k_f}{L} \] (54)

The equation of overall heat transfer coefficient considering convection and conduction is:

\[ U = \frac{1}{\sum_{i=1}^{n} h_i + \sum_{i=1}^{n} \frac{k_i}{L_i}} \] (55)

3. Assumptions and limitations of the MATS-CSM

3.1. MATS-CSM assumptions

1. The simulation model assumes a perfectly matched condition (i.e., no reflection). This means that the injected microwave energy from the selected microwave port is completely absorbed by the load (i.e., circulating water in the cavity and food trays or pouches).
2. Since reflection occurs in the actual MATS system, the total microwave energy injected into each cavity in MATS-CSM is only the transmitted microwave energy measured in MATS. Transmitted microwave energy is equal to the actual incident microwave energy from the generator minus the reflected microwave energy measured by the directional coupler (Table 3).

3. The transmitted microwave energy in the side arm of the E-plane tee-junction is evenly divided into its coplanar arms (i.e., Power / 2) whose amplitude is equal to $A/\sqrt{2}$ (Table 3). This assumption follows an ideal lossless reciprocal E-plane tee-junction (Pozar, 2005).

4. Waveguide parts such as elbows, tee-junction, spaces, circulator, probe-tuner, and directional coupler do not alter the characteristics of the electromagnetic wave (Chen, Tang, & Liu, 2008).

5. Alfredo sauce, due to its high viscosity and relatively small quantity, is assumed to have insignificant mobility. Therefore, heat transfer occurring within the Alfredo sauce and the Alfredo sauce – WPG boundary is assumed to be purely conductive.

6. The turbulent condition of circulating water in the cavity is considered in the model by allowing convection between the boundary of circulating water and food (i.e., between water and Alfredo sauce, and between water and WPG).

3.2. MATS-CSM limitations

1. Movement of food (dielectric material) is discretized to a certain number of steps. The MATS-CSM cannot mimic the real time movement of food but rather the path of the food’s trajectory is subdivided into discrete steps.

2. Each element (characterized by a certain medium) occupying a certain volume is assumed to be linear, homogeneous, isotropic, and non-dispersive. For example, a certain element
occupying a volume can only have one value of a physical property (e.g., dielectric and thermal property of WPG). Heterogeneous food (i.e., food with multiple components and each component having its own distinct properties) is allowable in MATS-CSM by combining elements into one object.

3. Combination of elements creates an interface among elements. In the MATS-CSM, there are no more than two elements sharing a common interface. In reality, especially for food that has more than 3 components, it is unavoidable to have more than 3 components having no contact with each other. However, this is not allowable in the MATS-CSM, so proper spacing among elements should be observed.

4. Each element should have a definite dimension that cannot change during simulation. In a real scenario, especially for a biological material, the dimensions might change during the microwave heating process (e.g., WPG might expel water during heating, thus causing a decrease in volume). Changes in the dimensions of the material cannot be considered in the MATS-CSM model.

5. Termination of the FDTD grid in the MATS-CSM is through a perfect electric conductor (PEC) that can cause error in the electromagnetic field distribution. To have an insignificant effect of errors due to termination of the grid on the desired computational domain, the grid is terminated at an infinite distance from the desired computational domain.
4. Experimental procedure

4.1. Microwave assisted thermal sterilization computer simulation model (MATS-CSM)

4.1.1. Components of MATS-CSM

Since coupled microwave and heat transfer heating occurs only in the heating section of the MATS, other sections (*i.e.*, preheating, holding and cooling sections) are not included in the MATS-CSM. Detailed reasons for exclusion of the three other sections are as follows:

- The purpose of the preheating section is to ensure a uniform initial temperature within the food pouches. The contribution of the preheating section is considered by assuming a uniform initial temperature of food pouches at the entrance of the heating section. Therefore, there is no need to include the preheating section in the MATS-CSM.

- The purpose of the holding section is to accumulate sterilization value by maintaining the temperature of the food pouch after exiting the heating section. Two possible scenarios that can happen to food when traveling through the holding section are:
  
  (a) Fast belt speed (≥1.7 cm/s). In this case, there is not much temperature change in the food while traveling in the holding section. This is because the residence time of the food pouch inside the holding section is relatively short (*i.e.*, belt speed is relatively fast) as compared to the rate of heat conduction within the food pouch. Therefore, the contribution of the holding section is quantified by assuming an adiabatic condition (*i.e.*, the initial and final temperature at the entrance and exit of the holding section are assumed to be the same) within the food pouch.

  (b) Slow belt speed (<1.7 cm/s). In this case, there is a significant temperature change in the food due to heat transfer. To consider this scenario in the MATS-CSM, the microwave
source is shut down. Without microwaves, the heating section functions similar to the holding section.

In both scenarios, there is no need to include the preheating section in the MATS-CSM.

- The contribution of the cooling section is to rapidly reduce the temperature of the food pouch. For thermal processing purposes, a food temperature of <70°C would result in minimal contribution to sterilization value (Richardson, 2001). Typical processing of food in the MATS system requires only a few min to reduce the temperature of food pouches from the initial temperature at the exit of the holding section to a temperature <70°C. Therefore, as far as contribution to lethality is concerned, the contribution of the cooling section is negligible and hence is excluded in the MATS-CSM.

Figure 6 shows a three-dimensional (3D) representation of the computational volume of the MATS-CSM. For simplicity, the waveguides that connect the cavities to their designated generators (e.g., cavity1 waveguide connection to generator 1) are not included. Instead they are replaced by two ports located at the top and bottom portion of the horn applicator (Figure 6a). Detailed assumptions for the use of ports are explained in Section 3.1 item 2 to 4.

For flexibility, the MATS-CSM has a small library of different objects and each has their own parameters that can be changed depending on a given scenario. Parameters such as dimensions, dielectric and thermal properties, mesh discretization, etc., can be easily modified by accessing the *.udo (user defined object) associated with each object file. Table 1 lists the objects within the MATS-CSM library, their default characteristics and variable parameters.
Figure 6: Computer simulation model consisting of four microwave cavities and four pairs of horn applicators: (a) location of microwave input port; there is a total of eight ports in the model; (b) direction of movement of pouch; (c) location of the pouch.

Table 1. Different components of MATS-CSM and the variable parameters for each component.

<table>
<thead>
<tr>
<th>MATS-CSM components</th>
<th>Illustration</th>
<th>Variable parameters</th>
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<tr>
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<td>Ultem™ bars</td>
<td>Meshing</td>
<td>Food</td>
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<td><img src="image2" alt="Image of Meshing" /></td>
<td><img src="image3" alt="Image of Food" /></td>
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<td><strong>Length</strong></td>
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<tr>
<td><strong>Each cavities have different Ultem™ bars configuration</strong></td>
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<tr>
<td>Number of heating time step</td>
<td>Thickness of refinement in (xy) plane</td>
<td>Size of cell in (xy) plane</td>
</tr>
<tr>
<td>Size of cell in (z) axis</td>
<td>110 mm</td>
<td>160 mm</td>
</tr>
<tr>
<td>16 mm</td>
<td>32</td>
<td>30 mm</td>
</tr>
<tr>
<td>3 mm</td>
<td>1 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Ports</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excitation field</td>
<td>Waveform</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Frequency</td>
<td>(TE_{10})</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>Depending on power input to the cavity</td>
<td>Depending on measured operating frequency of generators</td>
<td></td>
</tr>
<tr>
<td><strong>Food</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of food</td>
<td>Width of food</td>
<td>Height food</td>
</tr>
<tr>
<td>84 mm</td>
<td>127 mm</td>
<td>16 mm</td>
</tr>
</tbody>
</table>

### 4.1.2. Stability of the MATS-CSM

In this study the MATS-CSM was discretized such that the unit cell had a maximum size of 4 mm by 4 mm by 16 mm. These values gave an \(r_y = 1\) and \(r_z = 4.0\) as described in Equation 13. The stability index of the entire computational volume would be 0.6963, which is greater than the Courant number for a three-dimensional model (i.e., \(1/\sqrt{3} \approx 0.5574\)); hence, Equation 13 was satisfied. Furthermore, the mesh size for the dielectric media (i.e., food and water in the cavities) in the MATS-CSM was refined to have a smaller cell size complying with the 10 points.
per wavelength rule. For water, the size was 4×4×4 mm along the x, y, and z axes, respectively, and for food, the size was 4×4×1 mm on the x, y, and z axes, respectively with further mesh refinement on the edge along the x and y axes. Considering the dielectric constant of food and water used in this study (Tables 5, 6, and 7) at room temperature (20°C), the numbers of points per wavelength in food and in water were at least 25 and 16, respectively. Mesh refinement for food and water was done using the “spline” function of QuickWave™. A meshing.udo was created such that it would automatically refine the mesh of the food considering its path, size of the pouch, number of discretized steps, and the desired width of mesh refinement along the x and y directions (refer to Section 4.2 for more details).

### 4.2. Food representation in MATS-CSM

A whey protein gel (WPG) was used as a model food for validating the heating pattern generated by the computer simulation model through the chemical marker method (Section 4.10). The dielectric and thermal property of WPG was used to define food as a lossy material in the MATS-CSM (refer to Table 5 for dielectric and thermal properties). The whey protein gel slab was represented in the simulation model by drawing a bi-phase object consisting of: (a) a slab element in the middle with dimensions of 52 × 95 × 16 mm (*i.e.*, x,y,z); (b) four-4 half cylinder elements attached to the four sides of the slab element, each with a radius equal to 16 mm and a length equal to the length of the side of the slab to where the half cylinder was attached; and (c) four-4 quarter sphere elements attached to the four corners of the slab element with a radii equal to 16 mm (Figure 7). A bi-phase object is a term used to define 3D objects in QuickWave™ software. A bi-phase object is a collection of bi-phase elements. A bi-phase element can be either a simple element or a combined element. A simple element is composed of identical polygons on top and bottom with the same number of vertices (*e.g.*, slab element),
while a combined element can have different polygons on top and bottom but still have the same number of vertices (e.g., half cylinder and half sphere) (QWED, 2009).

Typical food products in pouches previously processed in the MATS contain sauces (i.e., viscous liquid) and mass of solids packed together inside the pouches (e.g., WPG and Alfredo sauce packed in a flexible pouch). To consider the sauce in the MATS-CSM model, the dielectric and thermal properties of commercially available Bertolli™ (Unilever United States, Inc., 800 Sylvan Avenue, Englewood Cliffs, NJ 07632) Alfredo sauce was used. The bi-phase object representing Alfredo sauce was incorporated in the model in the same manner in which WPG was represented in the model. The final dimensions of the Alfredo sauce were (95×140×16 mm) (i.e., x,y,z). The volume occupied by the bi-phase object representing WPG (94×127×16 mm) was embedded in the bi-phase object representing the Alfredo sauce (Figure 7), displacing an equal volume occupied by the Alfredo sauce.

![Figure 7: Whey protein gel (WPG) representation in computer simulation model (MATS-CSM) showing different planes (xy, xz, and yz).](image-url)
4.3. Dielectric and thermal property of Whey Protein Gel and Alfredo sauce used in this study

Table 2 summarizes the formulation of the WPG used in this study. Commercially available Bertolli™ Alfredo sauce was used for this study. A typical preparation of whey protein gel (WPG) was made in a batch of 1000 grams of WPG solution. Distilled water in a 2kg capacity glass beaker at room temperature was stirred using magnetic stirrer and stirring began. As soon as a vortex appeared, salt and D-ribose (pre-weighed based on 1000 g solution) were the first ingredients added, since these components easily dissolve in water. WP 392 and WP 895-I (New Zealand Milk Products, Santa Rosa, CA) are hydrophobes, and therefore, easily agglomerate upon contact with water. To prevent too much agglomeration, a pre-weighed amount of whey protein isolate based on 1000 g WPG solution was added into the stirring water little by little. The resulting WPG solution was allowed to stir for 1.5 h to completely dissolve the whey protein isolate. Excessive stirring, however, could incorporate micro bubbles into the solution. Presence of micro bubbles in the WPG solution, if not removed before solidifying, can alter the dielectric property of the WPG and is, therefore, undesirable. To remove those bubbles, the WPG solution was allowed to stand for about 12 to 15 h (typically overnight) in a refrigerator at 5°C. Rexam™ (710 West Park Rd., Union, MO 63084) 237 mL rigid polymeric trays were used as molders in solidifying the micro-bubble free WPG solution. An amount of 165±1 grams of WPG solution was poured into each Rexam™ trays (measured using a Mettler Toledo MS3002S balance) and partially submerged, making sure that no water from the water bath mixed with the WPG solution, into a preheated water bath at 70°C for 40 min to allow solidifying. Solid WPG was then allowed to cool for about 10 min before storing in a refrigerator at 5°C.
The instrument used to measure dielectric property (DP) was a Hewlett-Packard 8752C network analyzer. The dielectric property system and methodology described by Wang et al. (2003b) was utilized in this study. The dielectric property system consisted of: (a) a double pipe heat exchanger test cell connected to a silicon oil bath (PolyScience Inc., 400 Valley Road Warrington, PA 18976, USA); (b) a spring mechanism to keep the sample in contact with the coaxial probe, and also to hold the thermocouple system for measuring temperature; and (c) a mounting flange that holds the high temperature and pressure coaxial probe in place. Thermal properties of WPG and Bertolli™ Alfredo sauce were measured using a Decagon™ KD2-pro (Decagon, WA, USA). The specific heat and thermal conductivity were measured through the double needle method (Campbell, Calissendorff, & Williams, 1991). Enthalpy was calculated by taking the product of specific heat, density, and temperature change, considering 70°C as the reference temperature.

Table 2. Composition of whey protein gel (WPG)

<table>
<thead>
<tr>
<th>Components</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>75.4</td>
</tr>
<tr>
<td>Salt</td>
<td>0.6</td>
</tr>
<tr>
<td>D-ribose</td>
<td>1</td>
</tr>
<tr>
<td>WPG 392</td>
<td>18</td>
</tr>
<tr>
<td>WPG 895-I</td>
<td>5</td>
</tr>
</tbody>
</table>

Dielectric and thermal properties data were included in the MATS-CSM modify media parameter (*.pmo) files: (a) WPG.pmo; and (b) AlfredoSauce.pmo for WPG and Alfredo sauce, respectively. The parameters that must be included in a *.pmo file are (a) temperature, (b) enthalpy, (c) dielectric constant, (d) effective conductivity, (e) specific heat, (f) density, (g) thermal conductivity. All parameters were measured except for enthalpy, which was calculated from the specific heat, density, and temperature change. In updating the heating pattern, enthalpy
was used as the basis for temperature change (Section 4.5) since it describes the amount of heat that must be absorbed or released by Yee’s unit cell per volume to effect a temperature change (Celuch & Kopyt, 2009).

The dielectric property (DP) measurement was made over a temperature range of 20°C to 120°C with a 20°C increment. The oil bath used to ramp up the temperature of the sample inside the test cell had a maximum temperature of 120°C. However, in the actual processing of food pouches using MATS, some portions of the food inside the pouch during microwave heating can exceed 120°C, creating a high internal pressure. To counteract internal pressure inside the pouch, the pressure inside the MATS was set to 234.4 kPa by compressed air. Simulating the described scenario requires that dielectric and thermal properties of food beyond 120°C be included in the simulation model. In this study dielectric and thermal properties of WPG and Alfredo sauce were extrapolated up to 150°C. Furthermore, for accuracy of the computer simulation an increment of 10°C was considered; hence, the data of the WPG and Alfredo sauce were interpolated in 10°C increments. Cubic spline or piecewise-polynomial approximation (Burden & Faires, 2005) was used to interpolate and extrapolate values from the DP-temperature curve.

Aside from WPG and Alfredo sauce, water.pmo was also included in the MATS-CSM modify media parameter file. However, for water, since the objective was to maintain a temperature at 121-122°C during microwave heating, there were only two temperature levels in water.pmo: the property of water at 121°C and at 122°C. In actual operation of the MATS, the temperature of water in the heating section was maintained at 122°C by allowing it to circulate in a plate-type heat exchanger. In simulation, although the temperature of the water was supposed to increase due to the dissipated power from the microwave, during updates of the heating pattern of water based upon the water.pmo file, the QuickWave™ simulator updated the
temperature by taking the last entry in the water.pmo file, which was set at 122°C (regardless of whether the dissipated power in water would cause a temperature greater than 122°C). Therefore, water is assumed to have the same, constant temperature throughout the execution of the loop as described in Section 4.5.

Similar to water but of lesser relevance, the dielectric and thermal properties of Ultem™ materials (Table 8) were also declared in the Ultem.pmo file. There were two temperature levels in Ultem.pmo: (a) 70°C which was the initial temperature of all Ultem™ bars and windows; and (b) 122°C which is the constant temperature inside the heating section during microwave heating. Although Ultem™ bars can influence the EM field pattern inside the cavities, they have no influence on the heat transfer between food and water and within the food.

4.4. Input ports and designation of power level

In the FDTD simulation, proper designation of input ports is important since the whole computational volume depends on the initial value of the electric and magnetic fields at the port. QuickWave™ software allows for the initiation of EM field at a certain point or plane within the computational volume by using an object called “port”. In the MATS-CSM there are eight input ports consisting of four top-ports and four bottom-ports (i.e. two ports for each cavity). Ports were drawn within the top and bottom standard WR975 waveguide attached to the tapered end of every horn (Table 6-a). The parameter settings of the eight ports used in the MATS-CSM are summarized in Table 3.

The distance between the top and bottom port for a given cavity in the MATS-CSM is approximately 113 cm and the phase between the EM wave coming from the top and the EM wave coming from the bottom is zero (in-phase). In the actual MATS setup, each cavity is connected to a generator (e.g., cavity 1 is connected to generator 1, and cavity 2 is connected to
generator 2 and so on). Since the magnetrons of the microwave generators are of different ages and were made by different manufacturers, the output frequency might be different from the nominal frequency of 915 MHz. Using a B&K Precision TM-6250 handheld spectrum analyzer (22820 Savi Ranch ParkWay, Yorba Linda, CA 92887) and an AN-301 antenna, the frequency was monitored for a period of one year on a monthly basis. The tabulated frequencies in Table 3 are the average frequencies of the generators for a one year duration. Furthermore, in the actual MATS setup, each cavity has a different waveguide configuration resulting in different quantities of power reflection. Using directional couplers manufactured by Ferrite Microwave, Inc. (165 Ledge Street, Nashua, NH 03060), reflected power was measured for each cavity; the corresponding transmitted powers (Table 3) was used in the MATS-CSM model.

Table 3. Different input ports in MATS-CSM

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Name of Port</th>
<th>Exciting Field</th>
<th>Waveform</th>
<th>Frequency* / MHz</th>
<th>Transmitted Power / kW**</th>
<th>Amplitude***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity 1</td>
<td>topPortC1</td>
<td>TE₁₀</td>
<td>Sinusoidal</td>
<td>912.1</td>
<td>6.40</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>bottomPortC1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 2</td>
<td>topPortC2</td>
<td>TE₁₀</td>
<td>Sinusoidal</td>
<td>916.5</td>
<td>5.56</td>
<td>74.6</td>
</tr>
<tr>
<td></td>
<td>bottomPortC2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 3</td>
<td>topPortC3</td>
<td>TE₁₀</td>
<td>Sinusoidal</td>
<td>905.6</td>
<td>2.51</td>
<td>50.1</td>
</tr>
<tr>
<td></td>
<td>bottomPortC3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 4</td>
<td>topPortC4</td>
<td>TE₁₀</td>
<td>Sinusoidal</td>
<td>903.1</td>
<td>2.59</td>
<td>50.9</td>
</tr>
<tr>
<td></td>
<td>bottomPortC4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Measured using B&K Precision (22820 Savi Ranch ParkWay, Yorba Linda, CA 92887) TM-2650 spectrum analyzer and AN-301 antenna.

**Measured using directional coupler by Ferrite Microwave, Inc. (165 Ledge Street, Nashua, NH 03060).

***Calculation of amplitude was discussed in Section 3.1 item 3.

4.5. Simulation Routine

The simulation routines of the MATS-CSM were adopted from the routine described by Celuch et al. (2011). Upon exporting the necessary files from the QuickWave™ Editor (which
provided an interface for drawing and discretizing the computational volume of the desired modeled object) to the QuickWave™ Simulator (to implement the FDTD coupled heat transfer simulation), the EM field distribution within the computational volume was solved iteratively until steady state. On the first loop of the routine, the steady state condition was identified after 100 iterations with no further change in the EM field distribution, and consecutive loops used 5 iterations. After the steady state was achieved, the average dissipated power described in Equation 44 was determined on every cell within the computational volume. The average dissipated power was calculated considering the effective conductivity of the lossy medium at an initial temperature ($T_o$). The effective conductivity of the lossy medium at the initial temperature ($T_o$) was taken from the “modify media parameter” (*.pmo) files (Section 5.1). Afterwards, the enthalpy of each of Yee’s cells was updated using:

$$Enthalpy^{j+1}(x,y,z) = Enthalpy^j(x,y,z) + \frac{\varphi(x,y,z) \Delta \tau}{\Delta V(x,y,z)}$$

(56)

where $j$ and $\Delta \tau$ are the discretization of heating time and heating time step, respectively, described in Equation 46, and $\Delta V$ is the volume of the Yee’s cell. From Equation 56, the updated enthalpy $[Enthalpy^{j+1}(x,y,z)]$, say for WPG and Alfredo sauce, corresponded to a higher temperature. The updated temperature was interpolated from the *.pmo file of every lossy material (e.g., WPG.pmo and alfredosauce.pmo):

$$T^{j+1}(x,y,z) = T[Enthalpy^{j+1}(x,y,z)]$$

(57)

The MATS-CSM model incorporates the movement of food packages. Therefore, from an initial location, the food was moved to the next location after the temperature was updated. Furthermore, after updating the temperature, a temperature gradient existed within the food and between the boundary of the food and circulating water. Using the updated temperature of every cell and heating time step ($\Delta \tau$), the temperature was further updated using Equations 47 and 49.
within the food and in the boundary of food and water, respectively. The loop of the routine was then repeated until the food completed the number of discretized movements (QWED, 2009).

4.6. Electromagnetic field distribution and symmetry

In order to evaluate the electromagnetic field distribution generated from the MATS-CSM, we considered two simple scenarios: (1) the electromagnetic field distribution in empty cavities (i.e., cavities containing only water and no food pouches); and (2) the electromagnetic field distribution for loaded cavities (i.e., cavities that contain both water and food pouches). The snapshot of the electromagnetic field distribution for each cavity was taken after the MATS-CSM reached the steady state condition described in Section 4.5. For the first scenario, a snapshot of EM field distribution at the $xy$, $yz$, and $xz$ planes was taken at a certain phase of the field (all the snapshots were taken at the same phase). For the $xy$ and $yz$ plane snapshots, the centers of the computational volume along the $z$ direction and the $x$ direction were considered, respectively. For the $xz$ plane, the center of each cavity along the $y$ direction was considered. For the second scenario, 4 food pouches were situated at the geometric center of each cavity. A snapshot of the EM field distribution was taken at the same phase as with the first scenario along the $xy$ plane at the center with respect to the $z$ direction. Furthermore, the snapshot of the corresponding average dissipated power was taken. The color bar range used for all EM field distributions was from 0 to 200 V/m, while the color bar range for the dissipated power is from 0 to 10 MW/m$^3$.

4.7. Food movement and translation

The simulation routine described in Section 4.5 was terminated after the completion of the discretized movement of food. The heating section of the MATS had a fixed length of 3.1 m
and discretizing the movement of food moving across the heating section indicated discretizing the total heating time as well. For example, if the desired microwave heating time in the MATS was set to 180 s (achieved by adjusting the speed of the belt carrying the food), in simulation, if the total length was discretized into 16 steps, each step would be $3.1 / 16 = 193$ mm and equivalent to $180 / 16 = 11.25$ s of heating which is the $\Delta \tau$.

Table 4. Simulation schedule to determine optimum $\Delta \tau$.

<table>
<thead>
<tr>
<th>Step</th>
<th>Discretized movement step</th>
<th>Discretized heating time step ($\Delta \tau$)</th>
<th>Estimated computational time*</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>193.3 mm</td>
<td>11.3 s</td>
<td>19 h</td>
</tr>
<tr>
<td>32</td>
<td>96.6 mm</td>
<td>5.6 s</td>
<td>42 h</td>
</tr>
<tr>
<td>64</td>
<td>48.3 mm</td>
<td>2.8 s</td>
<td>111 h</td>
</tr>
</tbody>
</table>

*Workstation specification: (1) Model number: HP-Z800 (2) Processor: Intel Xeon X5680 @3.33GHz (3) Memory: 96GB DDR3 and (4) System type: 64-bit Windows 7 operating system

In numerical simulation of time dependent processes, selection of appropriate heating time step, $\Delta \tau$, is very important since it determines convergence of thermal diffusion (Equations 47 and 49). A very large $\Delta \tau$ (i.e., few discretized movements or steps) might cause immediate divergence. The simulated temperature within the food might be unrealistically low. Ideally, it is desirable to have as many discretized time steps or as small of a $\Delta \tau$ as possible to mimic the actual movement and heating time of food; however, the computational time would increases exponentially with a linear increase in the number of discretized time steps (QWED, 2009). To this end, it is important to determine the optimum $\Delta \tau$ that will allow solutions to converge. Table 4 summarizes the simulation schedule to determine an optimum $\Delta \tau$. For the three simulations conducted, all parameters except for those related to these steps (heating time step, and movement step) were the same.
4.8. Heating pattern in food estimated from coupled solution of EM-Heat transfer

This part of the study evaluates the importance of coupling heat transfer with the electromagnetic solution in terms of the resulting heating pattern in the WPG. Using the 32 step procedure (i.e., $\Delta t = 5.625$ s, and movement step = 96.6 mm) two simulations were performed: (a) electromagnetic-heat transfer coupled simulation, and (b) electromagnetic simulation without heat transfer.

(a) The dielectric and thermal properties of the WPG and Alfredo sauce were used. The overall heat transfer coefficient used was $115$ W/m²K.

(b) For simulation without heat transfer, only the dissipated power from the microwave energy was used as the source heat. Furthermore, without heat transfer, the boundary condition between the water-Alfredo sauce and the water-WPG is, by default, adiabatic.

4.9. Validation of the computer simulation model using the chemical marker method

To validate computer simulation results, the WPG with formulation as shown in Table 2 was used. A 162±5 g of WPG was cut into a slab with dimensions of $(84 \times 127 \times 16$ mm) and packed into an 237 mL flexible pouch with 65±1 g of Alfredo sauce. Six (6) sample pouches were loaded onto the microwave belt through the door and moved to the preheating section of the MATS. After 30 min of preheating at 70-72°C, the generators powering the MATS, at the setting described in Table 3, were turned on. The pressure inside the MATS was maintained at 234.4 kPa. The temperature at the heating section and holding section were maintained at $\sim122^\circ$C and at the cooling section at $\sim20^\circ$C. To maintain the temperatures of the heating, holding, and cooling sections, water was circulated through a plate heat exchanger at an average rate of 1.2, 0.85, and 1 L/s, respectively. After no significant change in temperature and pressure within the
MATS, the belt holding the pouches of the WPG was moved at a speed of ~1.7 cm/s, allowing transition from preheating, heating, holding and finally to the cooling section. This translates into 3 min (180 s) of microwave heating. The WPG inside the pouch was allowed to cool in the cooling section for 5 min before retrieving it through the cooling section door.

The heating patterns of six processed samples of WPG 16 mm thick slabs were determined using the computer vision method as part of the chemical marker method described by Pandit et al. (Pandit R. B., Tang, Mikhaylenko, & Liu, 2006); (Pandit R. B., Tang, Liu, & Mikhaylenko, 2007). In brief, each sample of processed WPG was cut in the middle layer along its thickness into two halves of 8 mm thickness. A standard cutting knife and a spacer 8 mm in height was used. The purpose of the spacer was to ensure that the blade of the knife would cut along the gel at a thickness of 8 mm. Using a high definition camera (Nikon™ D70 with AF-S DX NIKKOR 18-55 mm f/3.5-5.6 G VR lense) (Nikon Inc. 1300 Walt Whitman Road Melville, NY 11747-3064, U.S.A) images from the cut layer in the center of the WPG (i.e, the xy plane) were taken and prepared for color analysis. Adobe Photoshop™ CS4 (Adobe Systems Incorporated, 345 Park Avenue San Jose, CA USA) was used to prepare the images, and IMAQ Vision, a part of the library of LabVIEW (National Instrument product, Austin, TX) was used to determine the RBG equivalent of browning in WPG. Browning in the WPG was produced as a result of the non-enzymatic reaction between sugar (D-ribose) and protein (WPG 392 and WPG 895-I) (Lau, et al., 2003); (Pandit R. B., Tang, Mikhaylenko, & Liu, 2006).

Validation of the heating pattern was conducted by comparing the prominent temperature zones in a given area in the heating pattern of the chemical marker method, and mapping it with the result generated by the MATS-CSM. The location of the temperature zones and the weighted average of temperature in a given zone was the basis for validation.
4.10. Statistical analysis

The mean values of the dielectric properties of whey protein gel (WPG) and Bertolli™ Alfredo sauce were analyzed using the Generalized Linear Model (GLM) procedure from SAS V9.2 (SAS Institute Inc., Cary, NC). Statistical significance for the comparison of colors of heating patterns and the heat penetration test was set to $P < 0.05$.

5. Results and Discussion

5.1. Dielectric property of whey protein gel used in this study

The dielectric and thermal properties at 915 MHz of the whey protein gel (WPG) and the Alfredo sauce are summarized in Tables 5 and 6. Values corresponding to temperature 20°C, 40°C, 60°C, 80°C, 100°C, and 120°C were measured. Other values were either interpolated or extrapolated from the measured properties.

Table 5. Dielectric properties at 915 MHz and thermal properties of whey protein gel

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dielectric Constant ε' (unit less)</th>
<th>Loss factor ε'' (unit less)</th>
<th>Effective Conductivity 2πε₀ε'' (S/m)</th>
<th>Specific Heat (KJ/kg °C)</th>
<th>Thermal Conductivity (W/m °C)</th>
<th>Enthalpy (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>52.91±2.49</td>
<td>23.58±2.75</td>
<td>1.20</td>
<td>2.94**</td>
<td>0.40**</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>51.76±0.99</td>
<td>29.26±1.01</td>
<td>1.49</td>
<td>3.08**</td>
<td>0.45**</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>50.62±0.77</td>
<td>34.85±1.53</td>
<td>1.77</td>
<td>3.21±0.11</td>
<td>0.50±0.02</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>50.03*</td>
<td>39.75*</td>
<td>2.02</td>
<td>3.28±0.18</td>
<td>0.52±0.04</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>49.35±1.45</td>
<td>41.68±1.97</td>
<td>2.12</td>
<td>3.35±0.04</td>
<td>0.54±0.01</td>
<td>26.77</td>
</tr>
<tr>
<td>90</td>
<td>48.89*</td>
<td>46.76*</td>
<td>2.38</td>
<td>3.41±0.03</td>
<td>0.56±0.01</td>
<td>60.91</td>
</tr>
<tr>
<td>100</td>
<td>48.11±1.74</td>
<td>50.73±1.74</td>
<td>2.58</td>
<td>3.48±0.06</td>
<td>0.57±0.01</td>
<td>95.72</td>
</tr>
<tr>
<td>110</td>
<td>47.76*</td>
<td>53.77*</td>
<td>2.74</td>
<td>3.55±0.02</td>
<td>0.59±0.01</td>
<td>131.21</td>
</tr>
<tr>
<td>120</td>
<td>47.42±1.15</td>
<td>58.40±3.02</td>
<td>2.97</td>
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<td>0.60±0.01</td>
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<tr>
<td>130</td>
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<td>0.63**</td>
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*interpolated values **extrapolated values
Table 6: Dielectric properties at 915 MHz and thermal properties of Alfredo sauce

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<tr>
<th>Temperature (°C)</th>
<th>Dielectric Constant ε' (unit less)</th>
<th>Loss factor ε&quot; (unit less)</th>
<th>Effective Conductivity 2πfε0ε&quot; (S/m)</th>
<th>Specific Heat (KJ/kg.°C)</th>
<th>Thermal Conductivity (W/m.°C)</th>
<th>Enthalpy (MJ/m³)</th>
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<td>20</td>
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<td>0.671</td>
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</tbody>
</table>

*interpolated values  **extrapolated values

5.2. Electromagnetic field distribution and symmetry

Figure 8 shows the total electric field distribution (V/m) at a steady state along the xy plane at the center of the cavity traversing the center of the food with respect to the z axis. Figure 8 (a) includes water and food pouches located at the center of each cavity. Figure 8 (b) shows the electric field pattern in circulating water without food. From Figure 8 (b) it can be clearly seen that only a single mode electric field pattern exists within the cavities considering the frequencies and power settings of generators described in Table 3. Thus, in every cavity the electric field pattern is predictable and well-formed symmetrically along the xy plane. If more than one mode exists within the cavity, the electric field would have a random pattern due to interactions of waves (Chan & Reader, 2000). With the presence of food [Figure 8 (a)], the electric field distribution was still predictable and retained the single mode characteristic. It is important to point out that the single mode characteristic of the cavities demonstrated in Figure 8 is specific only to the frequencies and power settings described in Table 3. There is a need to determine the
stability of single mode characteristic of the cavities at a wider frequency band, which is the focus of Chapter 4.

Furthermore, the placing of the Ultem™ bars on the walls of each cavity was successful in creating a staggered electric field pattern for every cavity (Chen, Tang, & Liu, Simulation model for moving food packages in microwave heating processes using conformal FDTD method, 2008). For example, in cavity 1, the E field intensity was concentrated at the center, then at cavity 2, the E field was concentrated along the sides of the food as shown by three strips of E field pattern, then at the center again for cavity 3, and finally at the side again for cavity 4 (Figure 8-b). The effect of the alternating arrangement of electric field intensity was to produce a relatively uniform heating pattern in the food after it traverses the four cavities.

The staggered arrangement of the electric field is more visible in the dissipated power distribution (W/mm³) [Figure 8 (c) and (d)]. In this illustration, in cavity 1, the power was mostly dissipated to the middle of the food. For cavity 2, the power is dissipated horizontally along the side of the food; for cavity 3 toward the middle of the food and cavity 4 toward the side again. The xz and yz plane views of the total electromagnetic field distribution (Figure 9) shows the symmetry of the electric field in the z direction. Furthermore, since the pattern is symmetrical, it means that the two electric fields caused by microwaves from the top port and from the bottom port of each cavity are in phase. There is a zero degree phase shift between the incoming incident waves from the top and bottom of the horn. Figure 9 is also illustrates the standing wave patterns inside the cavities (i.e., encircle in red). The three distinct horizontal lines at the center of each cavity are the standing wave pattern resulting from the interaction of the incident field at the top and bottom horn. Notice that the middle horizontal line is exactly at the center of the cavity with respect to the z direction indicating a high intensity of electric field at the location of the food.
Figure 8: Electric field distribution (range from 0 to 200 V/m) in the xy plane at the center of the cavity for (a) loaded cavities, and (b) unloaded cavities. Dissipated power density (range from 0 to 10 MW/m$^3$) for (c) loaded cavities, and (d) unloaded cavities.
Figure 9: Electric field distribution along yz plane and xz plane. Color bar range similar to Figure 8(a) and (b)

5.3. Food movement and translation

This section summarizes the results of convergence of thermal diffusion at different heating time steps. The minimum number of heating time steps of foods in the computer simulation model that will not cause immediate divergence of EM-heat transfer solution was
determined. Figure 10 compares the simulated heating patterns using different heating time steps (11.3 s for 16 steps, 5.6 s for 32 steps, and 2.8 s for 64 steps calculations, respectively). The snapshots of heating patterns were taken at the center of the food with respect to its thickness in the z direction. Starting at the control (i.e., entrance of the food pouch at the first cavity), it can be noticed that the temperature distribution was uniform at 72°C. As food moves through different cavities, the heating pattern changes. Specifically, the second column from the left was the temperature distribution at the exit of cavity 1, the third column was the temperature distribution at exit of cavity 2, the fourth column was for the exit at cavity 3, and the fifth column for cavity 4. The temperature color bar range was from 72°F to 160°C. Notice that as far as the heating pattern is concerned there were no differences among the simulations when using 16, 32, or 64 steps. However, the magnitude of special variation in temperature was different between calculation using 16 and 32 steps. For example, the temperature predicted with 16 step calculation is much lower (approximately around 130°C for the hot area) compared to the value of temperature predicted with the 32 step calculations (approximately 135°C for the hot area). Nevertheless, there was no significant difference between the temperatures calculated with 32 or 64 steps. Simulation using 32 and 64 steps would give similar solution. Furthermore, simulating with less than 32 steps is not recommended because of the likelihood of immediate divergence of solutions. For example, the heating time step ($\Delta \tau$) used in 16 step simulation is too large ($\Delta \tau = 11.3$ s), resulting in immediate divergence of solution indicating a low temperature of the WPG (i.e., hot area was <130°C). This was more visible at the exit of cavity 1 (Figure 10). The hot area in 16 step simulation was just developing at the exit of cavity 1, while the hot areas in 32 and 64 step simulations were already clearly distinct at the exit of cavity 1. Therefore, the optimum time step was 5.6 s, which corresponds to 32 steps or 32-discretization in the heating
time for the complete movement of the food pouch through the four cavities. The approximate simulation time for 32 steps was 42 h per simulation run.

Since 32 steps, with a heating time step of 5.6 s and movement step of 97 mm, was identified as the optimum step, all simulations after this analysis were based on 32 steps.

Figure 10: Computer simulation result for temperature distribution in WPG slab using different heating time step (16 Step, 32 Step, and 64 Step). The first column represent the initial temperature (control) of the food, and the second, third, fourth and fifth column show the heating pattern of the food at the exit of first, second, third, and fourth cavity respectively.
5.4. Comparison of the microwave heating patterns of the simulation model with and without the surface heat transfer function

This section compares the results of heating patterns generated by computer simulation for two scenarios: (1) microwave heating without heat diffusion, and (2) combined effect of both microwave heating with heat diffusion through heat conduction within the food and heat convection on the surface of the food. One of the obvious effects of not incorporating heat diffusion in the solution of the electromagnetic field would be a more uneven distribution of temperature. Removing the heat transfer function from the MATS-CSM would result in accumulation of dissipated power in the cell throughout the microwave heating time following adiabatic condition in relation to neighboring cells. The result would be that cells exposed to high electric field concentration would accumulate more dissipated power than cells exposed to less electric field concentration. When equivalent temperatures, corresponding to the accumulated dissipated power in the cell (described in *.pmo file), were interpolated, some regions in the food exhibited a low temperature, while other regions reached a very high temperature (Figure 11 without Heat Transfer). Notice that in Figure 11 without Heat Transfer, the lowest temperature at the corner of the food at the exit to cavity 4 is about 72-75°C, while the highest temperature is already at 150-155°C. Considering actual processing in MATS, the large difference in temperature at the corner of the food is not possible because of the circulating water. Circulating water causes thermal diffusion at the surface of the food such that it may act as either a heat sink or a heat source which evens out temperature distribution at the surface.

For simulation results that allow heat diffusion (Figure 11 with Heat Transfer), the difference in temperature at the corner of the food at the exit to cavity 4 is relatively smaller. Furthermore, allowing heat transfer within the food and at the interface of food and circulating
water (using 115 W/m²-K as the overall heat transfer coefficient) results in an overall decrease in hot spots temperature of the food (Figure 11 with Heat Transfer) making the temperature distribution relatively uniform (lowest and highest temperature range was approximately at 110-113°C and 132-135°C, respectively). Figure 11 with Heat Transfer illustrates the advantage of having circulating water inside the cavities. Circulating water reduces the edge heating effect in food, and it homogenized temperature distribution in food resulting in a relatively uniform heating pattern.

Figure 8: Comparison of heating pattern for electromagnetic coupled heat transfer simulation (with heat transfer) and electromagnetic simulation alone (without heat transfer). Both simulations were run using 32 step simulation.

5.5. Validation of computer simulation model using chemical marker method

Figure 12 shows the result of six replicates of the heating patterns in the WPG as indicated by the accumulated chemical marker (M-2) (Pandit R. B., Tang, Liu, & Pitts, 2007). The results of the chemical marker method, unlike those of the simulation result, were not
perfectly symmetrical with respect to the $xy$ plane. The unsymmetrical heating pattern in the WPG could be due to: (a) relative position of the pouch containing the WPG during processing in the MATS, (b) errors in cutting of the whey protein gel along its thickness, (c) pockets of air inside the pouch, (d) micro bubbles within the WPG, or (e) possible moisture migration during processing of the WPG.

Figure 13 compares the heating patterns between the results of the MATS-CSM and the chemical marker method on the WPG. Figure 13 (a) shows a snapshot of the heating pattern taken from the 32-step simulation at the end of the fourth cavity with the heat transfer function using 115W/m$^2$-K as the overall heat transfer coefficient ($U$). Figure 13 (b) is a representative heating pattern result of chemical marker method.

The heating pattern of the MATS-CSM model and chemical marker on the WPG was summarized into three general temperature zones:

- **Cold Area 1.** These were the upper- and lower-most areas within the $xy$ plane. Since the heating pattern and temperature distribution is symmetrical in the $xy$ plane, these areas were designated as one (i.e., Cold Area 1).

- **Cold Area 2.** This area was at the middle of the $xy$ plane.

- **Hot Area.** These areas were the two intensely colored areas between cold area 1 and cold area 2. Since the two hot areas are symmetrical they were designated as one (i.e., Hot Area).

Based on the result of the MATS-CSM simulation, the combined area of cold area 1 and hot area comprises approximately 35% and 40% of the total area in the $xy$ plane, respectively, while cold area 2 comprises approximately 25%. The simulated average temperatures in the cold area 1, hot area, and cold area 2 were 112°C, 134°C, and 121°C, respectively. Therefore, the weighted average temperature of the result of the MATS-CSM (Figure 13 a) was 123°C. From
the results of the chemical marker method on the WPG (Figure 13 b), the approximate percent area for cold area 1, cold area 2, and hot area, were 35%, 30%, and 35%, respectively. However, the color value indicated by the chemical marker method cannot be directly correlated to temperature because the amount of M-2 marker formation depends on the accumulated lethality ($F_o$) and not on the final temperature (Pandit R. B., Tang, Liu, & Pitts, 2007). Therefore, Figure 13 (b) was more of a lethality pattern rather than a heating pattern. Nevertheless, for qualitative purposes, areas with high color value (reddish) received more lethality than areas with low color value (bluish). Since lethality is related to the time-temperature exposure of a certain area, and assuming that there is not much temperature deviation in food during processing, the final heating pattern described by temperature in Figure (13 a) would be comparable to the lethality pattern described by lethal rate ($F_o$) in Figure (13 b). Since the percent area and the relative position of cold area 1, cold area 2, and hot area in Figure 13 (a) was comparable to that of Figure 13 (b), the result of the MATS-CSM was verified to give a fairly accurate heating pattern, and therefore can be used as a tool for locating the cold spot in food.

Figure 9: Six (6) replicates of heating pattern in whey protein gel (WPG) determined through chemical marker method. Images were a snapshot of $xy$ plane of WPG at the center with respect to $z$-axis.
6. Conclusion

The MATS-CSM was created to provide tools for better understanding of the theoretical concept of electromagnetic and heat transfer phenomena applied to microwave assisted sterilization of food. This computer simulation model was specific to modeling the heating section of the microwave assisted thermal sterilization (MATS) located at WSU. With the main objective of improving and addressing the limitation of the previous computer simulation model created by Chen et al. (2008) and in reference to the specific objectives, this study was able to accomplish the following:

- Placing of Ultem™ bars on the walls of each cavity was successful in creating a staggered electric field pattern for every cavity, resulting in a relatively uniform heating pattern in food at the exit of the heating section of the MATS.

- The standing wave created due to the interaction of the field was precisely at the center of the cavity with respect to the z direction indicating a high intensity of electric field at the location of the food.
• The optimum time step for the MATS-CSM was 5.6 s, which corresponds to 32 steps or 32 discretization in heating time and movement of the food pouch across the four cavities of the heating section. The approximate simulation time for the 32 step simulation was 42 h / simulation run.

• Incorporating the heat transfer function in the electromagnetic solution in determining the heating pattern resulted in a relatively uniform temperature distribution as compared to the solution without the heat transfer function. Furthermore, this study proves that circulating water in the cavity can alleviate the edge overheating effect.

• Based upon the percentage of area and the relative positions of cold area 1, cold area 2, and the hot area, the result of the MATS-CSM was verified to give a fairly accurate heating pattern, and therefore can be used as a tool for locating the cold spot in food.

7. References


determine heating pattern using computer vision and chemical marker (M-2) yield.
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CHAPTER FOUR

EFFECT OF CHANGE OF OPERATING FREQUENCY OF THE MICROWAVE GENERATORS POWERING THE MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEM TO FOOD HEATING

Abstract

The Food and Drug Administration (FDA) recently accepted microwave assisted thermal sterilization (MATS) technology for sterilizing homogeneous and heterogeneous food. This technology combines microwave energy with surface heating using high temperature water circulation to reduce processing time. The first prototype of MATS technology was developed at Washington State University, Pullman WA. This system consists of a series of four cavities individually powered by magnetron-type microwave generators. Although each independent generator was manufactured to operate at 915 MHz, actual frequency measurement shows that operating frequencies fall within 900 MHz - 920 MHz range depending on the power setting of each generator. The objective of this study is to quantify the effect of different operating frequencies of generators to heating patterns in foods. The Federal Communications Commission (FCC) allocated industrial, scientific, and medical (ISM) frequency bandwidth for 915 MHz was considered in the simulation. Furthermore, frequencies resulting in change of heating pattern in food were determined by simulating at frequencies beyond allocated ISM bandwidth for 915 MHz. Finally, a simulation was conducted using the measured frequencies of the generators. For all simulation cases, the power setting used was 6.4 kW, 5.56 kW, 2.51 kW, and 2.59 kW for generator 1, 2, 3, and 4, respectively. These power settings represent the transmitted power on the cavities of MATS after appropriate tuning. Simulation cases were tested for two scenarios:
group (a) circulating water inside cavities with tap water, and group (b) circulating water inside cavities with deionized water. Results show that: (1) heating rate in food is higher when using deionized circulating water inside the cavities, (2) heating patterns in foods are not affected if the microwave generator is operating at frequencies within the allocated ISM bandwidth for 915 MHz, and (3) heating patterns in foods change if the operating frequency of generators is <880 MHz or >940 MHz.

1. Introduction

1.1. Microwave frequency

Although the Federal Communications Commission (FCC) of the United States has designated 915±13 MHz for industrial and domestic food heating/processing purposes, the operating frequency of a magnetron may deviate from 915 MHz. A common reason for frequency shift/deviation of the magnetron can be attributed to its length of use, typical power setting, and specifications of different manufacturers (IMPI, 2011). Naturally, a new magnetron by a certain manufacturer will operate close to its designated operating frequency but tends to shift as it ages. The natural deterioration of cathodes and anodes causes changes in the peak cathode current which may influence the operating frequency of the generator (CPI, 2011). Furthermore, the strength of the permanent magnet in the magnetron tends to decrease over time, which may cause changes in operating frequency of the generator (Decareau, 1985).

The microwave assisted thermal sterilization (MATS) system at Washington State University (WSU) is powered by four high-power magnetron generators. The first two generators powering cavity 1 and 2 are manufactured by Ferrite Microwave, Inc. (165 Ledge Street, Nashua, NH 03060) and the other two generators powering cavity 3 and 4 are by Microdry Industries, LLC (5901 W. Highway 22, Crestwood, KY 40014). A commercial
sterilization process using MATS for mashed potato packed in Rexam™ (710 West Park Rd., Union, MO 63084) polymeric tray and salmon in Alfredo sauce packed in a PrintPack™ (2800 Overlook ParkWay, NE Atlanta, GA 30339) flexible pouch was accepted by the Food and Drug Administration (FDA). Several other food products are in line for commercial sterilization process development using MATS, thus placing the microwave generators of MATS in constant use. Due to the regular use of the MATS system, the operating frequency of each generator was monitored for a period of one year (2009-2010) to document its stability; a study was conducted on the possible effects of heating patterns in food should a change in operating frequencies of generators occur.

1.2. Knowledge gap

Several researchers have developed computer simulation models using different numerical method such as finite difference time domain (FDTD) (Sundberg, Risman, Kildal, & Ohlson, 1996; Chen, Tang, & Liu, 2008) and Finite Element Method (Zhou, Puri, Anantheswaran, & Yeh, 1995; Romano, Marra, & Tammaro, 2005) to determine heating patterns in food. A typical assumption of those simulation studies is that the microwave energy from generators was at a fixed operating frequency. However, experimental validations for those simulations use systems with generators that may operate at slightly different frequencies. Several studies have been conducted relating microwave frequency to heating patterns in food (assuming a well behaved and fixed microwave operating frequency) (Chen, Tang, & Liu, 2008; Hossan, Byun, & Dutta, 2010) but no study has been conducted on determining the effect of heating patterns in food if a slight change in operating frequency of the microwave generator occurs. Furthermore, no study has been conducted specifying the boundary of operating
frequency bandwidth of the microwave generators that would not cause a change in heating patterns in food.

**1.3. Objectives**

The objectives of this study were:

- To establish the operating frequencies of generators in a MATS system over a period of one year, and to relate operating frequencies to power settings of the generators.
- To compare the operating frequency bandwidth of the microwave generators of MATS to the FCC allocated ISM bandwidth for 915 MHz.
- To determine the effect of different frequencies of generators in a MATS system to the heating patterns in foods through computer simulation when: (a) tap water and (b) deionized water are used as circulating water inside the cavities.
- To determine the limit of operating frequency of the microwave generators of MATS to which a significant change in heating patterns in foods may occur.
- To validate the simulated heating pattern through a chemical marker method using whey protein gel (WPG) as model food.

**2. Materials and methods**

**2.1. Microwave assisted thermal sterilization (MATS) system setup**

The first generation microwave assisted thermal sterilization (MATS) system at Washington State University (WSU) was used in this study. This MATS system consists of four sections—preheating, heating, holding and cooling—arranged in series representing the four sequential processing steps. A rubber door placed at the junction of each section allows the whole system to be pressurized at 234.4 kPa while water in a given section at a certain
temperature circulates without mixing. In a typical operation, the water temperature in the preheating, heating, holding and cooling sections was maintained at 72°C, 122°C, 122°C, and 20°C, respectively. A dedicated pressurized tank connected to a plate heat exchanger, supplied and received temperature controlled recirculating water to and from the designated section. A pocketed mesh conveyor belt made of non-metallic material extending from one end of the preheating section to the other end of the cooling section conveyed food trays or pouches across different sections of MATS. The manner by which food was loaded categorizes the first generation MATS as a semi continuous process. Each batch consisting of not more than 48 food trays or pouches moved along the sections of MATS.

The preheating section was for equilibrating the temperature of the food to a uniform initial temperature (IT) \(i.e.,\) target IT set at 70 to 72°C. The temperature of circulating water inside the preheating section is controlled by an RTD sensor. For physical monitoring, the temperature inside the preheating section was displayed in an Anderson™ Digital Reference Thermometer (DART).

As food trays or pouches in the belt conveyor traversed the heating section of the MATS system, food was heated by thermal energy from circulating hot water (122°C and 234.4 kPa) and the microwave energy infringing from the four cavities of the MATS system. The measured flow-rate of hot water circulating inside the heating section was approximately 50-55 L/min. The labeled operating frequency of microwave generators \(i.e.,\) magnetron type generator) was at 915 MHz. Similar to the preheating section, water temperature in the heating section of MATS system was controlled using an RTD sensor, and displayed using DART.

The holding section was an extension of the heating section of MATS system, but without microwave energy. Circulating water in the holding section at 122°C and 234.4 kPa
maintained the temperature of the food, or acted as a heat sink if the temperature of food was beyond 122°C, until the cold spot in food it reached the desired sterilization value ($F_o$). The holding section was also equipped with an RTD sensor and DART. Finally, the last section, the cooling section, lowered the temperature of the food to room temperature.

This study was primarily concentrated on the scenario occurring inside the heating section of the MATS system. The heating section was a series of four rectangular microwave cavities. The dimension of the inner cross-section of the microwave cavity was 247.7 mm by 81.0 mm with a total length of 773.2 mm. This configuration allows cavities to operate in a single mode (i.e., only one pattern of electromagnetic field distribution).

### 2.2. Computer simulation model for MATS

The computer simulation model for MATS system used in this study considered only the structure pertaining to the series of four cavities, which includes the 4-microwave heating zones and the horns attached to its windows (Figure 1). In computer simulation, the location of the microwave input port can be drawn anywhere within the waveguide as long as it is parallel to the cross section of the waveguide. A location just above and below the narrow end of the horn was selected (Figure 1a). Considering the media inside the horn and cavities (i.e., air at room temperature and water at 122°C) the distance between two input ports was calculated (i.e., 113 cm) such that interfering waves would have a zero phase shift. Furthermore, the selected location of the microwave input ports allows for the exclusion of other parts of the waveguide in the computer simulation model of the MATS system. Exclusion of other parts of the waveguide enables minimization of required computational resources; however, the following assumptions were made,
• The simulation model assumes perfectly matched conditions (i.e., no reflection). The injected microwave energy from the selected microwave ports were all absorbed by the load (i.e., circulating water in the cavity and food trays or pouches).

• Since reflection occurs in the actual MATS system, the total microwave energy injected for each cavity is only the transmitted microwave energy. Transmitted microwave energy is equal to the incident microwave energy from the generator minus the reflected microwave energy measured using the directional coupler (Table 1). Note that this study was conducted before installing a tuning apparatus in the MATS system and therefore shows a significant amount of reflected microwave energy (Table 1).

• The transmitted microwave energy in the side arm of the E-plane tee-junction is evenly divided into its coplanar arms (i.e., Power / 2) whose amplitude is equal to A/√2 (Table 1). This assumption follows an ideal lossless reciprocal E-plane tee-junction (Pozar, 2005).

• Waveguide parts such as elbows, tee-junction, spaces, circulator, probe-tuner, and directional coupler do not alter the characteristics of the electromagnetic wave (Chen, Tang, & Liu, 2008).

• Turbulent conditions of circulating water inside cavities was considered in the computer simulation model by allowing convection between the boundary of circulating water and the surface of the packaging material of foods. The convective heat transfer coefficient of water used was 115 W/m²-K. Furthermore, at 122°C, the relative dielectric constant and loss factor of water used in the simulation was, 55.54 and 2.70, respectively for tap water and 55.54 and 1.35, respectively for deionized water (Komarov & Tang, 2004).
The available dielectric property data (Tables 2 and 4) essential for characterizing dissipation of microwave energy into heat is only up to 120°C. For dielectric properties beyond this temperature, data were extrapolated.

Figure 1: Computer simulation model consisting of four microwave cavities and horn applicator. 
(a) Location of microwave input port. There are a total of eight ports in the model. (b) Direction of movement of pouch. (c) Location of the pouch

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<th>Reflected microwave energy measured by directional coupler (kW)</th>
<th>Transmitted microwave energy (kW)</th>
<th>Microwave input port setting (kW)</th>
<th>Amplitude of microwave in the input port (V/m)</th>
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</tr>
<tr>
<td>Cavity 3</td>
<td>4.7</td>
<td>2.2</td>
<td>2.5</td>
<td>1.3</td>
<td>50.1</td>
</tr>
<tr>
<td>Cavity 4</td>
<td>4.7</td>
<td>2.1</td>
<td>2.6</td>
<td>1.3</td>
<td>50.9</td>
</tr>
</tbody>
</table>

The numerical method used for both electromagnetic and heat transfer solution is finite difference time domain (FDTD). Implementation of FDTD was aided by commercial software (QuickWave version 7.5 64-bit). The FDTD cell size used was 4 × 4 × 1 mm in the x, y, and z direction, respectively, with mesh refinement on the edge of the food in both x and y directions.
The mesh refinement covers 30 mm of the four sides of the food, refining the mesh to 3 mm instead of the original 4 mm. The total number of cells for the simulation model was 8,806,182 (1167 × 77 × 98 in x, y, and z, respectively) which satisfies the stability requirement discussed in Chapter 3.

Food is represented in the computer simulation model by drawing a bi-phase object consisting of:— (a) a slab element in the middle with dimensions of 52 × 95 × 16 mm (x,y,z), (b) four half cylinder elements attached to the four sides of the slab element, with radius equal to 16 mm and length equal to the length of the side of the slab to where the half cylinder is attached, and (c) four quarter spherical elements attached to the four corners of the slab element with radius equal to 16 mm (Figure 1-c). A bi-phase object is a term used to define 3D objects in QuickWave™ software. A bi-phase object is a collection of bi-phase elements. A bi-phase element can be either a simple element or a combined element. A simple element is composed of identical polygons on top and bottom with the same number of vertices (e.g., slab element), while a combined element can have different polygons on top and bottom but still have the same number of vertices (e.g., half cylinder and half sphere) (QWED, 2009).

In actual operation in the MATS system, the belt that holds food moves at a speed of approximately 1 m/min along the x-y plane in the direction illustrated in Figure 1b. Considering the 3.1 m combined length of the four cavities, the belt movement would translate into approximately 180 s (3 min) total microwave heating time. To incorporate food movement in the simulation model, the total length of the four cavities was discretized into 32 steps wherein each step would be 96.8 mm (i.e., 3.1 m/32). The 32 steps discretization was determined in Chapter 3. It follows that each step would have a 5.6 s (i.e., 180 s / 32) heating time. Starting at the entrance of the first cavity, solution to coupled electromagnetic-heat transfer (EM-HT) phenomena was
applied to the first location of the food (Figure 1c). Afterward, the food was displaced to the next location, retaining the temperature distribution from the previous step as the initial temperature on the current location. The solution to the coupled EM-HT at the next location of food was applied. The sequence of instruction was executed in a loop until all of the 32 steps were completed at the end of the fourth cavity. The snapshot of the heating pattern of the food at the end of the 32nd step was then analyzed.

2.3. Measurement of frequency

The microwave generator for the first and second cavity of the MATS system was manufactured by Ferrite Microwave, Inc (165 Ledge Street, Nashua, NH 03060) and the generator for the third and fourth cavity was manufactured by Microdry Industries, LLC (5901 W. Highway 22, Crestwood, KY 40014). A B&K Precision TM-2650 spectrum analyzer with AN-301 antenna (22820 Savi Ranch ParkWay, Yorba Linda, CA 92887) was used to measure the frequency of the generators. Frequency measurements were carried out using the direct method described in ITU-R M.1177 (ITU, 2003).

AN-301 is a dipole antenna specified to work at a frequency range of 0.8 to 1.0 GHz. It has a gain equal to or greater than ≥1dBi with a voltage standing wave ratio (VSWR) equal to or less than ≤1.5 at the center frequency range. The TM-2650 spectrum analyzer was set to a central frequency of 915 MHz with a span of 200 MHz (i.e., from 815 MHz to 1015 MHz on the x-axis). The frequency span was subdivided into 10 divisions and each division was 20 MHz with resolution bandwidth (RBW) of 3 MHz. The oscillation power was set to -70 to 10 dBm on the y-axis subdivided into 8 divisions and each division was 10dB. The occupied frequency bandwidth (OBFW) was measured by considering 80% of the total power measured.
The operating frequency and the OFBW were measured for the first and second magnetron generators set at 2-10 kW with 1 kW increments. For the third and fourth magnetron generators, operating frequency and OFBW were measured from 1 kW to 4.7 kW with 1 kW increments. All frequency measurements were done in three (3) replicates every other month for a period of one year (i.e., 2009-2010).

2.4. Effect of different operating frequency of generator

Different simulation cases were conducted with operating frequencies of microwave generators set within and beyond the FCC allocated ISM bandwidth for 915 MHz (902-928 MHz) to determine the effect of different frequencies to the heating pattern of salmon and Alfredo sauce packed in flexible pouches and mashed potato packed in rigid trays. For the purpose of illustration, in this study, the corresponding snapshot of heating patterns in food are presented when the four microwave generators in MATS system were set at (a) 902, 910, 915, 920, and 928 MHz (within ISM allocated bandwidth for 915 MHz); (b) 880, 860, and 840 MHz (< lower limit of ISM allocated bandwidth for 915 MHz); and (c) 940, 960, and 980 MHz (> upper limit ISM allocated bandwidth for 915 MHz). Furthermore, a simulation emulating a real case scenario (e.g., actual power setting in Table 1 and the corresponding measured operating frequency of the four generators) was done. Dielectric property of the middle part of pink salmon in Wang et al. (2008) and dielectric property of mashed potato in Guan et al. (2004) was used in the computer simulation (Table 2). For this part of the study, circulating water in cavities of the MATS system was assumed to be tap water; therefore, dielectric property of tap water at 122°C (\(\varepsilon'_r = 55.54 \text{ & } \varepsilon''_r = 2.70\)) was used in the computer simulation model.

Another factor considered was the effect of loss factor of circulating hot water at 122°C inside the cavities of the MATS system to the heating patterns in food. To quantify the effect of
different loss factors of water, a simulation was conducted for a scenario wherein: (a) the loss factor of water used was similar to that of tap water which is \( \varepsilon_r' = 2.70 \) at 122°C and 915 MHz (Komarov & Tang, 2004); and (b) the loss factor of water used was similar to that of deionized water which is \( \varepsilon_r' = 1.35 \) at 122°C and 915 MHz. The dielectric constants of water for both scenarios were the same \( (\varepsilon_r' = 55.54) \). For this part of the study, salmon fillet was assumed as the food in the MATS system therefore, the dielectric property of salmon fillet was used in the computer simulation model (Table 2).

Table 2. Dielectric property of pink salmon and mashed potato used in computer simulation

<table>
<thead>
<tr>
<th>Temperature (^{\circ}\text{C})</th>
<th>DP of middle part of pink salmon (Wang, 2008)</th>
<th>DP of mashed potato at 87.8% moisture and 0.8% salt (Guan, 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relative dielectric constant ((\varepsilon_r'))</td>
<td>Relative loss factor ((\varepsilon_r'))</td>
</tr>
<tr>
<td>20</td>
<td>57.0</td>
<td>22.8</td>
</tr>
<tr>
<td>40</td>
<td>55.6</td>
<td>28.1</td>
</tr>
<tr>
<td>60</td>
<td>53.7</td>
<td>34.8</td>
</tr>
<tr>
<td>80</td>
<td>51.5</td>
<td>40.7</td>
</tr>
<tr>
<td>100</td>
<td>50.8</td>
<td>49.0</td>
</tr>
<tr>
<td>120</td>
<td>50.7</td>
<td>60.4</td>
</tr>
</tbody>
</table>

2.5. Whey protein gel (WPG) preparation

In this study, whey protein gel (WPG) was used as a model food for verification of the heating patterns generated by the computer simulation model. Preparation of WPG was described in the studies of Pandit et al. (Pandit, Tang, Liu, & Mikhaylenko, 2007; Pandit, Tang, Mikhaylenko, & Liu, 2006). The formulation of WPG used in this study is summarized in Table 3. The dimension of the WPG used was \( 84 \times 127 \times 16 \text{ mm} \) \((x, y, z)\) packed in an 8 oz. flexible pouch with a dimension of \( 95 \times 140 \text{ mm} \) \((x, y)\). The allowable thickness of food that the flexible pouch can handle is within the range of 14 to 18 mm. PrintPack® provided the pouches designed
for the microwave application. Each pouch consists of a laminate of: (1) polyethylene terephthalate (PET), (2) barrier-coated PET, (3) nylon, and (4) polypropylene (PP) held together by a polymer adhesive.

A Hewlett-Packard™ 8752C network analyzer was used to measure the dielectric property of the WPG following the procedure of Wang et al. (2008). Specific heat and thermal conductivity was measured through the double needle method (Campbell, Calissendorff, & Williams, 1991) using Decagon™ KD2-pro (Decagon, WA, USA). Enthalpy was calculated as the product of specific heat, density, and temperature change of WPG considering 60°C as the reference temperature. The density of WPG is approximately equal to 1.00 g/cm³ following the method described by Krokida & Maroulis (1997). Notice that the dielectric property of WPG used in this study is comparable to that of pink salmon (Table 2). Therefore, for the purpose of verifying computer simulated heating patterns, the heating pattern in WPG was compared against the computer simulated heating pattern in salmon.

Table 3. Composition of whey protein gel (WPG)

<table>
<thead>
<tr>
<th>Components</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>75.4</td>
</tr>
<tr>
<td>Salt</td>
<td>0.6</td>
</tr>
<tr>
<td>D-ribose</td>
<td>1</td>
</tr>
<tr>
<td>WPG 392</td>
<td>18</td>
</tr>
<tr>
<td>WPG 895-1</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 4. Dielectric properties and thermal properties of whey protein gel (WPG)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Relative dielectric constant* ($\varepsilon_r$)</th>
<th>Relative loss factor* ($\delta_r$)</th>
<th>Specific heat** ($c_p$) (KJ/kg·°C)</th>
<th>Thermal conductivity** ($k$) (W/m·°C)</th>
<th>Enthalpy ($H$) (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>23.58 ± 2.75</td>
<td>52.91 ± 2.49</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>29.26 ± 1.01</td>
<td>51.76 ± 0.99</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>34.85 ± 1.53</td>
<td>50.62 ± 0.77</td>
<td>3.1538 ± 0.130</td>
<td>0.5655 ± 0.027</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>41.68 ± 1.97</td>
<td>49.35 ± 1.45</td>
<td>3.4110 ± 0.019</td>
<td>0.5303 ± 0.015</td>
<td>68.220</td>
</tr>
<tr>
<td>100</td>
<td>50.73 ± 1.74</td>
<td>48.11 ± 1.74</td>
<td>3.6333 ± 0.031</td>
<td>0.5465 ± 0.004</td>
<td>140.886</td>
</tr>
<tr>
<td>120</td>
<td>58.40 ± 3.02</td>
<td>47.42 ± 1.15</td>
<td>3.6618 ± 0.164</td>
<td>0.5540 ± 0.028</td>
<td>214.122</td>
</tr>
</tbody>
</table>

*mean and standard deviation for five (5) replicates
**mean and standard deviation for four (4) replicates

2.6. Processing of model food in MATS

Whey protein gel was processed in MATS following the general description of MATS in Section 2.1. Pouches were loaded in the microwave belt through the door and moved to the preheating section of the MATS. After 30 min of preheating at 72°C, the generator powering the MATS at the setting described in Table 1 was turned on. The pressure inside the MATS was maintained at 234.4 kPa. The temperature at the heating section and holding section was maintained at ~122°C and the cooling section at ~20°C. To maintain the temperature of the heating, holding, and cooling sections, water was circulated through a plate heat exchanger at an average rate of 69, 51, and 61 L/min, respectively. After there were no significant changes in temperature and pressure within the MATS, the belt that holds the pouches of WPG was moved at a speed of ~1 m/min allowing transition from preheating, heating, holding and finally to the cooling section. This translated into 3 min (180 s) of heating. The WPG inside the pouch was allowed to cool in the cooling section for 5 min before retrieving through the cooling section door. Six samples (R1 to R6) of WPG were used for this purpose. Considering the dielectric property and the processing of WPG in the MATS system, the heating patterns in WPG were
compared against the computer simulated heating pattern in salmon for simulation emulating a real case scenario (actual power setting in Table 1 and the corresponding measured operating frequency of the four generators).

2.7. Computer vision for chemical marker method

The heating patterns of the processed WPG were determined through a computer vision method. The detailed procedure for determining the heating pattern in the RGB scale was described in the work of Pandit et al. (Pandit, Tang, Liu, & Mikhaylenko, 2007; Pandit, Tang, Mikhaylenko, & Liu, 2006). In brief, chemical marker M-2 is a product of the non-enzymatic browning reaction between D-ribose and amines, both of which are present in the WPG formulation during thermal processing. Production of M-2 is an irreversible process and is dependent on the intensity of heat treatment above 100°C (212°F). The M-2 is brown in color and the intensity of the brownness is directly proportional to the amount of M-2 produced. Different intensities of brown color at different locations in the WPG allows for a qualitative determination of heating pattern. Two standards were used as a basis for the lightest brown and the most intense brown color. The lightest brown was based on the unprocessed color of WPG, and the most intense brown was based on the WPG evenly heated at the sterilization temperature. The RGB values which describe the heating pattern were then scaled based on the two standards.

3. Results and discussion

3.1. Operating frequency of generators over a period of 1 year at different power levels

Figure 2a shows the measured operating frequency at different power settings of the generators. Figure 2b illustrates the typical peak frequency reading which corresponds to the operating frequency of the generator and the OFBW at 80% total power measured. The general
trend is that the operating frequency is directly proportional to the power setting. The higher the power setting of the generator, the higher will be the operating frequency. For generators 1 and 2, for every 0.5 kW increase in power, the operating frequency increased by 0.25 MHz. Also, when set to a similar power setting, generator 2, on average, operated at 4.8 MHz higher than generator 1. For generator 3 and 4, for every 0.5 kW increase in power, the operating frequency increased by 0.75 MHz. Also, when set to a similar power setting, generator 3, on average, operated at 2.7 MHz higher than generator 4. Considering the typical power setting of generators described in Table 1, the measured operating frequency and OFBW at 80% total power is tabulated in Table 5.

Table 5. Measured operating frequency for the typical power setting of microwave generators over a 1 year period

<table>
<thead>
<tr>
<th>Microwave Generator</th>
<th>Transmitted microwave energy (kW)</th>
<th>Operating Frequency (MHz)</th>
<th>OFBW at 80% total power (MHz) expressed as deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 1</td>
<td>6.4±0.2</td>
<td>912.1±1.0</td>
<td>±3.79</td>
</tr>
<tr>
<td>Generator 2</td>
<td>5.6±0.3</td>
<td>916.6±0.9</td>
<td>±4.18</td>
</tr>
<tr>
<td>Generator 3</td>
<td>2.5±0.1</td>
<td>905.6±0.2</td>
<td>±3.68</td>
</tr>
<tr>
<td>Generator 4</td>
<td>2.6±0.1</td>
<td>903.1±0.2</td>
<td>±4.25</td>
</tr>
</tbody>
</table>

Another notable characteristic among generators is the relative consistency in achieving similar values of operating frequencies every time they were turned on. Generators manufactured by Ferrite™ (Model GET-2024, 165 Ledge Street, Nashua, NH 03060) were less consistent in achieving a certain value of operating frequency than those manufactured by Microdry™ (Model IV-74, 5901 W. Highway 22, Crestwood, KY 40014). In Figure 2a, it can be seen that generators 1 and 2 (Ferrite™) produce an up and down trend of operating frequency with power and a relative high standard deviation (i.e., approximately ±1 MHz) among measurement trials. For
generators 3 and 4 (Microdry™) the curve is relatively smooth and standard deviation among trials is much lower (approximately ±0.2 MHz).

Figure 2a: Plot of frequency versus power output of generator and corresponding standard deviation from the six measurements of every frequency and power combination
Figure 2b: Typical peak or operating frequency reading from the B&K Precision TM-2650 spectrum analyzer and the OFBW at 80% total power measured.
Figure 3: Plot of frequency of generator over a period of 1 year for different power setting: (a) generator 1, (b) generator 2, (c) generator 3, and (d) generator 4.

Figure 3 summarizes the operating frequency of the four generators at different power settings over the period of one year. Generators 1 and 2 manufactured by Ferrite™ had varying operating frequencies (Figures 3 a & b) typically within 1-2 MHz for a specific power setting. Considering the 2-10 kW possible power settings for generators 1 and 2, the operating frequency bandwidth of generators 1 and 2 is 908-914 MHz and 912-919 MHz, respectively. In comparison, generators 3 and 4 manufactured by Microdry™ had relatively consistent operating frequencies (Figures 3 c & d). In fact, at a higher power settings (> 2 kW) there was no significant operating frequency shifting. Considering the 1-4.7 kW possible power settings for generators 3 and 4, the operating frequency bandwidth for generators 3 and 4 was 901-909 MHz.
and 898-905 MHz, respectively. The consistency of generators from operating at a certain frequency might be related to the differences in the design of the magnetrons of the generators.

Another inference that can be drawn from Figure 3 is the relative closeness of operating frequencies of generators to 915 MHz. Generators 1 and 2 operated at frequencies relatively closer to 915 MHz at different power settings, but generators 3 and 4 were operating at frequencies slightly lower to 915 MHz. In fact, the operating frequencies of generators 3 and 4 were close to the lower limit of FCC allocated ISM frequency bandwidth for 915 MHz. Specifically, when generator 4 was set at 1 kW, it operated at frequency < 902 MHz (Figure 3d). Therefore, generator 4 should not be set ≤1 kW otherwise it may potentially interfere with other wireless communication devices. Nevertheless, the typical power settings of the four generators (Table 5) allow them to operate within the allocated ISM frequency bandwidth for 915 MHz. Furthermore, even though the operating frequencies of generators 1 and 2 shifted with time at a given power setting, the bandwidth of all generators (i.e., as long as generator 4 is set >1 kW) considering all possible power combination settings would be within the FCC allocated ISM bandwidth for 915 MHz.

Generators 3 and 4 are operating at lower frequency possibly because of their length of use. Generators 3 and 4 are approximately 8 years older than generators 1 and 2 (approximately 7000h of operation). Although generators 3 and 4 had a consistent operating frequency over one year period, the operating frequencies of generators slowly drifted over time which may not be observable over a period of one year of frequency monitoring. It is, therefore, recommended, especially for microwave generators that are in constant use, to measure the operating frequency at least once a year and compare if they are still within the FCC allocated ISM bandwidth.
3.2. Heating pattern

Based upon the results of the computer simulation summarized in Figure 4, heating patterns in food are not affected by different operating frequencies of microwave generators as long as they are within the FCC allocated frequency bandwidth for 915 MHz. The noticeable attribute in Figure 4, however, comparing heating patterns at different frequencies, is that the temperature intensity, associated to heating rate, increases with frequency. The difference in temperature intensity at different frequencies is most visible at the exit of the second cavity (Figure 4a-iii and Figure 4b-iii). Comparing simulation at 920 MHz and 928 MHz in Figure 4a-iii, it can be seen that the hot area in 920 MHz is around 127°C, represented by a yellowish color while the hot area in 928 MHz is already at 130°C, represented by a red color. In Figure 4b-iii, the hot area in 920 MHz is mostly at a temperature >200°C, except for the middle part, which is around 180°C. However, for 928 MHz (Figure 4b-iii), except for the edge, the temperatures are all >200°C. It is important to note, however, that the temperatures in group (b) of Figure 4 (i.e., those using deionized circulating water inside cavities) are only an approximation through computer simulation. No actual validation of temperature through direct measurement was conducted. Therefore, the temperature 170-200°C and >200°C in group (b) of Figure 4 is only a relative temperature indicator in comparison to temperatures for group (a) of Figure 4. In reality, the temperature of food sample, considering the processing conditions in the MATS system, will not reach a temperature of 200°C.

Another noticeable attribute is the relative size of the cold and hot zones. At low frequency (e.g., 902 MHz), there is a clear distinction between cold area 1, cold area 2, and hot area (refer to Section 3.3 for definitions). But at a higher frequency, the size of each area expanded such that they were overlapping each other. This is because, cold area 2 is sandwiched...
between two hot areas and therefore the rate of heat conduction is relatively fast (Incropera, Dewitt, Bergman, & Lavine, 2007).

For simulation using the measured operating frequencies of the four generators in Table 5, the result of the heating pattern is between that of the simulation for 920 MHz and 928 MHz for both Figures 4a and 4b. Although the average frequency of the four generators (i.e., from operating frequency in Table 5) was 909.34 MHz, which is close to 910 MHz in Figure 4, generator 1 and generator 2 were operating at higher frequencies and were set at a higher power (Table 5), and therefore they should have a larger contribution to heating.

Comparing group (a) and group (b) in Figure 4, the obvious result of circulating water inside the cavity is the intensity of temperature. Although the heating patterns were similar for both groups, reduction of loss factor of circulating water into half (e.g., for tap water $\varepsilon_r = 2.70$ and for deionized water $\varepsilon_r = 1.35$) would result in approximately 23%-37% increase in temperature of the zones describing the heating patterns of food. The reason for this is the difference in the relative amount of microwave energy dissipated as heat in circulating water. For relatively lossy water such as tap water, part of the microwave energy is being absorbed by the water, thus reducing the amount that may be absorbed by the food. On average, during actual processing in the MATS system with tap water circulating inside the cavities, there is a 2°C -3°C increase in temperature of circulating water, from 122°C to 124°C - 125°C, as indicated in the DART. This shows that water is indeed absorbing microwave energy. The microwave energy absorbed by the water is then subsequently dumped into the heat exchanger attached to the heating section of the MATS system which then reduces the temperature back to 122°C. For relatively lossless water such as deionized water, little to no microwave energy is absorbed,
making circulating water partially invisible to microwaves. This scenario makes most of the incident microwave energy available to food material, producing higher rates of heating.

Figure 5 shows the computer simulated heating patterns of salmon fillet and mashed potato processed in MATS with tap water circulating inside the cavities. Figure 5 suggests that as long as the generators are operating within the FCC allocated ISM frequency bandwidth for 915 MHz (902-928 MHz), heating patterns in foods, with dielectric properties closed to that of salmon fillet and mashed potato will not be affected. Although there was a little overlap in hot areas in mashed potato at 928 MHz, in general, the heating pattern was essentially similar to that of 902 MHz and 915 MHz. A change in heating patterns in foods start to occur when the operating frequency of the generators was at <880 MHz or >940 MHz which was beyond the FCC allocated ISM frequency bandwidth for 915 MHz.
Figure 4: All images were snapshot at $x$-$y$ plane and at the center with respect to $z$ direction.

Column (i) is the initial heating pattern of food, and column (v) is the heating pattern at exit to cavity 4. Group (a) is simulation result wherein property of tap water was used ($\varepsilon_r' = 2.70$ at 122°C and 915 MHz) and Group (b) is simulation result wherein property of deionized water was used ($\varepsilon_r' = 1.35$ at 122°C and 915 MHz). The temperature scale gradient for Group (a) is from 72°C-160°C and for Group (b) is 72°C-200°C.
Figure 5: Heating pattern in salmon fillet and mashed potato at different operating frequency of the generators.
3.3. Comparison of simulated heating pattern using measured frequency of the generators with chemical marker method

For comparison purposes, Figure 6 shows a representative heating pattern generated through computer simulation (Figure 6-a) versus the heating pattern in WPG through the chemical marker method (Figure 6-b). Both are snapshots of the x-y plane taken at the center with respect to the thickness (i.e., z axis). Simulation results (Figure 6-a) suggest that the general heating pattern is symmetrical in the x-y plane and can be summarized into three groups of zones where the temperature distribution within a given zone is relatively uniform. Details of the zones were discussed in Chapter 3.

Figure 7 shows the result of six replicates of heating patterns in WPG. The results of the chemical marker method, unlike those of the simulation result, are not perfectly symmetrical with respect to the x-y plane. Possible reasons that may cause an asymmetrical heating pattern in WPG include:

- Relative position pouches of WPG during processing in MATS. Since pouches containing WPG were manually placed on the belt of the MATS, it is possible that during transition from the preheating to the heating section, the pouch moved off center with respect to the width of the cavities. Furthermore, there were instances where the belt was not tight enough such that when the pouch entered the cavity, the belt partially sagged causing an off center displacement of the pouch with respect to the height of the cavities.

- Cutting of whey protein gel. To take a snapshot of the heating pattern at the center of the WPG after processing in the MATS system, a knife and a spacer for guiding the knife were used during cutting. Since cutting was manually done, even with a spacer, it was still possible to cut WPG off center.
• Pockets of air inside the pouch. Although the WPG was vacuum-packed inside the pouch, several air pockets still remained, mostly unevenly distributed at the edge, and these could have potentially altered the E-field distribution inside the food.

• Micro bubbles within WPG. During preparation of the WPG, ingredients were constantly stirred to ensure uniformity. However, stirring can also incorporate bubbles within the mixture. The distribution and amount of micro bubbles during solidification of WPG is difficult to control. The dielectric property of WPG in an area with a high concentration of micro bubbles might not be the same as the other portions of the WPG.

• Moisture migration during processing. Although it took only 3 min to process the WPG, moisture in WPG can possibly migrate during processing, which can affect the dielectric property of WPG.

• Irreversible production of M-2 marker. The RGB equivalent in Figure 7 is from the brown discoloration brought about by the production of M-2 after the reaction of sugar (D-ribose) with amino acid (WPG 392 and WPG 895-I). The amount of M-2 produced is dependent on temperature, and even if there is a decrease in temperature (e.g., due to conduction within WPG or convection at the boundary of water and pouch), the brown intensity from previously produced M-2 will not decrease (Pandit, Tang, Liu, & Mikhaylenko, 2007).

Although heating patterns in WPG are not completely symmetrical with respect to the x-y plane (Figure 7), causing a slight discrepancy in comparison with computer simulated heating patterns, from qualitative comparison of the group of zones illustrated in Figure 6, it can be concluded that computer simulated heating patterns shows large resemblance in the heating patterns in WPG processed in MATS system and can therefore be considered as a good method for determining heating patterns in food processed in the MATS system.
Figure 6: Heating pattern comparison between simulated case 6 and result from chemical marker method

Figure 7: Six (6) replicates of heating pattern through chemical marker method using whey protein gel (WPG) as model food. Images are snapshot of x-y plane of WPG at the center with respect to z-axis. All WPG were processed with tap water circulating inside the cavity.

4. Conclusions

The frequencies of the four generators powering MATS were monitored at different power levels. The effect of different frequencies of generators on the heating patterns in food processed in MATS was studied and the following conclusions were derived:
• The operating frequencies of four generators powering MATS were related to the power setting. For generators 1 and 2, for every 0.5 kW increase in power, operating frequency increased by 0.25 MHz; for generators 3 and 4, for every 0.5 kW increase in power, operating frequency increased by 0.75 MHz.

• Generators 1 and 2 of MATS showed varying operating frequencies at a given power setting through a period of one year, but were generally closer to 915 MHz. The operating frequency bandwidths of generators 1 and 2 are 908-914 MHz and 912-919 MHz, respectively. Generators 3 and 4 of MATS showed a relatively consistent operating frequency at a certain power settings over a period of one year, but were generally closer to the lower limit of the FCC allocated ISM frequency bandwidth for 915 MHz. The operating frequency bandwidths of generators 3 and 4 are 901-909 MHz and 898-905 MHz, respectively. In general, the operating frequencies of all generators of the MATS system are within the FCC allocated ISM bandwidth for 915 MHz.

• The overall effect of reducing the loss factor of circulating water in the cavities is an increase in temperature of food; for instance, reduction of loss factor of circulating water in to half would result in a 23%-37% increase in temperature of the different group of zones in the heating pattern of foods.

• Heating patterns in foods, with dielectric property similar to salmon fillet and mashed potato (Table 2), will not change as long as generators of the MATS system are operating within the FCC allocated ISM frequency bandwidth for 915 MHz.

• Heating patterns in foods, with dielectric property similar to salmon fillet and mashed potato (Table 2), start to change when the operating frequencies of generators of the MATS system is <880 MHz or >940 MHz.
5. References


CHAPTER FIVE

IMPEDANCE MATCHING BETWEEN MAGNETRON GENERATOR AND THE MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEM USING VARIABLE LENGTH CYLINDRICAL TRIPLE- INDUCTIVE POSTS IN A RECTANGULAR WAVEGUIDE

Abstract

A variable length triple inductive post (3-probe tuner) was used for impedance matching between the generator and load of the microwave assisted thermal sterilization (MATS). The experiment was conducted considering one of the four cavities in MATS. The objective of this study was to determine the proper insertion depth combination of the 3-probe tuner that would give the lowest power reflection. A tuning scheme was developed and power reflection was monitored using a directional coupler. To verify the experimentally determined insertion depth combination of the 3-probe tuner, a computer simulation model was created based on the previously verified microwave assisted thermal sterilization-computer simulation model (MATS-CSM). The computer simulation model was implemented through the finite-difference time-domain (FDTD) numerical method. There was good agreement between the experimentally measured power reflection and simulated power reflection ($S_{11}$) for a given insertion depth combination of the 3-probe tuner. When microwave generator was at set at 4.7 kW, the appropriate insertion depth of the 3-probe tuner is 25.5 mm, 8.5 mm, and 21.5 mm for probes 1, 2 and 3, respectively. At this setting, the power reflection was measured at 6.1-11.7%.
1. Introduction

Waveguide connectors and junctions used in the microwave assisted thermal sterilization (MATS) system and possible misalignment of waveguide components has an equivalent reactance \((i.e., \text{inductive or capacitive})\) that contributes to the overall intrinsic impedance of the system. For high power transmission, to have an effective delivery of power from generator to load, the reactance of the load (including the reactance due to waveguide components and possible misalignment) should be equal and in an opposite direction to the reactance of the generator (Meredith, 1998). Furthermore, to have a good coupling between the generator and the load, the internal resistance of the generator ideally should be relatively small compared to the intrinsic impedance of the load. The said conditions, if not satisfied, would result in a mismatch between the microwave source (the generator) and the load (the cavity containing food trays as load). A mismatch would result in high reflection of microwave energy and therefore low overall efficiency.

Inclusion of an inductive cylindrical post in a rectangular waveguide has been widely used for adjusting the reactance of the transmission line for source-load matching. Reactance of single and multiple posts in terms of induced current was first described in the lectures of Schwinger in 1945 and was summarized in Schwinger and Saxon (1968). The concept was elaborated in Marcuvitz’s Waveguide Handbook (Marcuvitz, 1951). Although requiring a correction factor (Mariani, 1965), Craven and Lewis (1956) emphasizes the advantage of using triple post of equal radius across the waveguide in comparison with a single post.

Recent studies on inductive posts have considered an off-center and variable length post (Williamson, 1986; Roelvink & Williamson, 2007; 2008). Williamson (1986) derived the reflection and transmission of \(\text{TE}_{10}\) mode on a waveguide that has an off-center variable length
hollow cylindrical post. Using similar post configuration Roelvink & Williamson (2007; 2008), described the induced current and the reactance of the post, respectively. The use of arbitrarily shaped multiple posts of constant length has been treated by (Hesham & Harrington, 1984; Esteban, Cogollos, Boria, San Blas, & Fernando, 2002), and variable lengths by (Jiang & Li, 1991). Several studies have utilized numerical analysis to treat multiple inductive posts in a rectangular waveguide (Moglie, Rozzi, & Marcozzi, 1994; Oliver & McNamara, 1994; Dou & Yung, 2000). In this chapter, the finite-difference time-domain numerical method through computer simulation (QWED, 2009) was used to analyze the reflection on the waveguide with a variable length multiple inductive 3-probe/posts tuner for impedance matching. The configuration of the probe is illustrated in Figure 2 and details are presented in Figure 3.

1.1. Study Gap

Typical application of impedance matching using cylindrical posts in a rectangular waveguide is for communication and detection purposes. Limited studies describing a similar principle were reported for high power electromagnetic transmission in dielectric heating applications. In fact the use of multiple inductive posts in a rectangular waveguide for transmission system operating at >10 kW at 915 MHz was discourage due to the possibility of arcing as a result of induced current at the post (Meredith, 1998). This study was conducted to demonstrate that multiple inductive posts in a rectangular waveguide can be used for impedance matching in a high power transmission of microwaves at 915 MHz applied to dielectric heating.

1.2. Objectives

The objective of this study was to test the possibilities of matching the internal resistance of the microwave generator providing electromagnetic wave energy, supposed to be at 915 MHz to

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the impedance of the load \textit{(i.e.,} the microwave cavity with circulating water and food moving across the cavity) \textit{for high power microwave sterilization applications. The purpose of impedance matching is to reduce the overall reflection coefficient to have efficient power delivery to the load. The specific objectives were as follows:}

1. To characterized the power-operating frequency relationship of the microwave generator used in this study.

2. To develop a scheme for determining insertion depth combination of the 3-probe tuner that would result in low power reflection.

3. To verify the overall reflection coefficient of the system with the determined insertion depth combination of the 3-probe tuner through computer simulation method utilizing FDTD.

\textbf{1.3. Related concepts}

\textbf{1.3.1. S}$_{11}$ \textbf{Parameter}

For a given an \textit{n}-port network, the scattering parameter or \textit{S}-parameter shows the relationship of incident wave to the reflected wave (in terms of amplitude of voltage wave) on a given port (Pozar, 2005). Let \( V_n^+ \) represent the amplitude of voltage wave incident on port \( n \), and \( V_n^- \) represent the amplitude of the voltage wave reflected on port \( n \), the matrix representation of \textit{S} parameter is:

\[
[V_n^-] = [S][V_n^+]
\]  \hspace{1cm} (1)

Let \( j = 1,2,3\ldots n \) be the port that provides incident voltage wave \( V_j^+ \) and \( i = 1,2,3\ldots n \) be the port that provides reflected voltage wave \( V_i^- \), then \( S_{ij} \) is equal to:

\[
S_{ij} = \frac{V_i^-}{V_j^+}
\]  \hspace{1cm} (2)
Therefore, $S_{ii}$ is the reflection coefficient at port $i$, when all other ports match, and $S_{ij}$ is the transmission coefficient from port $j$ to port $i$ when all other ports match.

### 1.3.2. Directional coupler

Typical directional couplers are made up of four ports arranged in a reciprocal network (Figure 1). Directional couplers are passive, lossless, symmetrical, and ideally matched (Meredith, 1998). In Figure 1, the upper line coinciding with ports 1 and 2 is the main line, while the lower line coinciding with ports 3 and 4 is the coupled line. Considering port 1 as the incident port, port 2 would be the through port, port 4 would be the coupled port, and port 3 would be the isolated port (ideally zero power output). The same is true if port 2 is the incident port; here, port 1 would be the through port, port 3 would be the coupled port and port 4 would be the isolated port. Due to the nature of input and the corresponding output, the network is considered directional (Meredith, 1998). For the purpose of power measurement, if port 1 is connected to the source of microwave energy and port 2 is connected to the load (e.g. microwave cavity with food), then the power emerging in port 4 is proportional to the forward power, and the power emerging from port 3 is proportional to the reflected power. Furthermore, for the purpose of power measurement, directional couplers are weakly coupled such that only a portion of the forward and reflected power needs to be sampled, on the order of milliwatts to do the measurement.
Figure 1: Reciprocal network representation of a directional coupler. Complying with IEEE Standard 315-1975 (IEEE Standard, 1993), the coupling loss and directivity of coupler used in this study were 60 dB and 30 dB respectively.

Although proportional, the magnitude of the sampled forward and reflected powers in the directional coupler is much less than the actual power. Thus, the coupling factor and directivity that pertains to proportionality between actual power and sampled power needs to be defined.

(1) Coupling factor (CF) – amount of the forward and reflected power sampled from the actual forward and reflected power. This quantity is expressed in decibels (dB):

\[
CF = 10 \log \left( \frac{P_4}{P_1} \right) = 10 \log \left( \frac{P_3}{P_2} \right) \quad [\text{dB}]
\]  

(2) Directivity (D) – the amount of power to the supposedly zero output port or the isolated port:

\[
D = 10 \log \left( \frac{P_3}{P_4} \right) \approx 10 \log \left( \frac{P_2}{P_1} \right) \quad [\text{dB}]
\]

Since the ideal directional couplers are perfectly matched, S parameters with similar subscript (e.g., \( S_{11} = \ldots = S_{44} = 0 \)) and with infinite directivity (\( S_{13} = S_{31} = S_{24} = S_{42} = 0 \)) are all equal to zero. Also, since the ideal directional coupler is lossless, the S parameters with identical subscript are all equal (e.g., \( S_{12} = S_{21} \) etc):

\[
S = \begin{bmatrix}
0 & S_{12} & 0 & S_{14} \\
S_{21} & 0 & S_{23} & 0 \\
0 & S_{32} & 0 & S_{34} \\
S_{41} & 0 & S_{43} & 0
\end{bmatrix}
\]  

(5)
Furthermore, in a lossless condition, power emerging from the corresponding main and coupled line must come from a given port (e.g., power at port 2 and port 4 must come from port 1):

\[ S_{12}^2 + S_{14}^2 = S_{21}^2 + S_{23}^2 = S_{32}^2 + S_{34}^2 = S_{41}^2 + S_{43}^2 = 1 \equiv \cos^2\theta + \sin^2\theta = 1 \quad (6) \]

where the first term of the equation represents the power that remains in the main line and the second term represents the sampled power, and \( \theta \) is the coupling of the directional coupler. The coupling factor can, therefore, be written in terms of power coupling coefficient as (Lomer & Crompton, 1957):

\[
CF = 20 \log [S_{14}] = 20 \log [S_{23}] \quad [\text{dB}]
\quad (7)
\]

The concept of directional coupler when applied to reflectometry for measuring forward and backWard field only requires weak coupling of the coupled line to the main line (e.g., 30 dB or a coupling power ratio of 0.001:1). The customary method of measurement of reflection coefficient on waveguide is through slotted line or impedance bridge (Metaxas & Meredith, 1993). Figure 1 is an example of a two slot (i.e., four ports) branched waveguide coupler. The two slots are ports 3 and 4 which are \( \lambda_g/4 \) apart (Meredith, 1998). For better accuracy of measurement of the forward and reflected power, several designs of reflectometer use six ports (with 4 slots) (Yakabe, Kinoshita, & Yabe, 1994; Ulker & Weikle, 2001; Yao & Yeo, 2008) and ten ports (with 8 slots) (Cabrera, Molina, Guerrero, & Morcillo, 2010)

### 1.3.3. Inductive post

Typical design of multiple inductive cylindrical posts was earlier categorized by Marcuvitz (1951) as part of a microwave network with the post considered as discontinuity (i.e., an obstacle along the cross sectional shape of the waveguide). A solution to electromagnetic propagation along waveguides with discontinuity was obtained through an equivalent circuit
representing the discontinuities. The arrangement of the inductive post inside the waveguide can be: (a) a single post of variable insertion depth, or (b) a multiple post of variable insertion depth. A multiple post arrangement can be: (i) a single array perpendicular to the direction of wave propagation, or (ii) a single array parallel to the direction of wave propagation. Equation of reflection coefficient \(i.e., \text{equal to } S_{11}\ \text{parameter}\) on a full-height post for a single post and an array of post was previously derived (Li, Adams, Leviatan, & Perini, 1984). Roelvink (2007) which modified the equation of the reflection coefficient of Li et al (1984) to obtain an expression for a variable length single post as a function of induced current in the post, which was in turn dependent on post radius and insertion depth. Newer design of a multiple inductive post considers a combination of (i) and (ii) consisting of a double array along the direction of wave propagation wherein posts within an array were arranged in a staggered formation with the posts of another array. For an obstacle consisting of three posts, arrangement would be in a triangular manner (Figure 2-a).

2. Experimental Details

2.1. Microwave assisted thermal sterilization (MATS) system setup

A microwave assisted thermal sterilization system (MATS) was developed at Washington State University (WSU). The MATS is a closed system consisting of four sections—preheating, heating, holding and cooling—arranged in a series representing the four sequential processing steps. Each section has localized circulating water controlled at temperature 72°C, 122°C, 122°C, and 20°C, respectively. A rubber door placed at the junction of each section prevents mixing of circulating water between different sections. The system is normally operated at 234.4 kPa. Food trays or pouches move across different sections of the MATS on a non-metallic conveyor belt that extends from the end of preheating section to the end of cooling section.
Typical operation consists of not more than 48 food trays or pouches per batch and moves in series continuously.

The preheating section of the MATS system is for equilibrating the temperature of the food to a uniform initial temperature (IT) (target IT set at 70 to 72°C). Food inside the heating section was simultaneously heated by microwave energy to immediately attain sterilization temperature and by circulating water at 122°C and 234.4 kPa through convection/conduction surface heating. Microwave heating was through volumetric dissipation of transmitted microwave energy into heat as a result of dipole relaxation and ionic absorption (Risman P., 2009). Microwave energy was generated through a magnetron type generator operating at a nominal frequency of 915 MHz. The holding section was an extension of the heating section without microwave energy which maintained the food at the sterilization temperature to accumulate the desired lethality. Circulating water in the holding section at 122°C and 234.4 kPa acted as a heat source to maintain the temperature of the food at 122°C or acted as a heat sink to lower the temperature of the hot spot in food (>122°C). Finally, the cooling section reduced the temperature of the food to room temperature using circulating water at 20°C and 234.4 kPa.

The primarily concern of this study was to reduce the reflected microwave energy from the microwave cavities of the heating section. The MATS consists of four cavities in a series comprising the heating section. The procedure for reducing microwave reflection was the same for all cavities. Therefore, in this study, only one cavity of the heating section was considered. Due to the simplicity of waveguide configuration, cavity 3 was selected. Detailed configuration of cavity 3 is illustrated in Figure 2.
Figure 2: Cavity 3 assembly consists of (a) single mode cavity, (b) Ultem™ window at the top and bottom of the cavity, (c) horn, and (d) tee waveguide junction. Waveguide assembly for connecting cavity 3 to generator consists of (e) 90°H-bend waveguide elbow, (f) 90°E-bend waveguide elbow, (g) 3-probe tuner, P1, P2, and P3.

The dimension of the inner cross-section of the cavity is 247.7 mm by 81.0 mm with total length of 773.2 mm (Figure 2 a). This configuration allows the cavity to operate in a single mode (i.e., only one pattern of electromagnetic field distribution regardless of the presence of load). The cavity has two windows made of Ultem® polymer (Ultem-1000) by Plastic International (7600 Anagram Drive, Eden Prairie, MN 55344) of size 557.2 mm by 185.7 mm (Figure 2 b). Microwave applicators consist of two horns on the top and bottom of the cavity (Figure 2 c). The horn is a tapered shape parallelogram with inner cross sectional dimension at the narrow and wide end similar to the cross sectional dimension of a standard WR975 waveguide (inner cross sectional is 247.7 mm by 123.8 mm) and the cavity windows, respectively. Guided microwave energy through 90° E-bend WR975 elbow (Figure 2 f) and 90° H-bend WR975 elbow (Figure 2
is bifurcated in a tee WR975 junction (Figure 2 d) for the top and bottom infringement of microwave in the cavity. Due to the nature of a tee-junction, the microwave portion travelling at the lower part going to the bottom horn has a $90^\circ$ phase difference with the microwave portion travelling at the upper part going to the top horn. To ensure a zero phase shift inside the cavity, the total length of the upper part was $\frac{1}{2} \lambda$ (one half wavelength) longer than the lower part. Parts comprising the waveguide system and horns were manufactured by Ferrite Microwave, Inc. (165 Ledge Street, Nashua, NH 03060). The triple inductive post was located at the end of the waveguide system (Figure 2 g) and was connected to the microwave magnetron generator.

2.2. Triple inductive post

The triple inductive post or 3-probe tuner used in this study was manufactured by Mega Industries LLC (28 Sanford Dr., Gorham, ME 04038). Figure 3 shows the detailed specifications of the tuner previously illustrated in Figure 2 g. Figure 3 a, shows the top view of a one foot section of a standard WR975 waveguide used to contain the 3-probe tuner. Three holes (number 1, 2 and 3) with radius 1.63” (41.4 mm) were drilled in a triangular configuration (staggered arrangement). The midpoint of hole number-3 lies within the horizontal center and the left side is tangential to vertical center. The midpoint of holes number-1 and number 2 were 2.15” (54.6 mm) offsetting the midpoint of hole number-3 with respect to the horizontal center, and both right sides were tangential to the vertical center. Figure 3-b represents the side view of the WR975 section and the flange for connecting with other similar sized waveguides. Figure 3-c shows the 3D finished assembly of the WR975 section (i.e., without the probe). Finally, Figure 3-d illustrates the detailed specification of the probe that fits on the three holes of the WR975 section. The outside diameter of the probe is 1.97” (50.0 mm) with total insertion length of 3.34” (84.9 mm).
Each probe was mounted on a metal casing (i.e., cast iron) that exactly fits in the holes of the WR975 section allowing for insertion of the probe at variable length (maximum insertion length would be 3.34” = 84.9 mm). The midpoint of the probe of diameter 0.39” (9.9 mm) was attached to a screw allowing for manual insertion. Insertion of the probe was done by rotating the screw clockwise and dislodging by rotating counter clockwise. The outer surface of the probe was made up of bronze metal.

Figure 3: Three probe tuner specification: (a) top view of the WR975 waveguide section that contains three holes for the location of the probe; (b) side view of the WR975 waveguide without probe; (c) finished assembly of WR975 without probe; and (d) specification of the probe, all measurement in inches.
2.3. Measurement of frequency

The magnetron generator providing power for the cavity considered in this study was manufactured by Microdry Industries, LLC (5901 W. Highway 22, Crestwood, KY 40014). A B&K Precision TM-2650 spectrum analyzer and an AN-301 antenna (22820 Savi Ranch ParkWay, Yorba Linda, CA 92887) were used to measure the frequency of the generators. Frequency measurements were carried out using the direct method described in ITU-R M.1177 (ITU, 2003).

The AN-301 is a dipole antenna specified to work at a frequency range of 0.8 to 1.0 GHz. It has a gain of $\geq 1\text{dBi}$, and voltage standing wave ratio (VSWR) of $\geq 1.5$ at the center frequency range. A spectrum analyzer TM-2650 was set to a central frequency of 915 MHz with a span of 200 MHz (i.e., from 815 MHz to 1015 MHz on the x-axis). The frequency span was subdivided into 10 divisions and each division was 20 MHz with a resolution bandwidth (RBW) of 3 MHz. The oscillation power was set to -70 to 10 dBm on the y-axis subdivided into 8 divisions and each division was 10 dB.

The peak frequency (i.e., nominal frequency) was measured from different power settings of the magnetron generator (0.5 kW to 4.7 kW with 0.5 kW increments). All frequency measurements were done in three replicates every other month for a period of one year (2009-2010).

2.4. Measurement of forward and reflected power and the S_{11} parameter

In this study, the instrument used for measuring forward and reflected power was a Dual-Directional WR-975 waveguide coupler manufactured by Micronetixx Microwave, LLC (1 Gendron Drive, Lewiston, ME 04240). The center frequency of the coupler was at 915 MHz with coupling factor for both forward and backWard power and directivity of 60 dB and 30 dB,
respectively. The coupler was made of aluminum with a chromate surface finish. Two directional couplers (DC) were used in this study; DC-1 was located at the input port of the circulator on the generator side, and DC-2 was located on the reflection port of the circulator terminated by a matched water load (Figure 4). The 3-probe tuner illustrated in Figure 2-g was connected to the output port of the circulator on the load side (Figure 4). The matched water load and the circulator used in this study were manufactured by Ferrite Microwave Technologies, LLC (165 Ledge Street, Nashua, NH 03060). The purpose of the water load was to absorb all the reflected microwave energy through heat dissipation on circulating water inside the water load. The detailed specification of the water load is described in the study of Eves & Yakovlev (2002). The circulator used in this study had three ports; (1) the input port, (2) output port, and (3) the reflection port. The center of the circulator was made of a ferrite material activated by a strong magnetic field from a permanent magnet. The purpose of the circulator was to divert reflected microwave energy from the load side of the output port to the reflection port instead of the input port, thereby preventing reflected microwave energy from going back to the generator. In this manner, the magnetron powering the generator was protected from internal heating and frequency instability caused by excessive reflected microwave energy (Meredith, 1998).

In Figure 4, the reading from DC-1 represents pure incident microwave energy provided by the magnetron generator. It was expected that DC-1, depending on the effectiveness of the circulator, would measure minimal to no reflected microwave energy. The reading from DC-2 represents pure reflected microwave energy. From the load side of the circulator, due to impedance mismatch between load and source, it was expected that both forward and reflected wave would coexist. The sum of forward and reflected microwave energy is equal to the incident...
microwave energy measured by DC-1. In this study, the reflection coefficient, which is the $S_{11}$, was calculated as the ratio of the reading from DC-2 to DC-1 (i.e., $S_{11} = \frac{DC-2}{DC-1}$).

Figure 4: Diagram of the location of directional coupler (DC), circulator, and the 3-probe tuner

### 2.5. Determination of proper probe insertion depth

Proper insertion depth combinations of the 3-probe tuner were determined at different power settings of 1 kW, 2.5 kW, and 4.7 kW. This was done because of the dependency of operating frequency of the generator at different power settings (Figure 5). Since there are limitless possibilities for insertion depth combinations for the 3-probe tuner, a simple scheme (Table 1) was adapted to determine appropriate insertion depth combinations considering stability of reflected power at a reasonable frequency bandwidth. In Table 1, starting at combination 1 (0%, 0%, and 0%) for P1, P2, and P3, respectively (Figure 3a), P1 was inserted by
manually turning the knob to change the depth of insertion at a rate of approximately 20 rpm. When insertion depth of P1 reached 100% (84.9 mm maximum depth of probe) in combination 3, P2 was then inserted at the same manner as with P1 in combination 4, and then P1 was dislodged to 50% in combination 5 and so on until the last combination in Table 1. While following the scheme in Table 1, incident and reflected power was continuously monitored in DC-1, and DC-2, respectively (Figure 4).

Percentage of insertion was measured by dividing the total length of the screw to where the probe and knob were connected. The location of the attachment of the knob in the screw is equal to 0% insertion, the location of attachment of the probe in the screw is equal to 100% insertion, and finally, half of the length of the screw (i.e., 84.9 mm / 2 = 42.5 mm) is equal to 50% insertion. A Mitutoyo™ digital caliper (958 Corporate Blvd. Aurora, IL 60502 USA) model number SC-6” was used to measure the half length of the screw. Furthermore, following the manual turning of knob at the rate of 20 rpm, it took approximately 32 seconds to change from combination 1 to combination 2. Therefore, to complete the 27 different insertion depth combinations of the 3-probe in Table 1, it took approximately 832 s or 14 min.

$S_{11}$ parameter (i.e. ratio of DC-2 / DC-1 power reading) was plotted against different insertion depth combinations (Table 1). The combination that gave low reflection was further fine-tuned by slowly changing the insertion depth starting from the most reactive probe. The most reactive probe is the one near the microwave source which was probe-2 (P2), followed by probe-3 (P3) then lastly probe-1 (P1).
Table 1. Probe combination scheme for determining proper insertion depth combination of the 3-probe tuner that will give minimum reflected power.

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<th>Time</th>
<th>% insertion depth</th>
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2.6. Computer simulation model

Figure 2 is a 3D representation of the computational domain for computer simulation used in this study. Based on the previously verified microwave assisted thermal sterilization computer simulation model (MATS-CSM), a computer simulation model was created specifically for cavity 3 of the MATS and the waveguide system associated with it. With the aid of commercial software QuickWave™ 7.5 (QWED, Warszawa, Poland 1132173057), the finite-difference-time-domain (FDTD) numerical method was implemented to determine the $S_{11}$ parameter using the computer simulation model. The size of the mesh in the model was optimized by the Amigo™ function of QuickWave™ 7.5 software setting a minimum of 10 cells per wavelength in all direction ($x$, $y$, and $z$). Also, emphasis was given to the volume occupied by the 3-probe tuner by refining the mesh to $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$ along $x$, $y$, and $z$ axis, respectively. The total number of cells for the whole computational volume of the simulation model was $434 \times 885 \times 401$ along $x$, $y$, and $z$ axis, respectively.

Referring to Figure 2-g, at the end of the WR975 waveguide containing the 3-probe tuner, an input port and a reference plane were positioned 70 mm and 35 mm away from edge of the probe nearest to the microwave source (P2). The size of the input port cover is similar to the cross sectional area of the waveguide at that location (width = 247.7 mm and height = 123.8 mm). The excitation field of the input port was set at TE$_{10}$ mode with pulse of spectrum ranging from 700 MHz up to 1.2 GHz as its waveform (Pathak, Liu, & Tang, 2003). The frequency bandwidth chosen covers the operating frequency bandwidth of the generator used in this study and other possible frequencies that might propagate in a WR975 waveguide. Given a fixed geometry of a certain computational domain, the $S_{11}$ parameter is independent of the amplitude of the field since it is the ratio of reflected and incident power. In this study, the amplitude was
set to a constant value of 97.0 V/m which corresponds to 4.7 kW of incident power. Although result shows that the operating frequency of the generator used in this study is dependent on power setting (see Section 3.1), for the computer simulation, a constant value of amplitude is sufficient because $S_{11}$ was extracted at a range of frequency covering the operating frequency bandwidth of the generator. For example, for the power level of 2.5 kW at operating frequency of 905 MHz of the generator (Figure 5), simulation result of $S_{11}$ at 2.5 kW would be that which corresponds to 905 MHz even though simulation was carried out at an amplitude specific to 4.7 kW. Furthermore, in this study even though $S_{11}$ was simulated at a frequency range of 700 MHz to 1.2 GHz, only relevant frequency ranges were presented, which were those specific to the operating frequency bandwidth of the generator (900 MHz to 910 MHz).

2.7. Verification of computer simulation model

Not all factors affecting power reflection on the actual MATS system can be accounted for in the computer simulation model. For example, the junctions between waveguide parts were assumed to be properly aligned in the computer simulation model, whereas for the real system, a minute misalignment might occur and can potentially cause significant power reflection. To this end it is important to verify the accuracy of the computer simulation model in determining $S_{11}$ parameter and the necessary correction factor for the purpose of calibration.

A 50% insertion depth for the 3-probe tuner was selected since this setting gave the most stable reflected power reading in the directional coupler. Simulated $S_{11}$ was compared side by side with the measured $S_{11}$. Accuracy of the computer simulation model was verified qualitatively and the correction factor was determined quantitatively considering the ratio of $S_{11}$ for actual measured value and simulated value (Equation 11);

$$CF = \frac{\text{measured } S_{11}}{\text{simulated } S_{11}}$$ (11)
Measured $S_{11}$ is the ratio of DC-2 and DC-1 (Figure 4) from the actual MATS setup at different power levels (1 kW, 2.5 kW, and 4.7 kW), respectively, which gave different operating frequencies (903.5 MHz, 905.9 MHz, and 909.5 MHz), respectively (Section 3.1), and simulated $S_{11}$ was taken from the simulation result using the computer simulation model.

2.8. $S_{11}$ Parameter extraction for different insertion depth of 3-probe tuner through computer simulation

The $S_{11}$ determination using QuickWave™ was straightforward. The 3-probe tuner incorporated in the computer simulation model described in Section 2.6 and illustrated in Figure 2 was modified based on the probe combination scheme in Table 1. Using QuickWave™ editor, the total inserted length of the probe was changed considering the total allowable length that could be inserted. From the design of the 3-probe tuner (Figure 3 d), the total allowable insertion length was 84.9 mm. For example, combination 2 in Table 1 requires 50% insertion depth for probe-1 (P1); therefore, the total insertion depth of P1 would be 42.5 mm ($i.e.$, $84.9 \text{ mm} \times 0.50 = 42.5 \text{ mm}$). A separate simulation was necessary for every insertion depth combination of the 3-probe tuner.

To this end, it was important to differentiate simulation results and actual experimental measurements. In actual measurements, $S_{11}$ was measured in transit, which means $S_{11}$ was continuously monitored during insertion and dislodged of the probes. For example, considering combination 2 in Table 1, as P1 was inserted from 0% to 50%, at rate of 20 rpm, $S_{11}$ was continuously monitored within the range of 0% to 50% P1 insertion. In contrast, $S_{11}$ results from computer simulation were specific only to a certain position of the probe. If, for example, $S_{11}$ is required at 25% insertion of P1, a separate simulation needs to be executed. Considering the
The objective of this study, the practicality of using a computer simulation model is to give an idea of $S_{11}$ at a certain insertion depth combination of the 3-probe tuner. This can be used as a starting point for actual measurement of $S_{11}$ eliminating the need to measure all possible combinations of the 3-probe tuner, as described in Table 1.

In this study, since $S_{11}$ was experimentally measured on all possible combinations of the 3-probe tuner following the scheme in Table 1, fine tuning of probe insertion was also conducted for a certain power setting of the generator. The purpose of the computer simulation model was to verify $S_{11}$ by considering the experimentally determined insertion depth of the 3-probe tuner.

No fine tuning was conducted for power setting of 1 kW and 2.5 kW because generator 3 of the MATS was usually set at the highest power output (4.7 kW). Fine tuning was only conducted at the 4.7 kW power setting; therefore, the optimized insertion depth combination of the 3-probe tuner as determined through fine tuning was used in simulation at 4.7 kW (@909.5 MHz) power setting. For 1 kW and 2.5 kW, several simulations were conducted based on the $S_{11}$ spectrum result for 1 kW and 2.5 kW (Figure 6a and 6b respectively). The combination scheme in Table 1 that shows low $S_{11}$ reading for 1 kW and 2.5 kW was further refined by considering intermediate insertion depth (75% was considered which is at the intermediate of 50% and 100%). The simulation scheme for 1 kW and 2.5 kW is summarized in Tables 3, and 4 in Section 3.4.

### 2.9. Statistical analysis

The data gathered for the frequency measurement at different power level was analyzed to determine the influence of power level to frequency output of generator powering the cavity. SAS™ 9.2 software was used to conduct Analysis of Variance (ANOVA). A confidence level of 95% was used for all analysis.
3. Results and Discussion

3.1. Frequency at different power setting

Figure 5 shows the operating frequency corresponding to different power settings of the generator (i.e., power setting vs. frequency). Statistical analysis based on Fisher’s LSD (least square difference) shows that only the operating frequency at power levels 2.0 kW and 2.5 kW were not significantly different. The rest of the operating frequencies at other power levels were significantly different at 95% confidence level. The operating frequency increases with the power setting/output of the generator. Specifically, for every 0.5 kW increase in power, operating frequency increased by 0.75 MHz. Another notable characteristic of the generator (Figure 5) was the relative consistency in achieving similar value of operating frequency every time it was turned on (standard deviation among trials was approximately ±0.2 MHz). The nominal operating frequency of the generator used in this study was 915 MHz; however, the measured operating frequency from 0.5 kW to 4.7 kW was from 901.1 MHz to 909.5 MHz, which is slightly lower than the nominal value. This inconsistency might have been due to the age of generator (Cooper, 2009). Furthermore, the operating frequency of the generator at 1 kW, 2.5 kW, and 4.7 kW, which is a concern for this study, was 903.5 MHz, 905.9 MHz, and 909.5 MHz, respectively.
Figure 5: Plot of frequency versus power output of generator 3 attached to cavity 3 and the corresponding standard deviation from the six (6) measurements of every frequency and power combination.

3.2. Determination of proper probe insertion depth

The experimentally measured transient $S_{11}$ at different probe combination (Table 1) are summarized in Figure 6. The y axis corresponds to the ratio of DC-2/DC-2 ($S_{11}$) and the x axis corresponds to the time during insertion of the probe from one combination to the next. When the generator was set at 1 kW the lowest reflection measured was when the probe was between combination 7 and 8 (P1@0%; P2@100%; P3@0% and P1@50%; P2@100%; P3@0%) and
between combination 12 and 13 (P1@0%; P2@100%; P3@50% and P1@0%; P2@50%;
P3@50%). When at 2.5 kW, the lowest reflection was when the probe was between combination 6 and 7 (P1@0%; P2@50%; P3@0% and P1@0%; P2@100%; P3@0%) and between combination 14 and 15 (P1@50%; P2@50%; P3@50% and P1@100%; P2@50%; P3@50%). Finally, when the generator was set at 4.7 kW the lowest reflection measured was when the probe was between combination 17 and 18 (P1@50%; P2@0%; P3@50% and P1@0%; P2@0%; P3@50%) and between combination 23 and 24 (P1@50%; P2@50%; P3@100% and P1@0%; P2@50%; P3@100%).

Althought the S_{11} spectrum was measured for 1 kW and 2.5 kW, the specific generator used in this study was usually set at maximum power output of 4.7 kW. Therefore, the 3-probe tuner along the rectangular waveguide was only fine-tuned at 4.7 kW. In the case that this generator will be used at lower power settings, Figure 6-a and 6-b will be useful.

Based on fine tuning of the 3-probe tuner when the generator was set at 4.7 kW operating at 909.5 kW, the best combination of the tuner that gives the lowest power reflection was when at P1@30%; P2@10%; P3@25%. This probe combination was found from combination 17 to combination 18 of Table 1 (Figure 6-c). At combination 17, P1, P2, and P3 was at 50%, 0% and 50% depth inserted, respectively. Going to combination 18, probe 1 was slowly dislodged from 50% to 30% (approximately 25.5 mm inserted), then for fine tuning, probe 2 was slowly inserted to 10% (approximately 8.5 mm inserted), then probe 3 was gradually dislodged from 50% to 25% (approximately 21.5 mm inserted). This position of the 3-probe tuner gave a reflection range of 6.1% to 11.7% when the cavity is loaded (i.e., the cavity contains food pouch/tray and circulating water) and 17.7% to 21.4% when the cavity is unloaded (i.e., the cavity contains only circulating water). In comparison to the MATS system that has no probe tuner (i.e., reflection is
at least 50%), there was a significant 75% to 88% reduction of reflected power in a loaded cavity, and 55% to 65% in an unloaded cavity for a system that has a properly tuned 3-probe tuner.

Notice that in this study, only one combination of 3-probe tuner was fine-tuned and presented, whereas according to the $S_{11}$ spectrum for 4.7 kW (Figure 6-c) there were two possible combinations (the other combination was between combination 23 and 24). The other combination gave a relatively unstable reflected power as compared to the one presented and therefore not a good option.
Figure 6: Plot of power reflection ($S_{11}$) and time at different insertion depth of the 3-probe tuner;
(a) 1 kW, (b) 2.5 kW and (c) 4.7 kW
3.3. Correction factor for computer simulation model

Comparisons of $S_{11}$ parameter are summarized in Figure 7 and Table 2 for both simulated results and actual measurement from the selected cavity of the MATS system, for the purpose of determining the correction factor for a computer simulation model. It was noticed that computer simulation results for $S_{11}$ on average was 64% higher (average $CF$ is 0.64) than the actual measured $S_{11}$ from the MATS system (using directional coupler). This result is because in defining the computation volume of the computer simulation model no optimization was done for the tee-junction attached to the waveguide system. In the actual system, the tee-junction used has a built in inductive posts tuner to effectively split incident field and minimize reflection. The built in tuners inside the tee-junction were not considered in the computer simulation model. In addition, it was mentioned that the computer simulation model assumed perfect alignment in all waveguide junctions, which may not be true in the actual MATS system.

Despite the limitations of the computer simulation model in this study, it can be seen that the contribution of the built in tuner in the tee-junction of the MATS and the possible misalignment along the waveguide junctions of the MATS is measureable and well behaved. In Figure 7, the curve of $S_{11}$ at different power settings of the generator (i.e., at different operating frequencies) from 1 kW to 4.7 kW corresponds closely to the curve of $S_{11}$ generated by the computer simulation model. It can also be noticed that at higher frequency (e.g., 909.5 MHz, which corresponds to 4.7 kW generator output), the difference between measured and simulated $S_{11}$ was smaller compared to lower frequency (e.g., 903.5 MHz, which corresponds to 1 kW generator output). This findings leads to the conclusion that correction factor ($CF$) correlates properly with frequency. In general, the higher the frequency, the lower the $CF$, and vice versa.
The relationship of $CF$ and frequency were summarized in a second degree polynomial equation with a fit of $R^2=0.999$:

$$CF = 2.13 \times 10^{-3} f^2 - 3.87f + 1763.92$$

(12)

where $CF$ is the correction factor and $f$ is the frequency in MHz. Successive $S_{11}$ simulation results were corrected using Equation 12.

Figure 7: Comparison of $S_{11}$ parameter of simulated and actual measurement in MATS at different frequencies with no probe tuner and with a 3-probe tuner inserted 50% of its length for the determination of correction factor for computer simulation model.
### Table 2. Correction factor for the computer simulation model

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Frequency (MHz)</th>
<th>S_{11} at No probe</th>
<th>CF</th>
<th>S_{11} at P1@50%;P2@50%;P3@50%</th>
<th>CF</th>
<th>Ave. CF</th>
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<tbody>
<tr>
<td></td>
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<td>MATS</td>
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<td>MATS</td>
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<tr>
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<td>4.7</td>
<td>909.5</td>
<td>0.52</td>
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<td>0.50</td>
<td>0.28</td>
<td>0.59</td>
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</table>

### 3.4. Simulation results

For a power setting of 1 kW of the generator with operating frequency of 903.5 MHz, and considering S_{11} between combinations 12 and 13 (Table 1) for power setting 1 kW (Figure 6 a), simulations with the following probe settings were conducted (Table 3):

### Table 3. Probe combination for simulation at generator set at 1 kW

<table>
<thead>
<tr>
<th>Probe-1 (P1)</th>
<th>% insertion depth</th>
<th>Probe-2 (P2)</th>
<th>% insertion depth</th>
<th>Probe-3 (P3)</th>
<th>% insertion depth</th>
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*combination 12 (P1@0%; P2@100%; P3@50%)

** combination 13 (P1@0%; P2@50%; P3@50%)

Considering combinations 12 to 13 (Table 1), for fine tuning of the 3-probe tuner when the generator is set to 1 kW (@903.5 MHz), since probe-1 (P1) is at 0% insertion it was assumed that 25% would be the maximum insertion depth for P1 that would result in good impedance matching. For probe-2 (P2), from 100% dislodge to 50%, it was assumed that a good impedance
matching would occur at 100%, 75% and 50%. Finally for probe-3 (P3), combination 12 to 13 suggest 50% insertion so at most, P3 would have a good impedance matching at 25%, 50% and 75%. The possible percent insertion depth combinations of the 3-probe are summarized in Table 3. Among the 3-probe combinations shown in Table 3, the one indicating the lowest power reflection near 903.5 MHz was the setting (P1@25%; P2@50%; P3@75%) with less than 10% power reflection at 903.5 MHz (Figure 8-a). A similar procedure was conducted between combinations 7 and 8 (Table 1) for 1 kW (as suggested by $S_{11}$ spectrum for 1 kW in Figure 6-a), but the result did not give a low power reflection.

For a power setting of 2.5 kW of the generator with operating frequency of 905.9 MHz, considering combinations 14 and 15 (as suggested by $S_{11}$ spectrum for 2.5 kW in Figure 6-b) the following simulation was conducted (Table 4). The 3-probe combination that showed low power reflection (<15%) at 905.9 MHz was the setting (P1@100%; P2@50%; P3@75%) (Figure 8-b). Again, the reflected power on the other combination (combination 6 and 7) suggested by $S_{11}$ spectrum for 2.5 kW (Figure 6-b) was not as stable compared to the reflected power base on combinations 14 and 15.

Since there was no actual fine tuning on power settings 1 kW and 2.5 kW, it was necessary to conduct several simulations to determine the possible combinations of the 3-probe that would give the lowest power reflection. Of course, these combinations need to be tested on the actual MATS system for verification. However, for power setting 4.7 kW, actual fine tuning was done on the 3-probe tuner. The optimum tuner setting was determined to be at P1@30%; P2@10%; P3@25% (see Section 3.2). Conducting a computer simulation at this setting would give a reflected power of 15.2% at 909.5 MHz in a loaded cavity (Figure 8-c). The power reflection determined by computer simulation was comparable to the measured power reflection,
which was in a range of 6.1% to 11.7% in a loaded cavity. Discrepancy can be attributed to the simplification on the 3-probe tuner in the computer simulation model in which the tuner was assumed to have a flat end (sharp edge), but the actual tuner has a hemispherical end and curved edge with radius of curvature of 9.7 mm (0.38”).

Table 4: Probe combination for simulation at generator set at 1 kW

<table>
<thead>
<tr>
<th>Probe 1 (P1)</th>
<th>% insertion depth</th>
<th>Probe 2 (P2)</th>
<th>Probe 3 (P3)</th>
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* combination 14 (P1@50%; P2@50%; P3@50%)
** combination 13 (P1@100%; P2@50%; P3@50%)
Figure 8: Simulation result for $S_{11}$ parameter at specific to: (a) 1 kW power output of generator at 903.5 MHz, (b) 2.5 kW power output of generator at 905.9 MHz, and (c) 4.7 kW power output of generator at 909.5 MHz.

4. Conclusion

This study was able to prove that a multiple inductive post (3-probe tuner) along a WR975 rectangular waveguide of the MATS system can match the impedance of the load and source thereby reducing power reflection for efficient transmission of microwave energy for the purpose of dielectric heating. Using a simple scheme as described in Table 1, the proper insertion depth combinations of the 3-probe tuner were determined experimentally. Furthermore, a computer simulation model to mimic section of the MATS under study was successfully created and calibrated with correction factors for the purpose of verifying the result of
experimentally measured power reflection at different insertion depth combinations of the 3-probe tuner. In summary, for a generator set at 4.7 kW operating at 909.5 MHz, the optimum percent insertion depth of the 3-probe tuner that would give the lowest power reflection was at P1@30%; P2@10%; P3@25% corresponding to an insertion depth of 25.5 mm, 8.5 mm, and 21.5 mm, respectively. At this tuner setting, the power reflection was in a range of 6.1% to 11.7% in a loaded cavity, which corresponds to 75% to 88% reduction as compared to a MATS system without the 3-probe tuner. Using the experimentally determined insertion depth combination of the 3-probe tuner on the computer simulation model, a power reflection of 15.2% was determined which is comparable to the experimentally measured power reflection. Good agreement between experimental and simulated power reflection indicates that the computer simulation model can be a useful tool in verifying experimental results and vice versa. Moreover, several simulations were conducted to determine the insertion depth combination of the 3-probe tuner when the generator is set to a lower power (e.g., 1 kW and 2.5 kW). A proper combinations that gave low power reflection were found but were not experimentally confirmed because the generator used in this study was usually set at higher power output. Finally, no arching was observed during the insertion of the probes which was possibly expected to occur at high power transmission.

5. References


CHAPTER SIX

EFFECT OF PRECOOKING ON THE DIELECTRIC PROPERTY OF SALMON FILLET AT 915 MHz

Abstract

Numerous studies have confirmed that the use of microwave for thermal processing of food can produce high quality products. Recently, FDA accepted the Washington State University (WSU) filing for a microwave process of pre-packaged mashed potato, thus offering opportunities for potential application of new thermal processing technology. The WSU’s Microwave Assisted Thermal Sterilization (MATS) system is designed based on a hybrid concept that takes the advantage of traditional over-pressure surface water heating and single mode microwave heating at 915 MHz. We further explored MATS for processing salmon fillet in Alfredo sauce packed in flexible pouches. In the process development, we preheated salmon fillet in pouches to about 70-72°C for 30 min before processing in MATS. Preheating of salmon partially denatures fish protein, possibly causing changes in its dielectric property. Dielectric property (i.e., dielectric constant and loss factor) relates the macroscopic interaction between food and the microwave electric field during volumetric microwave heating. The objective of this study was to investigate the effect of preheating on the dielectric property of salmon fillet at 915 MHz. Samples used for dielectric property measurement was pink salmon fillet previously marinated in Alfredo sauce. The preheating conditions were (a) temperatures 60-70-80°C, and (b) time 10-20-30 min, analyzed on a full factorial design. Hewlett-Packard 8752C network analyzer was used to measure dielectric property. Preheating condition in salmon fillet causes moisture loss and possibly change in salt content resulting in change in its dielectric property at 915 MHz measured over a temperature range of 20-120°C.
1. Introduction

1.1. Dielectric property

Dielectric property (DP) is an important characteristic of materials in microwave heating. It consists of electric permittivity ($\varepsilon$) and magnetic permeability ($\mu$). Foods are non-magnetic dielectric materials, thus microwave heating is related only to the complex electric permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of food. In this study, emphasis is given on accurate measurement of complex electric permittivity of the food materials. Dielectric constant ($\varepsilon'$) is the real part of complex permittivity while dielectric loss factor ($\varepsilon''$) is the imaginary part. Dielectric constant ($\varepsilon'$) pertains to the electric charge (i.e., energy) storage capability of food (Mudgett R. E., 1986) and dielectric loss factor ($\varepsilon''$) pertains to the ability of food to absorbed energy from electric field and subsequently dissipate into heat (Icier & Baysal, 2004). The mechanism of heat dissipation is due to dipole relaxation (e.g., polar molecules such as water) and ionic relaxation (e.g., dissolved ions such as salt in food) (Risman P. O., 2009). Due to the nature of the materials considered in this study, discussion of dielectric property pertains only to both dielectric constant (DC) and dielectric loss factor (LF).

Dielectric property of food is dependent on different factors including: (1) the frequency of electromagnetic field (e.g., microwave field), (2) temperature of food samples, (3) moisture content of food, (4) salt content of foods (Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010), (5) processing and pre-processing treatment in the foods, and (6) composition of foods.

1.2. Related study

Several studies were published relating dielectric property of food to temperature and frequency. Depending on material components (e.g., moisture, fat, and salt contents), dielectric
constant may decrease or increase with temperature (Tang J., Dielectric properties of foods, 2005). In general, however, for food with relatively high moisture content (>80%) dielectric constant decreases with increasing temperature above the freezing temperature, whereas a reverse trend and a relatively low dielectric constant were reported for frozen foods below subfreezing temperature (Rissman & Bengtsson, 1971). This is because at subfreezing temperature, majority of water molecules are bounded in rigid crystal ice structure. Furthermore, for high moisture foods, loss factor generally decreases with temperature above the freezing temperature, except for food with considerable amount of salt or dissolved ions (e.g., cooked ham) (Rissman & Bengtsson, 1971). An increasing trend was reported for loss factor and temperature relationship for high moisture food below subfreezing temperature (Risman P. O., 2009).

The dependence of dielectric property of food on frequency is related to the polarization (i.e., dipole rotation as a reaction to applied field) of molecules and charged ions in the food (Risman P. O., 2009). As frequency increases, dielectric constant may decrease or remain constant depending on the ability of dipole molecules in food to keep up with the direction of the changing field (i.e., dipole rotation) (Icier & Baysal, 2004). As the frequency continues to increase, a phase lag between dipole rotation and field occurs, causing a decrease in dielectric constant and increase in loss factor (i.e., absorption of energy) (Icier & Baysal, 2004).

Presence of dissolved ions in food generally affects the dielectric property by decreasing dielectric constant and increasing dielectric loss factor (Icier & Baysal, 2004). Dielectric loss factor of food containing considerable amount of salt is affected by a combined effect of dipole rotation and migration of ions due to ionic conductivity (Mudgett R. E., 1986). Ionic conductivity itself is frequency independent quantity; however, since movement of ions is
dependent on characteristic of the applied electric field, the net effect of ions becomes frequency dependent (Risman P. O., 2009). A study conducted by Wang et al. (2008) concluded that at frequencies 100-1000 MHz, the contribution of ionic conductivity to loss factor of salmon is greater than that of dipole rotation. At 915 MHz, approximately 85% of loss factor of salmon is due to ionic conductivity and only ~15% is due to dipole rotation (Wang, Tang, Rasco, Kong, & Wang, Dielectric properties of salmon fillet as a function of temperature and composition, 2008). Similar trend were observed for mashed potato with different NaCl concentration (Guan, Cheng, Wang, & Tang, 2004). Ionic conductivity also increases with increasing temperature. Therefore, salt containing foods are expected to have increasing loss factor with increasing temperature.

The depth of penetration ($D_p$) of microwave is dependent on the dielectric property of food materials. Dielectric property is a temperature dependent quantity hence $D_p$ is dependent on the temperature distribution of the food during microwave heating. By definition $D_p$ is the distance travelled by incident microwave from the surface of the food onto a distance where microwave’s amplitude is $1/e$ lower than the original. In this study the $D_p$ of microwave at 915 MHz in salmon fillet was calculated using the equation (Datta, Fundamental of heat and moisture transport for microwaveable food product and process development, 2001):

$$D_p = \frac{328 \text{ mm}}{2\pi \sqrt{2\varepsilon'\left(1+ \left(\frac{\varepsilon''}{\varepsilon'}\right)^2 \right)-1}}$$  \hspace{1cm} (1)

where 328 mm is the wavelength of microwave at 915 MHz in free space and $\varepsilon'$ and $\varepsilon''$ are dielectric constant and loss factor respectively.

In this study, pink salmon (Oncorhynchus gorbuscha) fillets was the material of concern. Similar to other skinless biological material, several changes in physical property may occur during storage, handling, and preprocessing, which can alter salmon’s dielectric property.
Included in the changes of physical properties are; (1) loss of moisture after thawing of frozen salmon samples, and (2) changes in salt and moisture content during marination in medium with high concentration of salt. In a related study of Atlantic salmon (Salmo salar) quality, it was concluded that freezing and thawing affects texture, color, and drip loss of salmon fillet (Alizadeh, Chapleau, De Lamballerie, & LeBail, 2007). Changes in texture and color was explained to be related to denaturation of protein in salmon fillets (i.e., myofibrillar and sarcoplasmic proteins) if pressure-shift freezing is used. For drip loss, the amount of water expelled after freezing and subsequent thawing depends on the rate of freezing. Atlantic salmon fillet samples were subjected to two freezing methods (i.e., pressure-shift freezing, PSF, and air-blast freezing, ABF). Since PSF is faster than ABF, less drip losses were observed in salmon fillet treated with PSF (Alizadeh, Chapleau, De Lamballerie, & LeBail, 2007). This was explained to be related to the size of initial ice crystal formation at the start of freezing. In the case of PSF (i.e., higher rate of freezing), the initial size of ice crystal formed were smaller than that of ABF, hence, lower drip loss (Fennema, Powrie, & Marth, 1973).

A more profound effect in the change of property in the salmon fillet can be observed during thermal processing. Physical and chemical changes occurring simultaneously to different degrees depending on the processing condition may directly or indirectly influence the dielectric property of salmon fillet. Physical changes includes: (1) textural changes, (2) cook loss, (3) shrinkage, and (4) muscle fiber structural changes. A study reported by Kong et al. (2007) on the effect of thermal processing at 121.1°C at various heating time of pink salmon (Oncorhynchus gorbuscha) fillet concluded that a four-phase textural changes occur. The first phase is rapid toughening that occurs during the first 2.5 min of heating at 121.1°C. The second phase is rapid tenderization that occurs on the next 20 min of heating at 121.1°C. The third and fourth phase is
slow toughening and slow tenderization that consecutively occur after the next one and two hour of processing at 121.1°C respectively (Kong, Tang, Rasco, Crapo, & Smiley, 2007). Concurrent to textural changes are the loss of moisture and shrinkage of muscle of salmon fillet. Loss of moisture was quantified through cook loss (i.e., express as percent ratio of weight reduction of cooked versus raw salmon sample), and shrinkage of muscle through area shrinkage on both longitudinal and transverse direction in reference to the muscle fiber of salmon fillet (Kong, Oliveira, Tang, Rasco, & Crapo, 2008). Result shows that 26.2% of the total loss of moisture occurs at the first 20 min of heating at 121.1°C. The next succeeding heating time shows gradual moisture loss and at the end of 2 hours of heating at 121.1°C, the moisture content of salmon fillet decreases from 73.43% to 67.12% wet basis. The overall decrease in moisture content reflects to the total area shrinkage of salmon fillet. The longitudinal and transverse area shrinkage parallel to muscle fiber for salmon is 20% and 2% respectively (Kong, Oliveira, Tang, Rasco, & Crapo, 2008).

Chemical changes in salmon fillet as affected by thermal processing includes: (1) myofibrilar and sarcoplasmic protein denaturation, and (2) collagen solubilization (Bracho & Haard, 1996). (1) thiamin degradation (Kong, Tang, Rasco, & Crapo, 2007), (2) darkening of salmon fillet due to oxidation of carotenoid pigments (Haard, 1992).

1.3. Knowledge gap

Several studies dealt with measurement of dielectric properties of salmon as affected by different factors such as temperature, composition, frequency of electromagnetic field (Wang, Tang, Rasco, Kong, & Wang, Dielectric properties of salmon fillet as a function of temperature and composition, 2008); (Al-Holy, Wang, Tang, & Rasco, 2005), and addition of transglutaminase (MTGase) to improve thermal stability of salmon (Basaran, Basaran-Akgul, &
Rasco, 2010). No data are available for the dielectric property of salmon fillet as affected by marination and preheating treatments. In a related study, Bircan and Barringer (2002) investigated dielectric property as affected by protein denaturation during heating of several muscle foods (e.g., beef, chicken, perch, cod, and salmon). However, the experimental condition used was different from the preheating condition used this study.

1.4. Objective

This chapter reports the result of a research as part of a larger study related to processing of salmon fillet in Alfredo sauce packed in flexible pouch using Microwave Assisted Thermal Sterilization (MATS) system. For this purpose, dielectric property data for salmon fillet as affected by marination in Alfredo sauce and precooking conditions are needed as an important reference for proper food formulation and are an essential input parameters in computer simulation modeling for determining heating pattern and identifying cold spot in food. Furthermore, the developed process protocol requires preheating of food pouches at 70°C for approximately 30 min before microwave heating in MATS. The specific objectives of this study were;

- to determine the effect of precooking temperatures of 60°C, 70°C and 80°C, for 10, 20, and 30 min on the dielectric property of salmon fillet (Oncorhynchus gorbuscha) and marinated salmon fillet in Alfredo sauce;
- to determine the resulting change in the penetration depth at 915 MHz microwave as affected by marination and precooking;
- to compare the dielectric property of marinated and precooked salmon and the corresponding microwave penetration depth at 915 MHz to the untreated (untreated) salmon fillet; and finally
to propose a model equation incorporating the effect of marination and precooking to the dielectric property of salmon fillets.

2. Materials and methods

2.1. MATS system

In brief, the Microwave Assisted Thermal Sterilization (MATS) consisted of four sections—preheating, heating, holding and cooling—arranged in series representing the four sequential processing steps. The whole system is pressurized at 234.4 kPa and each section has its own circulating water preset at a certain temperature. The typical circulating water temperature in the preheating, heating, holding and cooling sections are at 72°C, 122°C, 122°C, and 20°C, respectively. A pocketed mesh conveyor belt made of non-metallic material extending from one end of the preheating section to the other end of the cooling section conveys food pouches across different sections of MATS.

The preheating section equilibrates the temperature of the food to a uniform initial temperature (IT) (i.e., target IT set at 70 to 72°C). For salmon in Alfredo sauce packaged in pouches, preheating to 70 to 72°C was approximately 30 min based on direct temperature measurement at the center of salmon fillet. The food pouches were loaded in the belt conveyor which traversed pouches across the heating section of MATS. In this section, the food is heated by the combined action of thermal energy from hot water (i.e., 122°C and 234.4 kPa) circulating at 50-55 L/min and microwave energy at 915 MHz infringing from the four applicators attached to the heating section. The heating section of MATS consists of four connected rectangular microwave cavities. Each cavity operates in a single mode (i.e., only one pattern of electromagnetic field distribution regardless of the presence of load). The holding section is an
extension of the heating section of MATS. Circulating water in the holding section is set at 122°C and 234.4 kPa to maintain the temperature of the food, or acts as a heat sink if the temperature of food goes beyond 122°C until it reaches the desired sterilization value \((F_o)\). Lastly, when moved into the cooling section, the food pouches are cooled rapidly to room temperature.

2.2. Materials

Pink salmon (\textit{Oncorhynchus gorbuscha}) fillets were used in this study. Ocean Beauty Seafood (OBS, 1100 West Ewing Street, Seattle, Washington, 98119 USA) provided the salmon fillet from a caught and processed (i.e., de-boned and deep-skinned) Alaskan wild pink salmon. The fillets, which normally consist of the anterior and middle portion of salmon, was vacuum packed in a heat-sealed polyethylene (PE) bags and deep frozen to about -31°C using Individually Quick Frozen (IQF) freezer before shipping to Washington State University (WSU) Pullman, WA campus. Received salmon fillet were then stored in a walk-in freezer facilities maintained at about -30°C. Commercially available Bertolli™ Alfredo sauce (Unilever United States, Inc., 800 Sylvan Avenue, Englewood Cliffs, NJ 07632) was used as marinating sauce. Printpack Inc. (2800 Overlook ParkWay, NE Atlanta, Georgia, 30339 USA) provided the flexible pouches specifically designed for microwave processing purpose with proprietary provision. The pouches consisted of laminates of; (1) 12 µm polyethylene terephthalate (PET), (2) 12 µm barrier-coated PET, (3) 15 µm nylon, and (4) 76 µm polypropylene (PP) held together by a polymer adhesive. The shape of a pouch is a regular rectangle heat sealed from three corners (\textit{i.e.}, one shorter lateral end was unsealed to allow placing of samples) with size 140 x 95 mm measured from manufacturer’s seal end.
2.3. Sample preparation

In this study, the effect of precooking temperature and precooking time on the dielectric property of salmon was studied on: samples (a) salmon fillet alone, and samples (b) salmon fillet marinated in commercially available Bertolli™ Alfredo sauce. Results were then compared to the dielectric property of samples (c) untreated (i.e., no precooking or marination) salmon fillet. Salmon fillet has different portions with different dielectric properties (Wang, Tang, Rasco, Kong, & Wang, Dielectric properties of salmon fillet as a function of temperature and composition, 2008). But in this study only the middle portion of salmon fillet was used. Frozen salmon fillet with thickness of 16±2 mm were thawed in a 4°C refrigerator for about 10-12 hours. In preparing samples (a), 100±10 grams of salmon fillets (initial weight of salmon fillet used for every sample were recorded) were placed inside a Printpack™ pouch, vacuum sealed with pressure setting of -0.85 bar. With this sealing condition the estimated residual air were 3.5±0.5 cm³. In preparing samples (b), 100±10 grams of salmon fillet was immersed in 30±10 grams of Bertolli™ Alfredo sauce (i.e., 7:3 ratio) then placed in Printpack™ pouch and vacuum sealed in a condition similar to sample (a). Adequately thawed salmon fillet was used as samples (c) without any further treatment. Mettler-Toledo™ precision balance (model MS3002S, Mettler-Toledo Inc., 1900 Polaris ParkWay, Columbus, OH 43240 USA) was used to measure the necessary weight of salmon fillet samples.

2.4. Precooking treatment on samples

Pre-cooking treatment consists of three levels of temperature (60°C, 70°C, and 80°C) and three levels of time (10 min, 20 min, and 30 min) (Table 1). In actual processing of food in MATS, a batch of pouches (i.e., consisting of not more than 48 pouches) were preheated in the preheating section of the MATS system at 70-72°C for 30 min before going through the series of
microwave cavities. These preheating conditions as well as the condition for denaturation of protein in salmon described in Bircan & Barringer (2002) were the basis for the selected levels of temperature and time. A well circulated water bath (Model WD02L11B, Polyscience, 6600 W. Touhy Avenue, Niles, Illinois, 60714 USA) maintained at the desired temperature was used to carry out the precooking treatment. After sample preparation, pouches of samples (a) were immediately treated (Table 1), however, for pouches of sample (b), to realize the marinating effect of Alfredo sauce in salmon fillet, contents were allowed to marinate for 10-12 hours before subjecting into precooking treatment (Table 1). Considering the combinations of temperature and time (3x3), nine pouches of samples (a), and nine pouches of samples (b) were prepared (Table 1). Precooked pouches were stored in a 4°C until it reached room temperature before dielectric property measurement. Pouches of samples at room temperature were opened and expelled water due to precooking and Bertolli™ Alfredo sauces were drained. Adhering moisture and Alfredo sauce on the surface of salmon fillet were removed using absorbent cotton tissue.

Table 1. Precooking treatment in sample pouches

<table>
<thead>
<tr>
<th>Pouch number</th>
<th>Precooking Temperature (°C)</th>
<th>Precooking Time (min)</th>
<th>Pouch number</th>
<th>Precooking Temperature (°C)</th>
<th>Precooking Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>10</td>
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<td>7</td>
<td>80</td>
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<td>16</td>
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<tr>
<td>8</td>
<td>80</td>
<td>20</td>
<td>17</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>30</td>
<td>18</td>
<td>80</td>
<td>30</td>
</tr>
</tbody>
</table>
2.5. Dielectric property measurement

The instrument used to measure dielectric property was Hewlett-Packard 8752C network analyzer (HP, 3000 Hanover St. Palo Alto, CA 94304). A double pipe heat exchanger type temperature test cell (Wang, Wig, Tang, & Hallberg, 2003b) with cylindrical inner diameter of 22 mm and height of 100 mm (Figure 1a) was used to ramp the temperature of the sample, approximately 1°C/min during dielectric property (DP) measurement. Oil bath manufactured by PolyScience Inc. (Model 9006, Polyscience, 6600 W. Touhy Avenue, Niles, Illinois, 60714 USA) was used as heat source for the test cell. High temperature polyurethane foam was used to insulate the test cell as well as the high temperature flexible hose that connects the test cell to the oil bath (Figure 1).

An Omega™ type T thermocouple (Model: TMQSS-032(*)-6, Omega Engineering, Inc., One Omega Drive Stamford, CT, 06907 USA) with sheath diameter of 0.8 mm and length of 152.4 mm was mounted through the center of the bottom flange of the test cell (Figure 1b). The thermocouple tip was inserted through the center of a cylindrical metal holder, which was pushed by a spring mechanism (Figure 1b). Thermocouple reading was monitored by a Barnant™ (Model: 600-1040, 28W092 Commercial Avenue, Barrington IL, 60010 USA) data logger. A high temperature silicone rubber o-ring was used to prevent leakage of expelled salmon juice and to ensure pressure seal.
Figure 1: Dielectric property (DP) measurement setup. Consist of computer, DP network analyzer, temperature data logger, oil bath, and test cell. The test cell setup consist of (a) double pipe heat exchanger, (b) spring mechanism, (c) high temperature and pressure DP coaxial probe.

The salmon samples were homogenized by chopping into fine pieces and was loaded at the top end of the test cell up to the brim. The DP sensor was then mounted at the top flange of the test cell with insertion depth of about 15 mm pushing the spring that held the cylindrical metal holder at the same distance. The spring compression of about 15 mm kept the food sample in contact with the DP sensor especially during volume contraction brought about by cook loss during heating (i.e., moisture drip losses to free space of the spring mechanism -Figure 1b). For the same purpose as with the bottom flange, similar type of o-ring was inserted between DP sensor flange and top flange of test cell.
The DP sensor used was a high temperature and pressure open-ended coaxial probe with diameter of 18.5 mm (Figure 1c) connected to a single port of the network analyzer through a high temperature coaxial wire. Two-stage calibration was performed before every DP measurement of each sample. The first stage is the calibration of network analyzer port set at single port transmission using open, short, and load standard calibrating cell. The second stage is the calibration of network analyzer with attached DP sensor at the port (i.e., through the metal coaxial wire). A metal block for shorting, air, and water at 25°C was used as standards for this procedure.

The network analyzer was set to scan dielectric property within a frequency range of 800 MHz to 1 GHz with step resolution of 1 MHz (i.e., total of 201 dielectric property readings for every triggering of measurement). Since this study was specifically designed for microwave heating at 915 MHz, a narrow scanning range was selected (i.e., 800 MHz to 1 GHz) to favor accuracy. When sample reached the desired temperature (i.e., 20°C, 40°C, 60°C, 80°C, 100°C, and, 120°C), a measurement was triggered. A plot of DP versus frequency (800 MHz - 1 GHz) was prepared for every temperature. Dielectric property at 915 MHz (i.e., dielectric constant and loss factor) was interpolated on DP-frequency plot.

2.6. Water Loss

To quantify percent water loss after precooking treatment on salmon fillet samples described in Section 2.4, cook loss equation described by Kong et al. (2007) was used.

\[
\text{cook loss} = \frac{\text{initial weight} - \text{precooked weight}}{\text{initial weight}} \times 100\% 
\]  

(2)

Before precooking, salmon fillet samples were weighed using Mettler-Toledo™ precision balance (model MS3002S) to obtain the initial weight. After draining the pouches and removing
the adhering moisture and Alfredo sauce on the surface of precooked salmon fillet, samples were reweighed to obtain the precooked weight.

2.7. Statistical analysis

The experimental design of the precooking treatment considered in this study is a full factorial of (i) precooking temperature (PTemp) with three levels (i.e., 60°C, 70°C, and 80°C), (ii) precooking time (PTime) with three levels (i.e., 10 min, 20 min, and 30 min), and (iii) marinating condition (MC) with two levels (i.e., salmon fillet without marination, and salmon fillet with marination in Alfredo sauce). The temperatures, to which the dielectric property was measured, with six levels (i.e., 20°C, 40°C, 60°C, 80°C, 100°C, and 120°C) were considered as blocking. Considering the factorial design with blocking, there were 18 unique combinations of treatments and each treatment has six dielectric property responses corresponding to six temperature levels on a block, giving a total of 108 responses (18x6). Since measurements of dielectric property were done in triplicate, the 108 responses were the means of three replicates. Generalized Linear Model (GLM) implemented in SAS™ was used to perform analysis of variance (ANOVA) of the experimental design, as well as the interaction among treatment factor. Furthermore, ADX™ function of SAS™ was used to conduct fit regression considering the main effect of PTemp, PTime, and MC as independent variables.

3. Results and discussion

3.1. Effect of precooking on dielectric constant

Table 2 summarizes the dielectric property at 915 MHz of salmon fillet as affected by precooking treatment. In general, dielectric constant decreases with temperature over the measured range from 20°C to 120°C (with $P$ value < 0.05) (Figure 2). The decreasing trend of
dielectric constant with temperature is expected for food that has moisture content of above 70% (w/w) (Ohlsson, Bengtsson, & Risman, 1974). This can be attributed to the Brownian movement, a basic property of water that is dependent on temperature (Risman P. O., 2009). Figure 2 describe the effect of precooking treatment in dielectric constant of salmon fillet for sample (a) and sample (b). The higher the precooking temperature, the lower would be the resulting dielectric constant (Figure 2). Similarly, the longer the precooking time, the lower would be the resulting dielectric constant (Figure 2). However, exception to this trend was observed, for salmon fillet of sample (a) and sample (b) treated at 80°C and 10 min (Table 2 & Figure 2). Salmon fillet samples treated to such condition show rapid decrease in dielectric constant at temperature beyond 70°C resulting in a lower value of dielectric constant than that of salmon fillet samples treated at 80°C-20 min and 80°C-30 min. The denaturation of the most heat labile protein component of salmon (i.e., actin) occurs at 76-77°C (Ofstad, et al., 1996). A precooking temperature treatment of 80°C will completely denature salmon protein if and only if all portions were uniformly heated. This is not the case in this study because the thickness of salmon used (i.e., 16±2 mm), considering its thermal property, would provide substantial amount of heat resistance making the middle portion of salmon fillet, with respect to its thickness, at a lower temperature (i.e., lesser than the precooking temperature treatment) at any time during precooking treatment. Therefore, a precooking temperature treatment of 80°C, would only result into partial denaturation of protein and the percent of denatured protein increases with precooking time treatment. Furthermore, protein denaturation is directly proportional to water losses (Bircan & Barringer, 2002). Water content in salmon directly affects the value of dielectric constant. Salmon treated at 80°C-10 min has the least percentage of denatured protein thus would have relatively low percent water losses as compared to salmon precooked at 80°C-
20 min and 80°C-30 min (Figure 4). Therefore, during dielectric constant measurement, when sample reach a temperature of 70°C, retained un-denatured protein during precooking treatment starts to denaturize causing excretion of moisture. The spring mechanism in test cell immediately separates excreted moisture through compression causing sharp decrease in dielectric constant.

Table 2. Mean* ± standard deviation of dielectric properties at 915 MHz for middle part of pink salmon fillet as affected by precooking condition and marination with Bertolli™ Alfredo sauce.

<table>
<thead>
<tr>
<th>Dielectric constant ((\varepsilon'))</th>
<th>Temp</th>
<th>Sample (a) salmon fillet alone</th>
<th>Sample (b) salmon fillet marinated in Bertolli™ Alfredo sauce</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Precooking Time (PTime)</td>
<td>Precooking Temperature (PTemp)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min</td>
<td>20 min</td>
</tr>
<tr>
<td>60°C</td>
<td>20</td>
<td>57.6±0.6</td>
<td>57.1±1.2</td>
</tr>
<tr>
<td>70°C</td>
<td>40</td>
<td>56.1±0.4</td>
<td>55.6±2.2</td>
</tr>
<tr>
<td>80°C</td>
<td>60</td>
<td>54.8±0.6</td>
<td>54.2±2.3</td>
</tr>
<tr>
<td>70°C</td>
<td>80</td>
<td>53.3±0.7</td>
<td>52.4±2.1</td>
</tr>
<tr>
<td>80°C</td>
<td>100</td>
<td>51.5±0.9</td>
<td>50.3±1.5</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
<td>49.9±1.2</td>
<td>49.1±1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loss Factor ((\varepsilon''))</th>
<th>Temp</th>
<th>Sample (a) salmon fillet alone</th>
<th>Sample (b) salmon fillet marinated in Bertolli™ Alfredo sauce</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Precooking Time (PTime)</td>
<td>Precooking Temperature (PTemp)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min</td>
<td>20 min</td>
</tr>
<tr>
<td>60°C</td>
<td>20</td>
<td>22.0±0.6</td>
<td>22.6±0.5</td>
</tr>
<tr>
<td>70°C</td>
<td>40</td>
<td>25.4±0.8</td>
<td>25.6±0.7</td>
</tr>
<tr>
<td>80°C</td>
<td>60</td>
<td>30.4±1.1</td>
<td>29.9±0.8</td>
</tr>
<tr>
<td>70°C</td>
<td>80</td>
<td>36.7±0.9</td>
<td>35.6±1.1</td>
</tr>
<tr>
<td>80°C</td>
<td>100</td>
<td>43.9±2.0</td>
<td>41.6±1.1</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
<td>48.9±3.6</td>
<td>48.2±1.7</td>
</tr>
</tbody>
</table>

* mean of at least 3 replicates
Figure 2: Surface plot of dielectric constant as a function of temperature at different precooking temperature and time treatment on sample (a) and sample (b)
For untreated salmon, at the start of dielectric constant measurement, all protein types were still intact. As temperature increased, dielectric constant decrease gradually until a sharp decrease in dielectric constant at temperature 45-50°C (Table 3), which is the denaturation temperature of myosin and collagen (Ofstad, et al., 1996). This is for the same reason that water is being expelled parallel to denaturation of protein. Although there is a significant percent difference in the measured dielectric constant at 915 MHz of untreated salmon fillet (i.e., at the middle part) by this study and those of Wang et al. (2008), similar trend between dielectric property-temperature relationships was observed.

Table 3. Mean* ± standard deviation of dielectric properties at 915 MHz for middle part of untreated pink salmon fillet (i.e., no precooking and marination)

| Temp | This Study* | Wang et al. (2008)* | % difference*
|------|-------------|---------------------|----------------
|      | ε' | ε'' | ε' | ε'' | ε' | ε'' |
| 20   | 59.8±2.1 | 24.5±0.4 | 57.0±0.6 | 22.8±1.2 | 4.7 | 6.9 |
| 40   | 58.6±1.9 | 27.5±0.6 | 55.6±1.0 | 28.1±2.7 | 5.1 | 2.2 |
| 60   | 56.6±2.3 | 32.0±0.7 | 53.7±1.7 | 34.8±4.2 | 5.1 | 8.7 |
| 80   | 54.2±2.2 | 36.4±0.7 | 51.5±1.1 | 40.7±4.2 | 5.0 | 11.8 |
| 100  | 51.8±2.1 | 41.3±1.1 | 50.8±1.9 | 49.0±7.4 | 1.9 | 18.6 |
| 120  | 50.5±1.8 | 47.3±1.4 | 50.7±2.9 | 60.4±11.7 | 0.4 | 27.7 |

*dielectric property from this study
b dielectric property from Wang et al. (2008) study
c % difference = (a-b/a)×100%
d dielectric constant
e loss factor

For the dielectric constant of sample (b) at 915 MHz with temperature (Figure 2), similar to sample (a), marinated precooked salmon fillet (i.e., marinated in Bertolli™ Alfredo sauce before precooking) exhibited lower dielectric property within temperature range of 20°C to 120°C as compared to untreated salmon (Figure 2 & Table 3). However, in comparison with sample (a), marinating salmon fillet in Alfredo sauce further lowers the dielectric constant-temperature curve. On the average, there is a 2.7% further reduction in dielectric constant measured in a temperature range of 20°C-120°C as a result of marination on all precooking
treatment conditions. Alfredo sauce used in this study has relatively low moisture content (approximately 60%-65% wb) and high salt concentration (approximately 0.75% wb) compared to salmon fillet. A marinating time of 10-12 hours is significant to cause osmotic dehydration effect on salmon fillet (Larrazabal-Fuentes, Escriche-Roberto, & Camacho-Vidal, 2009) driven by the net gradient in moisture and salt content between Alfredo sauce and salmon fillet. A point-by-point comparison of percent water loss between sample (a) and sample (b) indicates that marinating salmon fillet in Alfredo sauce indeed result into a higher percent water loss (Figure 4). On the average, the percent water loss in sample (b) is 16.7% higher than in sample (a).

3.2. Effect of precooking on dielectric loss factor

Table 2 shows the dielectric loss factor (LF) of sample (a) at 915 MHz. In general, the dielectric loss factor increases with temperature over the measured range of 20°C to 120°C with \( P \) value < 0.05 (Figure 2). The increase in dielectric loss factor with temperature is attributed to the dependency of ionic conductivity to temperature. At higher temperature, viscosity of foods generally decreases allowing more rigorous movement of ions resulting into overall increase in ionic conductivity (Tang, Feng, & Lau, Microwave heating in food processing, 2002). Furthermore, at temperature beyond 70°C, a reduction in of loss factor for untreated salmon occurred (Table 3) was observed. A temperature of 70°C is the denaturation temperature of most protein in salmon (Bircan & Barringer, 2002), a point of extensive moisture discharge, hence reduction of ions.

The effect of precooking treatment in sample (a) is an overall decrease in to loss factor (Figure 3). The percent decrease in loss factor is dependent on the severity of precooking treatment condition, that is the higher the precooking temperature time treatment combinations,
the lower would be the resulting loss factor. In reference to the untreated salmon loss factor there is a 3% reduction in loss factor after salmon fillet was treated at 60°C-10 min and further reduction of 7% and 2.3% for every 10°C increase in precooking treatment temperature (i.e., 70°C and 80°C) and 10 min increase in precooking treatment time (i.e., 20 min and 30 min), respectively. Since dielectric loss factor is mainly dependent on ionic conductivity at 915 MHz (Guan, Cheng, Wang, & Tang, 2004), an overall decrease in loss factor as affected by precooking treatment signifies reduction of ions in salmon fillet. During precooking treatment of salmon, there was a considerable percent water loss (Figure 4). In the case of sample (a), expelled water from salmon after precooking might carries ions possibly causing an overall decrease in ionic conductivity of salmon fillet.

In sample (b) however, marination of salmon fillet in Alfredo sauce before precooking treatment alters the ionic conductivity and fat content of salmon fillet resulting into irregular pattern of loss factor at different precooking treatment conditions (Figure 3). Even though most of the Alfredo sauce adhering to the surface of salmon fillet was removed after precooking treatment, small amount of Alfredo sauce can still remain causing variable change in fat and ion content of the homogenized salmon sample for dielectric property measurement. In comparison with untreated salmon fillet, loss factor of sample (b) beyond 85°C, considering all precooking conditions, were all higher (Figure 3 & Table 2). This means that total ionic content in sample (b) increases because of marination. The effect of increase in fat content is a decrease in loss factor (Gunasekaran, Mallikarjunan, Eifert, & Sumner, 2005). Although not quantified in this study, the increase in loss factor due to increase in ionic content is greater than the decrease in loss factor due to increase in fat content as evident by the overall increase of loss factor in comparison with that of untreated salmon.
Figure 3: Surface plot of loss factor as a function of temperature at different precooling temperature and time treatment on sample (a) and sample (b)
Figure 4: Water loss or cook loss in salmon fillet at different precooking temperature (60°C, 70°C, and 80°C) and precooking time (10 min, 20 min, and 30 min). Sample (a) drawn in solid line are salmon fillet alone and Sample (b) drawn in broken or dash line are salmon fillet marinated in Bertolli™ Alfredo sauce.

Although the overall effect of marination of salmon fillet in Alfredo sauce is an increased in loss factor at temperature range of 20°C to 120°C, the result is difficult to correlate with the precooking treatment. This is because the dominant factor that influence change in loss factor is not the loss of moisture during precooking but rather the unavoidable traces of Alfredo sauce left at the surface of the salmon fillet after marination. The amount of Alfredo sauce that adheres to the surface of the salmon before precooking is difficult to control and quantify, and is
independent on precooking condition. Furthermore, the increase in ions and fat content due to the adhering Alfredo sauce after marination has counteracting effect on loss factor.

### 3.3. Penetration depth

For sample (a), the depth of penetration ($D_p$) correlates well with pre-cooking temperature and precooking time. This is because (1) dielectric constant has a good correlation with loss of moisture, and (2) no additional source of ions and fat (i.e., since sample (a) is not marinated) which may influence the loss factor, therefore, loss factor in sample (a) is only affected by the decrease of ions that goes with the expelled water during moisture loss. In general, precooking increases the $D_p$ of sample (a) (i.e., salmon fillet without marination) (Figure 5). The higher the precooking temperature and the longer the precooking time, the longer would be the penetration depth of microwave at 915 MHz in unmarinated precooked salmon fillet from temperature range of 20°C to 120°C. Furthermore, $D_p$ of microwave at 915 MHz in sample (a) is longer than in untreated salmon fillet. On the average, depending on severity of precooking treatment in salmon fillet, precooking treatment can increases the $D_p$ of microwave at 915 MHz in salmon fillet to up to 2 mm in comparison with untreated salmon fillet.

For sample (b), since marination provides additional source of ions and fat that may influence loss factor in a contrasting manner, the trend in $D_p$ with respect to precooking temperature and precooking time treatment is difficult to conclude. However, comparing sample (b) with untreated salmon, the former, in general, has lower microwave $D_p$ at 915 MHz (Figure 5). It can therefore be concluded that although precooking treatment of salmon fillet can increase $D_p$ of microwave at 915 MHz to up to 2 mm, marinating salmon fillet before precooking treatment would result into a 3 mm to 4 mm decrease in $D_p$, bringing the $D_p$ of sample (b) lower than in untreated salmon (Figure 5).
Figure 5: Depth of penetration of microwave at 915 MHz on treated salmon fillet at temperature of 20°C, 40°C, 60°C, 80°C, 100°C, 120°C in comparison with fresh salmon fillet. Data presented are main effect of marinating condition on salmon fillet. These means average dielectric property for different precooking temperature and time treatment for sample (a) and sample (b) were the basis for calculating depth of penetration.

3.4. Model fitting

The SAS 9.2 ADX™ interface for the design and analysis of experiment was used to conduct a Response Surface Methodology (RSM) to obtain a fit regression on the factors that may influence dielectric property of salmon fillet. The factors considered are marinating condition (MC), precooking temperature treatment (PTemp), precooking time treatment (PTime), and temperature of salmon fillet (Temp) as the independent variables, and dielectric constant, and dielectric loss factor as the response. The following equations are the predictive fit regression
model for both dielectric constant ($\varepsilon'$) and dielectric loss factor ($\varepsilon''$) as a function of $MC$, $PTemp$, $PTime$, and $Temp$;

$$\varepsilon' = 69.82102 + 1.345075(MC) - 0.210386(PTemp) - 0.068448(PCTime) - 0.056649(Temp)$$  \hspace{1cm} (3)

$$\varepsilon'' = 30.24607 - 4.888236(MC) - 0.152827(PTemp) - 0.088581(PCTime) + 0.263158(Temp)$$  \hspace{1cm} (4)

where $MC = 1$ if no marination done on salmon fillet (e.g., sample a) and $MC = 0$ if salmon fillet has been marinated before precooking (e.g., sample b). The range of $PTemp$, $PTime$, and $Temp$, are 60°C to 80°C, 10 min to 30 min, and 20°C to 120°C, respectively.

Figure 6: Comparison of measured dielectric property and predicted dielectric property for (a) dielectric constant using Equation 3, and (b) loss factor using Equation 4.

Measured dielectric property was compared with the predicted dielectric property generated using the predictive fit regression model (i.e., Equations 3 and 4). Result shows that for dielectric constant, values generated using Equation 3 in comparison with measured dielectric
constant gave a root mean square error (RMSE) of 0.923 and the coefficient of determination ($R^2$) of 90.18%. The value of 0.923 for RMSE suggests that Equation 3 would give a dielectric constant close to the measured dielectric constant with only up to 1.830 coefficient of variation (Figure 6a). However, relative to unity, the dielectric constant that can be generated using Equation 3 is somewhat spread (Figure 6a) as indicated by a relatively low $R^2$. For a predictive fit regression model with four independent variables, a value of 90.18% for $R^2$ is a good indicator of the relative accuracy of the Equation 3. For loss factor, RMSE and $R^2$ values are 2.01 and 95.85% respectively. Relatively higher value of RMSE suggests that the generated loss factor using Equation 4 may deviates to the measured loss factor to up to 5.952 coefficient of variation. This is specifically true for loss factor ranging from 26 to 46 from which most of the predicted values are higher than the measured value (Figure 6b). The overall fit to unity ($R^2 = 95.85\%$) of Equation 4, however, is better than Equation 3.

4. Conclusions

The dielectric properties at 915 MHz of pink salmon fillet ($Oncorhynchus gorbuscha$) were measured at temperature range of 20°C to 120°C. The effect of precooking treatment on salmon fillet were determined and the following conclusions were derived:

- For unmarinated salmon, the higher the precooking temperature and time treatment combinations, the lower would be the resulting dielectric constant and loss factor- within 20°C to 120°C range,

- Marinating salmon fillet in Alfredo sauce before precooking treatment causes further reduction of up to 2.7% in dielectric constant. Furthermore, since considerable amount of Bertolli TM Alfredo sauce retains in the surface of salmon fillet after marination, adhering
salt and fat from Alfredo sauce cause an overall increase in loss factor within 20°C to 120°C range,

- For the penetration depth of microwave at 915 MHz in salmon fillet, the higher the precooking temperature and time treatment, the longer would be the penetration depth for unmarinated salmon fillet (i.e., up to 2 mm increase in $D_p$ of microwave at 915 MHz in reference to the $D_p$ of untreated salmon). Penetration depth of microwave at 915 MHz is affected by adhering Alfredo sauce on the surface of salmon fillet after marination. However, no conclusion was made since the amount of salt and fat from Alfredo sauce that may adhere varies and is independent on precooking treatment conditions.

- A predictive fit regression model for dielectric constant and loss factor as a function of marination, precooking temperature, precooking time, and temperature were proposed. The RMSE of the predictive fit regression model for dielectric constant and loss factor were 0.923 and 2.01 respectively.

5. References


CHAPTER SEVEN

INFLUENCE OF DIELECTRIC PROPERTIES OF SALMON FILLET IN ALFREDO SAUCE ON MICROWAVE HEATING IN MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEM

Abstract

A previously validated computer simulation model was used to evaluate the influence of dielectric property on microwave heating of salmon in Alfredo sauce packed in an 8-oz flexible pouch when processed in a four-cavity microwave assisted thermal sterilization (MATS) system. Heating patterns in salmon fillet and heat penetration at the cold spot were examined to quantify the influence of dielectric property of salmon fillet. Heating pattern and location of cold spot were obtained through: (1) a computer vision method based on chemical marker M-2 using whey protein gel (WPG) as a model food for salmon fillet and (2) a computer simulation model. A heat penetration test at the identified cold spot was conducted through direct temperature measurement. Since dielectric properties (DP) of WPG, within a temperature range of 20°C and 120°C, deviated from that of salmon fillets up to 22% considering inherent and disparity variation in DP, complete matching of DP between salmon fillet and WPG is difficult to achieve. It was, therefore, necessary to determine the effect of both inherent and disparity variation in DP in model food (WPG) and the real food (salmon fillet) in terms of heating patterns and stability of the locations of the cold spots. This was achieved by varying the DP of salmon in MATS-CSM, i.e., adding or subtracting 10%, 30% and 50% on DP of salmon at every temperature point. The objective of this study was to select and evaluate a suitable whey protein gel (WPG) formulation as model food for salmon. Selected WPG was then used to determine heating pattern
and location of cold spot. Results were verified through computer simulation modeling considering the effect of variation in DP of salmon on heating pattern and location of cold spot.

1. Introduction

1.1. Background

Recent Food and Drug Administration (FDA) acceptances of filing of new microwave sterilization processes for mashed potato in 10 oz trays and salmon fillets in Alfredo sauce in 8 oz pouches has encouraged the food industry to explore commercial application of microwave sterilization for production of low acid shelf stable foods (Brody, 2011). The system used for sterilization of both mashed potato and salmon in Alfredo sauced is the microwave assisted thermal sterilization (MATS) system located at Washington State University (WSU). Several challenges encountered in sterilization of foods using MATS include: (a) characterization of heating pattern in foods; (b) establishing methods for identification of cold spot, and heat penetration at the cold spot; (c) matching the dielectric property of actual food to model food (Tang J., 2005); and (d) characterization and control of electromagnetic (EM) field distribution inside the cavities of MATS and within the food samples (Ramaswamy & Tang, 2008).

The characterization of EM field distribution in MATS is critical since it directly translates to the heating pattern in foods, which in turn is vital in mapping the correct location of the cold spot (Tang & Chow Ting Chan, 2007). Major contributing factors that dictate EM field distribution in foods during microwave sterilization processes include the dielectric property of material (dielectric constant and loss factor) (Tang J., 2005), and the design of the cavities (Tang & Chow Ting Chan, 2007). For a more predictable and stable EM field distribution, MATS was designed to operate in a single-mode (i.e., only one, or few resonant modes or pattern in a small well-defined volume). The design of MATS also incorporates polymeric slabs strategically
placed on the side walls of the cavity. Changing the dimension of the polymeric slabs (i.e., thickness and length) provides control of the EM field distribution inside the cavities of the MATS (Chen, Tang, & Liu, 2008).

The contribution of dielectric property of food to heating pattern, however, is not straightforward due to its dependency on temperature (Wang, Tang, Rasco, Kong, & Wang, 2008). A study conducted by Bengtsson et al. (1971) on measurement of different food materials suggests that at 2.8 GHz the dielectric property above the freezing point in general decreases with temperature except for cooked ham, which is high in salt content. In this study, the food used consisted of a solid and a viscous liquid. The salmon fillet as the solid was located at the center of the package, and around the edge was the Alfredo sauce as the viscous liquid packed together in one flexible 8oz pouch. It was expected that since salmon fillet has different composition from Alfredo sauce, the temperature response of dielectric properties of the two materials would be different. Furthermore, even for the same species of salmon, inherent variations in dielectric properties with temperature were still present (Wang, Tang, Rasco, Kong, & Wang, 2008). In fact, the dielectric property at 915 MHz of pink salmon considered in the study of Wang et al. (2008) had up to ±13 and ±8 standard deviation among replicates in dielectric constant and loss factor, respectively. Inherent variation in dielectric properties among samples in the same species of salmon can be attributed to: (1) different composition of the different parts of the salmon anterior, middle, tail, and belly part (Wang, Tang, Rasco, Kong, & Wang, 2008); (2) size, gender, sexual maturity and fecundity, diet, time of year, and water temperature and salinity to where salmon grew (Weatherly & Gill, 1987); (3) length of storage of salmon (it has been observed that frozen salmon after thawing loses considerable amount of moisture as compared to untreated unrefrigerated salmon) (Sathivel, 2005); (4) pre-processing of
salmon fillet (in this study salmon fillet in Alfredo sauce packed in flexible pouch was precooked to 70-72°C for 30 min before processing) (Kong, Tang, Lin, & Rasco, 2008); and (5) accuracy of calibration of instruments for measuring dielectric property.

Another challenge in processing food in MATS is the proper selection of a model food to locate the cold spot of the real food system. In this study whey protein gel was used as a model food for salmon fillet (Wang, et al., 2009). Heating pattern and cold spot was determined through a chemical marker method (Pandit R. B., Tang, Mikhaylenko, & Liu, 2006); (Pandit R. B., Tang, Liu, & Mikhaylenko, 2007). Although a disparity variation between the dielectric property of WPG and salmon fillet is unavoidable, the use of a model food, specifically whey protein, to identify heating pattern and location of cold spot has proved to be a reliable method (Guan, Liu, Tang, Pandit, & Pathak, 2003; Pandit R. B., Tang, Mikhaylenko, & Liu, 2006); therefore, a similar technique was utilized in this study.

1.2. Literature gap

Wang et al. (2009) outlined the different considerations for proper formulation and selection of whey protein gel (WPG) as a model food for salmon fillet (Oncorhynchus gorbuscha). However, the selection criteria used by the authors only considered matching the mean dielectric property of salmon and WPG at wide range of frequency (e.g., 27 MHz to 1800 MHz). Model food should not only match dielectric property of the actual food, but also thermal and physical properties. Furthermore, selection of model food should be frequency specific since one formulation might work at one frequency but not at another. Also, in the selection process of the said study, inherent variations among replicates in dielectric property of salmon and WPG were not considered. Finally, to conclude whether the selected formulation of WPG is a good model food for salmon fillet, a comparison of heating pattern and location of cold spot between
the selected WPG (i.e., through chemical marker method) and a computer simulation model that examines variation in dielectric property of salmon fillet should be conducted.

Computer simulation models for coupled electromagnetic and heat transfer are a widely acceptable tool for determining heating pattern and cold spot, which is necessary for process calculation in sterilization of foods (Celuch, Soltysiak, & Erle, 2011; Celuch & Kopyt, 2009; Chen, Tang, & Liu, 2008; Geedipalli, Rakesh, & Datta, 2007; Kopyt & Celuch, 2004; Zhao, Turner, & Torgovnikov, 1998). In this study a microwave assisted thermal sterilization computer simulation model (MATS-CSM) was used to validate heating pattern and location of cold spot determined using WPG through chemical marker method. Furthermore, MATS-CSM was used to determine the effect of inherent variation among replicates in dielectric property of salmon fillet. Varying the dielectric property of salmon fillet experimentally to a desired level is virtually impossible without affecting other properties of food (i.e., thermal, chemical, and physical properties), but can be done easily through computer simulation. No previous study has been conducted on the effect of varying the dielectric property of salmon fillet to the heating pattern and location of cold spot in relation to processing using MATS at 915 MHz.

1.3. Objectives

The general objective of this study was to study the possibility of using appropriate WPG formulations as model food for reliably identifying heating pattern and location of cold spot in salmon fillet in Alfredo sauce packed in 8 oz. flexible pouches processed in MATS at 915 MHz, and to verify the result using MATS-CSM considering the effect of inherent variation in dielectric properties of salmon fillet on heating pattern and location cold spot. The specific objectives of this study were:
• To select the appropriate whey protein gel (WPG) formulation to match the dielectric property of salmon fillet and at the same time be physically suitable for processing in MATS
• To established the dielectric property of salmon fillet and Alfredo sauce considering the processing condition in MATS (food samples were preheated in the preheating section to have a uniform initial temperature of 70-72°C)
• To determine the heating pattern and location of cold spot through a chemical marker method using the selected WPG formulation
• To utilize MATS-CSM to determine the effect of inherent variation in dielectric property of salmon in heating pattern and location of cold spot considering the processing condition of MATS
• To compare the heating pattern and location of cold spot determined by a chemical marker method using selected WPG formulation with heating pattern and location of cold spot determined by MATS-CSM
• To verify the real cold spot through heat penetration test if a discrepancy exists between the location of cold spot determined by chemical marker method and MATS-CSM

2. Methodology

2.1. Materials

A pink salmon fillet (*Oncorhynchus gorbuscha*) provided by Ocean Beauty Seafood (OBS-1100 West Ewing St. Seattle, Washington, 98119 USA) was used in this study. The middle part of the fillet from a deboned Alaskan wild pink salmon was packed and heat-sealed in a polyethylene (PE) plastic pouch, deep frozen in an individually quick frozen (IQF) freezer to about -31°C before shipping to Washington State University (WSU), Pullman WA. The received
salmon shipment was then temporarily stored in a freezer at about -30°C. The sauce used in this study was a commercially available Bertolli™ traditional Alfredo sauce (Unilever United States, Inc., 800 Sylvan Avenue, Englewood Cliffs, NJ 07632). The packaging material used was provided by Printpack, Inc., (2800 Overlook ParkWay, NE Atlanta, GA 30339). The packaging was in the form of flexible pouch of double layer flat rectangular shape specifically designed for the purpose of microwave sterilization. The laminate film consisted of: (1) polyethylene terephthalate (PET), (2) barrier-coated PET, (3) nylon, and (4) polypropylene (PP) held together by a polymer adhesive. Each pouch was 160 x 110 mm and heat sealed on three sides. Whey protein gel (WPG) was used as the model food for this study. The WPG contained water, salt, D-ribose, and whey protein isolate (WP392 and WP895) (Table 1). For heat penetration tests, Ellab™ sensors (Ellab Inc., 6551 South Revere ParkWay, Suite 145, Centennial CO 80111, USA) mounted on an Ultem™ polymeric frame was used; Ultem-1000 by Plastic International (7600 Anagram Drive, Eden Prairie, MN 55344).

2.2. Sample preparation

Salmon in Alfredo sauce packed in flexible pouch was prepared by first thawing the frozen salmon for approximately 2-3 hours in a refrigerated condition at about 5°C. The middle portion of salmon fillet was cut with a kitchen knife to approximately slab shape of 84×127×16 mm dimension. Each slab was approximately 162±5 grams. Concurrently, 65±1 grams of Alfredo sauce was weighed using a Mettler-Toledo™ precision balance (model number MS3002S) with readability of up to 0.01 grams, and placed directly into the pouch through the unsealed side. Then the slab of salmon was carefully slipped through the same opening of the pouch, making sure there was no, or minimal damage to the flesh of the salmon. The salmon to Alfredo sauce ratio inside the pouch was approximately 7:3. The open side of the flexible pouch
was heat sealed on a vacuum sealer under a vacuum pressure pull of -85 kPa. The estimated residual air for the sealing condition was approximately 3.5±0.5 cm$^3$. Typical processing of food pouches in MATS requires preheating of food pouches in the preheating section of MATS at 72°C for 30 min to have a uniform initial temperature. To replicate this condition for dielectric property measurement, prepared pouches of salmon in Alfredo sauce was preheated in a water bath at 72°C for 30 min.

Typical preparation of whey protein gel (WPG) was in a batch of 1000 grams of WPG solution (Table 1 shows the different formulations of WPG solution). Distilled water in a 2-Kg capacity glass beaker at room temperature was placed on top of a magnetic stirrer. As soon as vortex appeared, salt and D-ribose (pre-weighed based on 1000kg solution) was added first among other ingredients, since these components easily dissolve in water. WP-392 and WP-895 are hydrophobes, and therefore, easily agglomerate upon contact with water. To prevent too much agglomeration, a pre-weighed amount of whey protein isolate based on 1000 grams WPG solution was added into the stirring water little by little. The resulting WPG solution was allowed to stir for 1.5 hours to completely dissolve the whey protein isolate. It was found that excessive stirring however, can incorporate micro bubbles into the solution. The presence of micro bubbles in WPG solution, if not removed before solidifying the solution, can alter the dielectric property of WPG and is therefore undesirable. To remove the bubbles, WPG solution was allowed to stand for about 12 to 15 hours (typically overnight) in a refrigerated condition of 5°C. Rexam™ (710 West Park Rd., Union, MO 63084); 8 oz. rigid polymeric trays were used as molders in solidifying micro-bubble-free WPG solution. An amount of 165±1 grams of WPG solution was poured into a Rexam™ tray and then partially submerged, making sure that no water from the water bath will mixed with the WPG solution, into a preheated water bath at 70°C for 40 min to
allow solidifying. Solid WPG were then allowed to cool for about 10 min before storing in a refrigerated condition at 5°C.

Table 1. Formulation for whey protein gel to match the dielectric property of pink salmon fillet

<table>
<thead>
<tr>
<th>Formulation</th>
<th>Water, %</th>
<th>Salt, %</th>
<th>D-ribose, %</th>
<th>WP 392, %</th>
<th>WP 895, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample 1 (S1)</td>
<td>75.4</td>
<td>0.3</td>
<td>1</td>
<td>18.2</td>
<td>5.1</td>
</tr>
<tr>
<td>sample 2 (S2)</td>
<td>75.4</td>
<td>0.6</td>
<td>1</td>
<td>18.0</td>
<td>5.0</td>
</tr>
<tr>
<td>sample 3 (S3)</td>
<td>75.4</td>
<td>0.8</td>
<td>1</td>
<td>17.8</td>
<td>5.0</td>
</tr>
<tr>
<td>sample 4 (S4)</td>
<td>76.0</td>
<td>0.6</td>
<td>1</td>
<td>17.5</td>
<td>4.9</td>
</tr>
<tr>
<td>sample 5 (S5)</td>
<td>77.0</td>
<td>0.6</td>
<td>1</td>
<td>16.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>

2.3. Dielectric and thermal property measurement

A Hewlett-Packard 8752C network analyzer was used to measure dielectric property (DP) following the procedure described in Wang et al. (2003b). The dielectric property system (Figure 1) consisted of (a) a double pipe heat exchanger test cell connected to a silicon oil bath (Model 9006, Polyscience, 6600 W. Touhy Avenue, Niles, Illinois, 60714 USA), (b) a spring mechanism that keeps the food sample in contact with the coaxial probe and which contains the thermocouple system, and (c) a mounting flange that holds the high the temperature -pressure coaxial probe in place. A high temperature silicon O-ring was placed at the flanges of the test cell to prevent leakage during measurement. Furthermore, the network analyzer was interfaced into a computer for digital recording and storage of dielectric property data.

The network analyzer was calibrated and was set to scan DP within a frequency range of 1 MHz to 3 GHz with 201 data points for every triggering of measurement. Dielectric property measurement was triggered when the temperature of the sample reached a steady state temperature of 20°C, 40°C, 60°C, 80°C, 100°C, and, 120°C, respectively. Dielectric properties at 915 MHz were collected since MATS operates at this frequency. Dielectric property of salmon fillet was compared alongside the DP of different WPG formulation for matching purposes.
Figure 1: Dielectric property (DP) measurement setup consisting of computer, DP network analyzer, temperature data logger, oil bath, and test cell. The test cell setup consists of: (a) double pipe heat exchanger, (b) spring mechanism, (c) high temperature and pressure DP coaxial probe.

To prepare samples of salmon and WPG for dielectric property measurement, pouches of salmon and solidified WPG on trays prepared as described in Section 2.2 were equilibrated to room temperature for about 30 min. After opening each pouch of salmon, Alfredo sauce was drained and the remaining adhering Alfredo sauce on the surface of salmon was wiped with cotton tissue. Several sample cylinders were cut from salmon fillet using a cylindrical metal puncher with inner diameter similar to the inner diameter of the double pipe heat exchanger test cell (22 mm). Sample cylinders were stacked inside the test cell to a height of approximately 6 to 8 cm sufficient to retain compression between the coaxial probe and the spring mechanism. A
similar procedure was followed in preparing sample cylinders for WPG for dielectric property measurement.

Thermal properties of salmon fillet, Alfredo sauce, and different formulations of WPG were measured using Decagon™ KD2-pro (Decagon, WA, USA). Salmon fillet and WPG, as prepared in Section 2.2 and commercially available Bertolli™ Alfred sauce were used. Specific heat and thermal conductivity were measured using the double needle method (Campbell, Calissendorff, & Williams, 1991). Enthalpy was calculated by taking the product of specific heat, density, and temperature change considering 70°C as the reference temperature (QWED, 2009). Since the contribution of density difference is minimal, specifically in finding the solution of coupled electromagnetic-heat transfer phenomena, the density of salmon fillet, Alfredo sauce, and WPG were all assumed to be approximately equal to that of water (1.00 g/cm³). This assumption is valid since, in general, salmon fillet, Alfredo sauce, and WPG have relatively high moisture content (>80% wet basis).

2.4. Texture analysis

Besides matching the dielectric property of salmon, the handling properties of WPG were considered as well. Ideal handling properties of WPG include: (1) ease of cutting without breaking, (2) crumbliness, and (3) water syneresis. All desired handling properties of WPG were related to its texture. Several studies show that the texture of WPG deteriorates through time during storage (Pandit R. B., Tang, Liu, & Mikhaylenko, 2007), so the age of WPG samples were also considered in this study. To qualitatively examine the texture of WPG, a texture analyzer by Stable Microsystem™ (TA-XT2i) with 50 mm aluminum round probes was used. The experimental design includes: (Group 1) - Samples prepared and stored for two weeks; and (Group 2) - Freshly cooked samples. Sample cylinders of WPG prepared using a cylindrical
metal puncher with height and diameter equal to 2 cm and 2.2 cm, respectively, were subjected to a compression force until its height was reduced to 50%. Texture analysis through compression of different formulation of WPG belonging to Group 1 and Group 2 were tested in three replicates and the physical characteristics of compressed WPG were then analyzed.

2.5. Selection of appropriate formulation of whey protein gel as model food for salmon fillet

Based on the measured dielectric property in Section 2.3, a match between salmon fillet and the different formulation of whey protein gel (WPG) as described in Section 2.2 was conducted. The selection criteria among different formulations of WPG (Table 1) was the disparity variation between DP of WPG and salmon fillet or the closeness of dielectric constant and loss factor of different WPG formulations to the dielectric constant and loss factor of salmon fillet. We also considered the inherent variation in DP among measurement replicates of different formulation of WPG and of salmon fillet, and the texture of WPG prepared from different formulations.

It is apparent that regardless of which formulation of WPG was selected, a disparity variation or a certain degree of difference between the dielectric property of salmon fillet and the selected WPG exists over a temperature range of 20°C to 120°C. To this end, it is important to identify the limit of allowable degree of difference. The limit should satisfy insignificant difference in heating parameters (i.e., heating pattern and location of cold spot) between salmon fillet and WPG. To identify the limit, a sensitivity study was conducted to examine the influence of varying the dielectric property of salmon fillet on heating parameters. The heating parameters in WPG were obtained by processing several samples of WPG using MATS and analyzing the end product through chemical marker method utilizing computer vision technique. For
determining the heating parameters in salmon fillet, actual variation in dielectric property to a certain degree is not possible without affecting its physical and thermal properties. However, virtual variation is possible in MATS-CSM. In MATS-CSM, dielectric, physical, and thermal properties of materials are assigned independently. Therefore, variation in dielectric properties of salmon fillet in MATS-CSM will not affect its physical and thermal properties.

2.6. Heating pattern and location of cold spot of the selected whey protein gel

To experimentally determine heating pattern and location of cold spot for the selected formulation of WPG, several pouches for each formulation were processed in MATS. In the sample preparation, a slab shape WPG with dimension 84 mm × 127 mm × 16 mm (i.e., x, y, and z respectively) with weight comparable to that of salmon fillet (162±5 grams) was packed in a flexible pouch together with 65±5 grams of Alfredo sauce. Since WPG thickness can also be a factor that might influence heating parameters, a 12 mm, and 14 mm thickness of the selected WPG was also prepared. Five sample pouches representing five replicates for each thickness of the selected WPG were prepared. A total of 15 pouches of the selected WPG formulation in Alfredo sauce packed and sealed (see Section 2.2) in a flexible pouch were processed in MATS.

Pouches of WPG were loaded into the preheating section of MATS and preheated to 72°C for 30 min. During preheating, generators powering the four cavities of MATS were warmed up to the desired power output (6.40 kW, 5.56 kW, 2.51 kW, and 2.59 kW for generators 1, 2, 3 and 4, respectively) until steady state. Also, circulating water inside the cavities and the adjacent holding section was preheated to 122°C at 234.4 kPa. Cooling water in the cooling section was maintained at 15°C to 20°C. After 30 min of preheating, a mesh belt carrying the pouches of WPG in Alfredo sauce were moved at a speed of ~1m/min across the heating section and holding section of the MATS. The residence time of pouches inside the
heating section was 3 min. Pouches were held in the cooling section for 5 min to lower the temperature. The operating pressure of the MATS was then brought to ambient condition and pouches were safely retrieved through the cooling section door.

Alfredo sauce was drained after opening the pouch and the slab of WPG was wiped with cotton tissue to remove any adhering Alfredo sauce. The slab of WPG was cut in the middle along its thickness using a knife and a spacer with a height of 8 mm (i.e., half the height of the WPG, which is 16 mm), ensuring that the knife would cut the WPG exactly at the middle. For 12 mm and 14 mm thickness WPG, 6 mm and 7 mm spacers were used, respectively. Heating pattern and the location of cold spot of the cut surfaced were analyzed using the computer vision method described in the study of Pandit et al. (2007). Furthermore, slabs of WPG were cut along longitudinal length (y direction) perpendicular to z direction (i.e., perpendicular to its thickness). Three cuts were made starting from the third part of the WPG length along x direction (Figure 9; S2-1; xy; 12 mm thickness). The heating pattern of the three sections showing surfaces along the WPG thickness were also analyzed using the computer vision method.

2.7. Microwave assisted thermal sterilization-computer simulation model (MATS-CSM)

The MATS-CSM used in this study focused only on the heating section of MATS (Figure 2). The transmitted microwave energy injected in each cavity (port of injection is illustrated in Figure 2 a) was equal to the incident microwave energy less the reflection. Incident and reflected microwave energy were measured using directional couplers manufactured by Ferrite Microwave, Inc. (165 Ledge Street, Nashua, NH 03060). Since there were two ports for every cavity, each port was set to half of the transmitted energy on that cavity. The transmitted microwave energy for cavities 1, 2, 3, and 4 were 6.40 kW, 5.56 kW, 2.51 kW, and 2.59 kW, respectively.
Figure 2: Computer simulation model consisting of four microwave cavities and horn applicator. (a) Location of microwave input port; there are a total of eight ports in the model. (b) Direction of movement of pouch. (c) location of the pouch

The conformal finite-difference time-domain (FDTD) numerical method was used to obtain the solution for both electromagnetic and heat transfer phenomena (Chen, Tang, & Liu, 2008). FDTD simulation was implemented using commercial software by QWED™ (Warszawa, Poland 1132173057) called QuickWave™ (version 7.5 64 bits) on a computer workstation (HP Z800 workstation) (Hewlett-Packard, 3000 Hanover St. Palo Alto, CA 94304). In QuickWave™, the volume designated as lossy material requires assignment of its dielectric properties (dielectric constant, and loss factor expressed as effective conductivity) and thermal properties (specific heat, thermal conductivity, density, calculated enthalpy, and heat transfer coefficient between boundaries) as a function of temperature. Furthermore, the initial temperature of lossy materials was also assigned. For this study, four lossy materials were identified: (1) water which is the volume occupied by the four cavities; (2) salmon fillet; (3) Alfredo sauce; and (4) Ultem™ bars and windows. Ultem™ windows separates cavities from the horn since the volume of these parts are occupied by two different media: water in the cavities and air in the horn. Ultem™ bars
controls the electric field distribution in each cavity. The size and orientation of the Ultem™ bars were arranged in such a way that concentration of the electric field is maximum at the center, side, center, and then side with respect to the longitudinal orientation of the cavities on the first, second, third and fourth cavity, respectively (Figure 3). The alternate sequence of maxima of E-field in a series of four cavities resulted in a staggered heating pattern leading to a relatively uniform overall heating pattern. The initial temperature of water and all Ultem™ bars and windows was set at 123°C, while salmon fillet and Alfredo sauce was at 72°C. The materials for pouches were not considered in the model because: (1) pouches are practically a lossless material (Mokwena, Tang, Dunne, Yang, & Chow, 2009) and, (2) pouches offers minimal resistance to heat transfer between the water-salmon and water-Alfredo sauce interfaces.

![Figure 3: Electric field distribution on xy plane at middle z axis.](image)

The salmon fillet representation in the simulation model was a slab. The dimension of the fillet in the simulation model from edge to edge along the xy plane was 84 mm × 127 mm in x and y direction, respectively, and the thickness was 16 mm in z direction. The slab shaped salmon was embedded on a group of bi-phase objects representing Alfredo sauce. Alfredo sauce objects were composed of a slab, 89 mm × 132 mm × 18 mm in x, y, and z direction, respectively and four wedges attached to the four sides of the slab. The bases of all wedges were 18 mm in length attached to the 18 mm thickness sides of the slab. The length of two wedges on left and
right (in reference to the xy plane) was 33 mm and the two wedges on the top and the bottom (in reference to the xy plane) was 26 mm (Figure 4).

Since the slab representing salmon fillet was embedded in the group of objects representing Alfredo sauce, the volume occupied by salmon fillet superimposed equal volume in Alfredo sauce. Table 2 summarizes the final volume and the equivalent mass of salmon fillet and Alfredo sauce used in the simulation model in comparison with the filling weight of the actual pouches of salmon in Alfredo sauce used in the experiment. The volume and weight representation of salmon fillet and Alfredo sauce in the simulation model was within the limit of the target volume and weight of the actual food pouches. The average difference in volume and weight was only 4.5 cm$^3$ and 4.6 grams, respectively.

Table 2. Comparison of volume and weight between food pouch in simulation model and actual food pouches

<table>
<thead>
<tr>
<th>Food pouch representation in simulation model</th>
<th>Volume (cm$^3$)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alfredo Sauce</td>
<td>Salmon fillet</td>
</tr>
<tr>
<td>Alfredo Sauce</td>
<td>55.70</td>
<td>168.74</td>
</tr>
<tr>
<td>Salmon in Alfredo sauce packed in flexible pouch</td>
<td>58 ± 4.5</td>
<td>162±5.0</td>
</tr>
</tbody>
</table>
Figure 4: Salmon fillet in Alfredo sauce representation in computer simulation model showing different plane (xy, xz, and yz).

The size of the FDTD cell in the computer simulation was 3.8 mm x 4 mm x 1 mm along x, y, and z, respectively. Since there was a need for accuracy in heat transfer on the interface of surrounding water and surface of salmon fillet and Alfredo sauce in the simulation model, a mesh refinement was included on the edge of the food along xy plane. The cell size starting from the outer tip of the Alfredo sauce going inward 30 mm was refined to 2.5 mm and 2.0 mm along the x and y direction respectively (Figure 4). Since the cell along the z direction was already 1 mm, no further refinement was done along the thickness of the food. The total cell number for the simulation model was 10,657,920, which was 1281×80×104 on x, y, and z respectively.
From the illustration of the computer simulation model shown in Figure 2, food pouches (Figure 2-c), starting at the right side of cavity 1, moved along the length of the four cavities in the direction illustrated in Figure 2 b. Movement started after electromagnetic field distribution reached a steady state condition. In simulation, food pouches at an initial temperature of 72°C started to move along the heating section of MATS in a discretized step. This means that the total length the food had to travel was subdivided into several short heating time steps. More time steps are desirable since simulation accuracy increases with increasing number of simulation time steps, preventing the possibility of “thermal jump” (i.e., an abrupt increase in temperature of FDTD cell) (QWED, 2009). However, the larger the number of heating time steps, the longer would be the simulation time (QWED, 2009). Preliminary simulation using 16, 32 and 64 heating time steps showed that simulation time increased exponentially with the number of heating time steps. Furthermore, no significant difference was found from the result of heating pattern, and EM field distribution for 32 and 64 heating time steps. Therefore, in this study, the movement of pouch was discretized into 32 heating time steps. The total length the food pouch had to travel was 3092.7 mm (i.e., total length of the four cavities) with equivalent heating time of 180 s (3 min). This means that for a 32 discretized step movement, the food pouch traveled 96.6 mm (3092.7/32) for every step, and each discrete step was equivalent to 5.6 s (180/32) of heating time step.

2.8. Variation of dielectric property of salmon in MATS-CSM

Dielectric property of salmon fillet as a function of temperature used in MATS-CSM was modified based on the cases listed in Table 3. Every variation requires complete execution of simulation. Therefore, in this study, thirteen simulation runs were executed. Heating pattern, cold spot location, and heating rate and final temperature at the cold spot for every simulation run
were obtained. For the heating pattern, snapshots at the center of salmon fillet with respect to its thickness at the end of the 32\textsuperscript{nd} discretized step were reported. The cold spot was located by comparing the temperature color value of each cell representing salmon fillet at the end of the 32\textsuperscript{nd} discrete step. Location of the cell containing the lowest temperature color value was identified as the cold spot, and the equivalent temperature was the final temperature at the cold spot. The time-temperature history (temperature profile) of the identified cell in the cold spot was extracted by considering the temperature of the cell at all 32 steps. Instantaneous and average heating rate was calculated using the temperature profile data.

Table 3. Simulation case schedule for the variation of dielectric properties of salmon

<table>
<thead>
<tr>
<th>Dielectric property</th>
<th>Simulation Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Constant</td>
<td>50% Higher Dielectric Constant</td>
</tr>
<tr>
<td></td>
<td>30% Higher Dielectric Constant</td>
</tr>
<tr>
<td></td>
<td>10% Higher Dielectric Constant</td>
</tr>
<tr>
<td></td>
<td>Average Dielectric Property*</td>
</tr>
<tr>
<td></td>
<td>10% Lower Dielectric Constant</td>
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<tr>
<td></td>
<td>30% Lower Dielectric Constant</td>
</tr>
<tr>
<td></td>
<td>50% Lower Dielectric Constant</td>
</tr>
<tr>
<td>Loss Factor</td>
<td>50% Higher Loss Factor</td>
</tr>
<tr>
<td></td>
<td>30% Higher Loss Factor</td>
</tr>
<tr>
<td></td>
<td>10% Higher Loss Factor</td>
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<tr>
<td></td>
<td>Average Dielectric Property*</td>
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<tr>
<td></td>
<td>10% Lower Loss Factor</td>
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<tr>
<td></td>
<td>30% Lower Loss Factor</td>
</tr>
<tr>
<td></td>
<td>50% Lower Loss Factor</td>
</tr>
</tbody>
</table>

*Dielectric Constant and Loss factor of the middle part salmon (Table 2.1.1). Preparation of sample was described in Section 2.2 and measurement of dielectric property was described in Section 2.3.

Although only 10\%-30\% inherent variation in dielectric property in salmon fillet was recorded (Wang, Tang, Rasco, Kong, & Wang, 2008), a wider range of up to 50\% was considered in this study to accommodate unforeseen factors that might influence variation in
dielectric property of salmon. Furthermore, conducting a sensitivity study at a wider range would allow determination of the limit of allowable degree of difference between the dielectric property of salmon fillet and the selected formulation of WPG. For example, if 50% variation in dielectric property of salmon would result in insignificant changes in the location of cold spot, heating rate, and heating pattern, then the selected WPG formulation would still be a valid model food for salmon only if the degree of difference between the dielectric property of salmon fillet and WPG and the inherent variation acquired during measurement replication is within the 50% variation.

2.9. Quantification of sterilization value

One of the requirements of commercial sterilization of low acid food is the evaluation of sterilization value ($F_o$). In the United State, pertinent requirements for processing low acid food are summarized in 21 C.F.R. of the Food and Drug Administration (FDA). The goal of this part of the study was to evaluate the sterilization value of simulation cases (Table 3) and to compare the sterilization value of an actual sample of salmon fillet in Alfredo sauce packed in a flexible pouch processed in MATS. This would allow quantification of the effect of the variation in dielectric property of salmon to sterilization value. A general method for calculating sterilization value was used.

2.10. Verification of location of cold spot

The location of cold spot was verified by conducting heat penetration tests at the identified cold spot (1) by the chemical marker method on WPG, and (2) by the MATS-CSM using salmon fillet in Alfredo sauce packed in flexible pouch with Ellab™ sensor at the identified cold spot (Figure 5). Two portions of salmon fillet each half the thickness ($16 \text{ mm} / 2 = 8 \text{ mm}$) where placed on top of each other, sandwiching the Ellab™ sensor in the middle
(double layer salmon fillet). In Figure 5, P1 and P2 were identified as the cold spot of the selected WPG formulation, while P3 and P4 were the identified cold spot of MATS-CSM (coordinates were discussed in the Section 3). The Ellab™ sensor tips for P1 and P2 were placed equidistance to each other; one was on the left side and the other on the right. The distribution of electric field along xy plane was symmetrical (Figure 3). Therefore, heating pattern should be symmetrical. Although only one cold spot was identified, the corresponding point at a symmetrical location is expected to have only a few temperature degrees difference than the cold spot. A similar setup was done for P3 and P4. Two replicates were prepared for each location, totaling 8 sample pouches. Pouches were processed in MATS following the procedure described in Section 2.6.

![Diagram](image)

Figure 5: Salmon fillet in Alfredo sauce representation in computer simulation model showing different plane (xy, xz, and yz).

Sterilization value ($F_o$) was calculated for P1, P2, P3 and P4. The point that gave the lowest sterilization value among P1, P2, P3, and P4 was assumed to be the correct location of
cold spot on the assumption that the slowest heating point would accumulate the least lethality, hence, low sterilization value. The identified cold spot among P1, P2, P3 and P4 was further verified by measuring neighboring points. Figure 6 illustrates the verification procedure for the identified cold spot. A heat penetration was conducted approximately 5±1 mm offset from the location of the identified cold spot. This location was on: (1) the identified cold spot; (2) the left and right of the identified cold spot with respect to the xy plane; (3) top and bottom of the identified cold spot with respect of the xy plane; and (4) up and down of the identified cold spot with respect to the yz plane. For every location, three heat penetration replicates were conducted, requiring twenty one pouches of salmon in Alfredo sauce packed in flexible pouch and processed in MATS.

Figure 6: Verification for the correct cold spot. Four points with 5 mm offset on the identified cold spot in xy plane; and two points in yz plane.
2.11. **Statistical analysis**

A generalized linear model (GLM) implemented in SAS™ was used to perform analysis of variance (ANOVA) for replicates of dielectric property measurement, temperature measurement using Ellab™, and sterilization values. Furthermore, a 95% confidence level was considered in all statistical interpretations.

3. **Results and Discussions**

3.1. **Dielectric and Thermal property of Salmon fillet and Alfredo Sauce**

Tables 4 and 5 summarize the measured dielectric properties at 915 MHz and thermal properties of the middle part of salmon fillet and Alfredo sauce, respectively. Thermal properties of salmon fillet and Alfredo sauce were measured since they are essential input data for proper heat transfer solution in MATS-CSM. The dielectric properties of Alfredo sauce were utilized only for simulation purposes and were not considered in heating pattern and identification of cold spot in salmon fillet.

Dielectric properties were extrapolated up to 150°C based on the obtained data following the experimental design in Section 2.3 which was set only up to 120°C. Furthermore, for accuracy of computer simulation, an increment of 10°C was adopted. Therefore, data for salmon fillet and Alfredo sauce were interpolated at 10°C increments. Cubic spline or piecewise-polynomial approximation (Burden & Faires, 2005) was used to interpolate and extrapolate values from the DP-temperature curve. The standard deviation from the mean was ±0.69 to ±0.85 for dielectric constant, and ±0.09 to ±1.88 for loss factor of salmon. In this study, standard deviation was considered as the measure of inherent variation in dielectric property of salmon.
Table 4. Dielectric properties at 915 MHz and thermal properties of middle part of salmon

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dielectric Constant ε' (unit less)</th>
<th>Dielectric Constant ε'' (unit less)</th>
<th>Effective Conductivity 2πfεoε'' (S/m)</th>
<th>Specific Heat (KJ/Kg·oC)</th>
<th>Thermal Conductivity (W/m·oC)</th>
<th>Enthalpy (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>50.49±0.73</td>
<td>21.96±0.09</td>
<td>1.12</td>
<td>3.57</td>
<td>0.518</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>49.86±0.69</td>
<td>25.89±0.21</td>
<td>1.32</td>
<td>3.58</td>
<td>0.523</td>
<td>-</td>
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<tr>
<td>60</td>
<td>49.13±0.78</td>
<td>31.25±0.21</td>
<td>1.59</td>
<td>3.62</td>
<td>0.527</td>
<td>-</td>
</tr>
<tr>
<td>70*</td>
<td>48.83</td>
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<td>1.76</td>
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<td>0.53</td>
<td>0.0</td>
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<td>3.41</td>
<td>0.534</td>
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<tr>
<td>110*</td>
<td>47.92</td>
<td>47.73</td>
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<td>3.55</td>
<td>0.539</td>
<td>138.1</td>
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<td>174.8</td>
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<tr>
<td>130**</td>
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<td>55.32</td>
<td>2.82</td>
<td>3.83</td>
<td>0.543</td>
<td>213.1</td>
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<tr>
<td>140**</td>
<td>47.49</td>
<td>59.35</td>
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<td>4.02</td>
<td>0.545</td>
<td>253.3</td>
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<tr>
<td>150**</td>
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<td>63.55</td>
<td>3.24</td>
<td>4.25</td>
<td>0.546</td>
<td>295.8</td>
</tr>
</tbody>
</table>

*interpolated values  
**extrapolated values

Table 5. Dielectric properties at 915 MHz and thermal properties of Alfredo sauce

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dielectric Constant ε' (unit less)</th>
<th>Dielectric Constant ε'' (unit less)</th>
<th>Effective Conductivity 2πfεoε'' (S/m)</th>
<th>Specific Heat (KJ/Kg·oC)</th>
<th>Thermal Conductivity (W/m·oC)</th>
<th>Enthalpy (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>55.11±0.45</td>
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<td>2.19</td>
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<td>0.514</td>
<td>-</td>
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<tr>
<td>40</td>
<td>52.60±0.32</td>
<td>57.44±1.29</td>
<td>2.92</td>
<td>3.62</td>
<td>0.522</td>
<td>-</td>
</tr>
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<td>3.74</td>
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<td>0.546</td>
<td>-</td>
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<tr>
<td>70*</td>
<td>48.56</td>
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<td>3.59</td>
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<td>80</td>
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<td>0.550</td>
<td>35.22</td>
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<td>90*</td>
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<td>3.55</td>
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<td>110*</td>
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<td>7.44</td>
<td>4.45</td>
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<td>304.68</td>
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</table>

*interpolated values  
**extrapolated values
3.2. Dielectric property of different formulations of WPG

Table 6. Dielectric properties of different formulations of WPG reported as means and standard deviation of at least 3 replicates per formulation.

<table>
<thead>
<tr>
<th>WPG formulation</th>
<th>Temperature, ºC</th>
<th>Dielectric properties at 915 MHZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dielectric Constant ε' (unit less)</td>
</tr>
<tr>
<td>S1</td>
<td>20</td>
<td>50.94 ± 1.44</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>50.75 ± 0.62</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>49.69 ± 0.33</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>48.42 ± 0.56</td>
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<tr>
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<td></td>
<td>120</td>
<td>45.85 ± 0.25</td>
</tr>
<tr>
<td>S2</td>
<td>20</td>
<td>52.91 ± 2.49</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>51.76 ± 0.99</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>50.62 ± 0.77</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>49.35 ± 1.45</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>48.11 ± 1.74</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>47.42 ± 1.15</td>
</tr>
<tr>
<td>S3</td>
<td>20</td>
<td>51.29 ± 2.31</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>48.34 ± 2.98</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>46.04 ± 4.70</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>45.94 ± 5.43</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>46.08 ± 4.22</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>45.93 ± 3.62</td>
</tr>
<tr>
<td>S4</td>
<td>20</td>
<td>55.27 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>53.74 ± 0.81</td>
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<td></td>
<td>60</td>
<td>52.74 ± 1.28</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>51.71 ± 1.71</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>50.08 ± 2.02</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>49.24 ± 1.36</td>
</tr>
<tr>
<td>S5</td>
<td>20</td>
<td>50.48 ± 5.66</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>49.43 ± 6.72</td>
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<tr>
<td></td>
<td>60</td>
<td>48.89 ± 7.10</td>
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<tr>
<td></td>
<td>80</td>
<td>48.94 ± 5.15</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>49.38 ± 2.44</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>49.41 ± 0.24</td>
</tr>
</tbody>
</table>
Table 6 summarizes the dielectric properties of different formulations of WPG at 915 MHz. Among the five samples, only S1, S4 and S2 had low standard deviations from the mean of dielectric constant. The dielectric constant of S1, S4, and S2 formulations has less inherent variation. The S1 and S2 formulation were the only two formulations showing low standard deviation of 1.83 and 2.0, respectively, for loss factor. Standard deviations for other formulations were greater than 3.0. In selecting WPG formulation as a model food for salmon it was desirable to have a low standard deviation from the mean of dielectric constant and loss factor so as to have less inherent variation. Low standard deviation is also a reflection of repeatability of measurement and stability physical properties. To this end, use of S1 and S2 formulation was a good candidate, but still needs a side by side comparison with the dielectric property of salmon fillet for verification.

3.3. Texture analysis

Physical stability of WPG as discussed in Section 3.2 reflects on the texture analysis of WPG. Result of texture analysis indicated that S2 (score 22) was the best formulation, almost equal to S1 (score of 20), and closely followed by S4 (score of 19). The criteria used for scoring to the texture of WPG after being subjected to the compression test were: (1) returning to its original dimension after compression test; (2) ease of cutting without breaking after compression test; (3) crumbliness after compression test; (4) formation of cracks after compression; and (5) water syneresis after compression test. A score of 1 to 5 for each criterion, with 1 being the least favorable and 5 being the most favorable attributes, was applied to every formulation.

In general, WPG cannot be easily separated from the tray in which they were molded. WPG with more than 0.6% salt content were more prone to cracking as they were cut. The S1 WPG formulation was able to retain its physical property after 2 weeks of storage, followed by
S4 and S2 (Table 7). In the case of S3 and S5, both Group (1) and Group (2) show excessive syneresis. Although it was possible to cut S3 and S5 by using a cylindrical puncher, resulting pieces were too crumbly, especially those stored for two weeks. Therefore, for the texture analysis, S3 and S5 formulation were the weakest possible WPG model food for salmon fillet.

Table 7. Summary of handling property of WPG based on texture analyzer test.

<table>
<thead>
<tr>
<th>Handling properties of WPG</th>
<th>Group 1 (WPGs stored for 2 weeks)</th>
<th>Group 2 (Untreatedly cooked WPG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best</td>
<td>S1</td>
<td>S1 and S4</td>
</tr>
<tr>
<td>Good</td>
<td>S4 and S2</td>
<td>S2</td>
</tr>
<tr>
<td>Inappropriate</td>
<td>S3 and S5 excessive syneresis and are too crumbly, but possible to cut</td>
<td>S3 and S5 excessive syneresis, but possible to cut</td>
</tr>
</tbody>
</table>

3.4. Selection of appropriate formulation of whey protein gel

Based on the measured of the inherent variation in dielectric property (i.e., measured through standard deviation from the mean) and the texture analysis of the different formulation of WPG, sample S1, S2 and S4 were selected as the most appropriate candidates for model food for salmon fillet. Although the three WPG formulations were qualified in terms of repeatability of DP measurement and physical stability, the most important consideration was the matching of DP to the DP of salmon fillet. Figure 7 shows the plot of dielectric constant at 915 MHz of the different formulations of WPG and salmon fillet at different temperatures. The S1, S2 and S5 formulation had a good match with mean percent difference (measure of disparity variation) of 1.95%, 2.37%, and 1.39%, respectively. Although S5 shows the closest match to the dielectric constant of salmon fillet, it was least desirable in terms of texture analysis.
In the case of S1 formulation, at temperature < 80°C, a one to one correspondence can be seen between the curve of S1 and curve of salmon fillet (Figure 7). However, at higher temperatures, dielectric constant of S1 becomes relatively unstable showing an up and down trend at 100°C and 120°C, respectively. This erratic behavior of S1 at high temperature contributes a majority of the 1.95% mean percent difference or disparity variation from the reference (i.e., salmon fillet), and was undesirable since the processing temperature in MATS occurs at temperature >70°C. For the case of S2 formulation, although the mean percent difference or disparity variation from the reference is 2.37% and is higher than that of S1, the majority of the high difference from the reference occurs at low temperature (<70°C).
Considering only a temperature of >70°C, the mean percent difference or disparity variation of S2 from the reference was only 0.86%, showing a close match at high temperature (Figure 7). Therefore, since lethal contribution was only significant at high temperature (>70°C) during thermal processing in MATS, for dielectric constant, S2 was the most appropriate WPG formulation as model food for salmon fillet.

Figure 8 shows the plot of loss factor at 915MHz of the different formulation of WPG and salmon fillet at different temperature. A good match was observed among S2, S4, and S5 with the reference, with mean percent difference or disparity variation of 11.63%, 11.50%, and 5.23%, respectively. In general, loss factor is more difficult to match, as demonstrated by the relatively high mean percent difference from the reference. This result can be attributed to the sensitivity of the WPG formulation to salt content. A small change of salt concentration is enough to change loss factor to a certain degree (Wang, et al., 2009). For example, the salt concentrations among different WPG formulations range only from 0.3% to 0.8% (Table 1), but resulted in large difference in loss factor, as illustrated in Figure 8.

As stated previously, S5 formulation, although it shows the closest match to salmon fillet in terms of loss factor at low temperature (<100°C), cannot be considered due to its inferior physical characteristics. The S4 formulation was also ruled out since the standard deviation among replicates (inherent variation) was relatively high, translating into a less repeatable measurement of DP. Therefore as far as loss factor is concerned, S2 formulation was the best choice among other formulations of WPG. Therefore, further discussion pertaining to WPG should refer to S2 formulation.
Figure 8: Comparison of loss factor of salmon fillet with the loss factor of different formulation of whey protein gel (WPG)

The mean percent difference of 11.63% in loss factor between S2 and the reference salmon fillet translates into average differences (i.e., disparity variation) of 4.29 in loss factor within the temperature range of 20°C to 120°C. Furthermore, considering the inherent variation (i.e. measured as standard deviation) in the loss factor of S2 and salmon fillet of ±2.00 and ±0.71, respectively, translates into a possible variation of 1.58 to 7.00 in loss factor between S2 and salmon fillet. For dielectric constant, considering the mean percent difference related to disparity variation between S2 and salmon fillet and the inherent variation in dielectric constant of S2 and salmon fillet would translate into a possible variation of 0.25 to 3.38 in dielectric constant between S2 and salmon fillet, which would translate into 0.51% to 6.90% variation in
dielectric constant and 4.86% to 21.53% variation in loss factor if S2 were to represent salmon as its model food. The percent variation in dielectric properties between S2 and salmon fillet were the basis for the sensitivity study described in Section 2.8. For instance, if the heating parameters (i.e., heating pattern and location of cold spot) are not affected by the 50% variation in dielectric properties (Table 3), then S2 formulation would still be a valid model food for salmon fillet since the possible percent variation in dielectric properties between S2 and salmon fillet are within the 50% variation in dielectric properties described in Table 3.

3.5. Heating pattern and location of cold spot of whey protein gel (S2 formulation)

Figure 9 summarizes the heating patterns of S2 formulation of whey protein gel (S2-WPG) obtained through chemical marker method. The horizontal label at the bottom (S2-1, S2-2, S2-3, S2-4, and S2-5) represents the different replicates tested. The vertical labels at the right and left were the different thickness of the sample (12 mm, 14 mm and 16 mm) and the plane of cutting (xy and yz plane), respectively. The xy planes were taken at the center of the food with respect to its thickness and the yz planes were taken perpendicular at the vertical lines illustrated in Figure S2-1; xy; 12 mm thickness. The vertical lines were spaced equidistance to each other, cutting the S2-WPG into three parts. Based on the results, it appears that thickness does not affect the overall heating pattern of S2-WPG. The location of the cold area (represented by blue/green in RGB scale) and hot area (represented by red in RGB scale) in xy plane in Figure 9 were comparable for all three thickness of S2-WPG. The heating patterns obtained in xy plane can be confirmed on the yz planes which show two distinct hot areas that are almost equidistance.
The experimentally determined heating patterns for S2-WPG are summarized in Figure 10 (b). There were three groups of zones within which temperature distribution was relatively uniform. These zones were:

- **Cold Area 1.** These were the lower and upper most areas within the x-y plane. Since heating pattern and temperature distribution was symmetrical, these areas were designated as one zone (Cold Area 1).

- **Cold Area 2.** This area was at the middle of the x-y plane.

- **Hot Area.** These areas were the two intense colored areas between cold area 1 and cold area 2. The two hot areas have symmetrical temperature distribution, and hence are designated as one zone (Hot Area).

The identified cold spots for different thicknesses of S2-WPG are summarized in Table 8. The cold spot locations for different thicknesses of S2-WPG formulation were close / relatively comparable to each other. The mean coordinates of the location of cold spot were at 64.5 mm, 61.0 mm, and 8.0 mm in x, y, and z direction, respectively. This coordinate is illustrated in Figure 10 (a). Therefore, it was concluded that the thickness of 12 mm, 14 mm, and 16 mm of S2-WPG formulation processed in MATS does not affect the location of cold spot nor the heating pattern.

Table 8. Summary of the location of cold spot for different thicknesses of S2-WPG.

<table>
<thead>
<tr>
<th>S2-WPG Thickness / mm</th>
<th>RGB Color Value</th>
<th>Location of cold spot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x / mm</td>
</tr>
<tr>
<td>12</td>
<td>31.08±8.12</td>
<td>64.18±2.80</td>
</tr>
<tr>
<td>14</td>
<td>29.30±8.31</td>
<td>65.13±1.93</td>
</tr>
<tr>
<td>16</td>
<td>43.55±11.96</td>
<td>64.24±2.84</td>
</tr>
</tbody>
</table>
Figure 9: Computer vision snapshot images of chemical marker method for different thickness of S2 whey protein gel formulation.
3.6. Simulated heating pattern and cold spot location

Figure 11 shows the simulated heating patterns of salmon fillet after 180 s (3 min) of simultaneous hot water and microwave heating. Average heating time per cavity was 45 s of the 180 s for four cavities. The xy plane snapshots of the simulated heating pattern shown in Figure 11 were all taken at the middle of the salmon with respect to its thickness (8 mm of the 16 mm thickness of salmon along the z direction). Furthermore, the black rectangle in each snapshot represents the interface between salmon and Alfredo sauce in the simulation model. The salmon occupied the area within the rectangle, while the Alfredo sauce occupied the area outside the rectangle.

Results of simulation for different levels of variation of dielectric property (Table 3) suggest that regardless of the variations in dielectric property, the heating pattern remains the same. More importantly, the simulated heating patterns were similar to the general heating pattern described in Figure 10 b. That is, the heating pattern can be described by the three zones where temperature at a given zone is relatively uniform. These zones were cold area 1, cold area
2, and hot area (Figure 10-b). It is also important to note that regardless of dielectric property variation for salmon, the final temperature of Alfredo sauce surrounding the salmon fillet was always higher than the temperature of salmon fillet in any area. The high temperature of Alfredo sauce located mostly at the sides and corner of the pouch can be attributed to the phenomenon called edge overheating effect (Risman P., 2009). The advantage of the configuration of packaging used in this study was that salmon fillet was not affected by the edge overheating effect, since the edge of the pouch was occupied by Alfredo sauce only. Furthermore, the circulating water at 121°C to 122°C outside the pouch acted as a heat sink, preventing the temperature of Alfredo sauce from further increasing. Actual processing of salmon fillet in Alfredo sauce packed in a flexible pouch shows that although a slight browning in Alfredo sauce occurred after processing in MATS, there was no burnt or off flavor produced.

Comparing the different levels of variation of dielectric property, results of simulation show that the intensity of temperature of heating pattern was directly proportional to dielectric property variation. Specifically, the lower the level of variation of dielectric property (-10%, -30% and -50%), the lesser the intensity of temperature of the three zones describing the heating patterns in salmon fillets (Figure 11). This observation was also true for a higher level of variations. Although the intensity of temperature of salmon fillet changes with different levels of variation of dielectric properties, the change in intensity of temperature was proportional to all zones resulting into similar heating pattern (i.e., the three zones describing the heating pattern remains the same).

Comparing the different levels of variations in dielectric constant (Figure 11 a) with the different levels of variations in loss factor (Figure 11 b), considering the similar level of variation, the intensity of temperature of the heating pattern corresponding to variation in
dielectric constant was always higher than that of variation in loss factor. For example, comparing +50% variation in dielectric constant (Figure 11 a; +50%) with +50% variation in loss factor (Figure 11 b; +50%), the intensity of temperatures for heating pattern corresponding to +50% variation in dielectric constant is higher than that of +50% variation in loss factor. Therefore, it was concluded that the intensity of temperature for heating pattern was more sensitive to dielectric constant variation as compared to loss factor variation.

![Figure 11: Simulated heating pattern for different variation (±10%, ±30% and ±50%) of dielectric constant (row a) and loss factor (row b) after 180 s of simultaneous hot water and microwave heating](image)

Table 9 summarizes the location of cold spot for different levels of variation of dielectric properties determined by MATS-CSM. The coordinates used in Table 9 are described in Figure 10 (a). According to simulation results, salmon in Alfredo sauce packed in a flexible pouch processed in a simulated condition similar to MATS would have a cold spot at 74.6 mm, 45.8 mm, and 8.0 mm along x, y, and z direction, respectively. Variation in the loss factor in both positive and negative direction of up to ±50% did not affect the location of cold spot. However, for dielectric constant, although negative variation of up to -50% did not affect location of cold
spot, positive variation did. The location of cold spot moves near the surface of the food along the z direction (i.e., thickness of the food), while maintaining the position along the x and y direction. The higher the positive variation in dielectric constant, the closer the cold spot to the surface. Specifically, from 8 mm which is at the center, the cold spot moved to position 11.5 mm, 13.5 mm, and 14.5 mm with respect to z direction for +10%, +30%, and +50% variation in dielectric constant, respectively. The movement of cold spot with positive variation in dielectric constant complies with the conclusion of heating pattern that is more sensitive to variation in dielectric constant than to variation in loss factor.

Table 9. Cold spot in salmon fillet determined through computer simulation method considering different levels of variation in dielectric property of salmon.

<table>
<thead>
<tr>
<th>Case</th>
<th>Position of cold spot in (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Dielectric Constant</strong></td>
<td></td>
</tr>
<tr>
<td>50% Higher Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td>30% Higher Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td>10% Higher Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td>Average Dielectric Property</td>
<td>74.6</td>
</tr>
<tr>
<td>10% Lower Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td>30% Lower Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td>50% Lower Dielectric Constant</td>
<td>74.6</td>
</tr>
<tr>
<td><strong>Loss Factor</strong></td>
<td></td>
</tr>
<tr>
<td>50% Higher Loss Factor</td>
<td>74.6</td>
</tr>
<tr>
<td>30% Higher Loss Factor</td>
<td>74.6</td>
</tr>
<tr>
<td>10% Higher Loss Factor</td>
<td>74.6</td>
</tr>
<tr>
<td>Average Dielectric Property</td>
<td>74.6</td>
</tr>
<tr>
<td>10% Lower Loss Factor</td>
<td>74.6</td>
</tr>
<tr>
<td>30% Lower Loss Factor</td>
<td>74.6</td>
</tr>
<tr>
<td>50% Lower Loss Factor</td>
<td>74.6</td>
</tr>
</tbody>
</table>
Figure 12: Depth of penetration for (a) variation in dielectric constant at average loss factor, and (b) variation in loss factor at average dielectric constant
According to Risman (2009) the depth of microwave penetration on a large flat surface and infinitely thick load irradiated by a plane wave on a given surface with incident angle equal to zero (i.e., perpendicular to the surface of food) is more sensitive to loss factor than to dielectric constant. In this study, the depth of microwave penetration indeed indicates a higher sensitivity in varying loss factor than in varying dielectric constant given by the relatively scattered curves of $D_p$ vs. temperature in Figure 12 (b) and a relatively close curve of $D_p$ vs. temperature in Figure 12 (a) for loss factor and dielectric constant, respectively. Furthermore, the depth of microwave penetration is directly proportional to the variation in dielectric constant. That is the higher the variation in dielectric constant at a given average loss factor, the higher the depth of microwave penetration. On the other hand, the depth of microwave penetration is inversely proportional to the variation in loss factor. That is, the higher the variation in loss factor at a given average dielectric constant, the lower the depth of microwave penetration.

In this study, the depth of microwave penetration alone is not sufficient to explain the sensitivity of dielectric property with respect to the location of cold spot. This is because the arrangement of MATS as depicted in the MATS-CSM allows for microwave penetration on both the top and bottom surface of the food. Furthermore, the thickness of the food used in this study was not infinite (i.e., thickness of salmon fillet was only 16 mm). Considering the manner by which microwaves penetrate the food and the thickness of the food, standing waves exist within the food as a result of interaction between oppositely directed microwave penetrations. Since heating pattern is not affected by the variation of dielectric property, it can be concluded that standing wave pattern within the food is also not affected by variation of dielectric property. However, since microwave penetration depth is affected by variation in dielectric property of food, the intensity or amplitude of standing wave may vary within the layer of food thickness.
Although the standing wave pattern is not affected by variation in dielectric properties of food (i.e., heating pattern is not affected by dielectric property of food), the amplitude of standing wave might cause overlapping of hot and cold areas (Figure 10 b), causing movement of cold spot.

3.7. Simulated temperature profile and rate of heating at the cold spot, and sterilization value

Simulation results corresponding to the variation in dielectric constant indicate that the percent change in the resulting final temperature, sterilization value and rate of heating at the cold spot is directly proportional to the variation in the dielectric constant (Figure 13 and Table 10). This means that (a) an increase in dielectric constant could result in an increase in final temperature, sterilization value, and rate of heating at the cold spot, and (b) a decrease in dielectric constant could result in a decrease in final temperature, sterilization value, and rate of heating at the cold spot. Furthermore, all changes as a result of variation in dielectric constant were significant ($P_{value}$<0.05). On average, final temperature at the cold spot changed by +1°C (i.e., equivalent to +0.9% change), and -1.2°C (i.e., equivalent to -1% change) for every +10% and -10% variation in dielectric constant, respectively. In the case of sterilization value and heating rate, a ±10% variation in dielectric constant would result in ±29.6% change and ±2.2% change, respectively.

The percent change in the resulting final temperature, sterilization value and rate of heating at the cold spot is directly proportional to the variation in loss factor (Figure 14 and Table 11). This means that (a) an increase in loss factor would result in an increase in the final temperature, sterilization value, and rate of heating at the cold spot; and (b) a decrease in loss factor would result in a decrease in the final temperature, sterilization value, and rate of heating.
at the cold spot. However, unlike variation in dielectric constant, percent change is minimal as far as the final temperature and rate of heating are concerned. In fact, a +50% variation in loss factor has insignificant influence on the final temperature of the cold spot and heating rate (i.e., percent change is +0.4% for final temperature at the cold spot and +0.95% for heating rate). Although there is a significant change in sterilization value as a result of +50% variations in loss factor (+10.8%), this percent increase may still have a minimal contribution if evaluation of sterilization value would include the holding and cooling section of MATS. For -50% variations in the loss factor, the decrease in the final temperature, sterilization value, and rate of heating at the cold spot is significant (-4.3%, -64.3%, and -10.8%, respectively).

Actual measurement of temperature profile at the cold spot, as identified by chemical marker method on the middle part of salmon using an Ellab™ wireless temperature sensor, shows good agreement with the simulated result. The final temperature at the cold spot of actual measurement is 118.7°C, which is only -0.1°C lower compared to simulation with average dielectric property. For sterilization value and heating rate, the difference between actual measurement and simulation with average dielectric property was +10% and +6%, respectively.
Table 10. Summary of final temperature and rate of heating at the cold spot, and sterilization value in cases of ±10% and ±20% variation in dielectric constant

<table>
<thead>
<tr>
<th>Case</th>
<th>Final Temperature at Cold Spot* (°C)</th>
<th>%Δ**</th>
<th>F_0*** (min)</th>
<th>%Δ**</th>
<th>Average Heating rate (°C/s)</th>
<th>%Δ**</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% Higher Dielectric Constant</td>
<td>122.0</td>
<td>+2.7</td>
<td>0.521</td>
<td>+129.8</td>
<td>0.269</td>
<td>+6.8</td>
</tr>
<tr>
<td>30% Higher Dielectric Constant</td>
<td>121.2</td>
<td>+2.0</td>
<td>0.424</td>
<td>+86.9</td>
<td>0.265</td>
<td>+5.2</td>
</tr>
<tr>
<td>10% Higher Dielectric Constant</td>
<td>119.8</td>
<td>+0.9</td>
<td>0.294</td>
<td>+29.6</td>
<td>0.258</td>
<td>+2.2</td>
</tr>
<tr>
<td>Average Dielectric Property</td>
<td>118.8</td>
<td>0.0</td>
<td>0.227</td>
<td>0.0</td>
<td>0.252</td>
<td>0.0</td>
</tr>
<tr>
<td>Actual Measurement****</td>
<td>118.7</td>
<td>-0.1</td>
<td>0.250</td>
<td>+10.0</td>
<td>0.267</td>
<td>+6.0</td>
</tr>
<tr>
<td>10% Lower Dielectric Constant</td>
<td>117.6</td>
<td>-1.0</td>
<td>0.171</td>
<td>-24.6</td>
<td>0.246</td>
<td>-2.6</td>
</tr>
<tr>
<td>30% Lower Dielectric Constant</td>
<td>115.1</td>
<td>-3.1</td>
<td>0.097</td>
<td>-57.2</td>
<td>0.232</td>
<td>-7.8</td>
</tr>
<tr>
<td>50% Lower Dielectric Constant</td>
<td>112.8</td>
<td>-5.1</td>
<td>0.056</td>
<td>-75.3</td>
<td>0.220</td>
<td>-12.9</td>
</tr>
</tbody>
</table>

*Temperatures correspond to the final temperature at the cold spot at the end of the fourth cavity
**Percent change in reference to the average dielectric property; “+” higher than reference, “-” lower than reference
***Sterilization value includes heating portion only (i.e., from initial temperature of 72°C up to the final temperature of cold spot at the end of the fourth cavity) and does not include, preheating, holding, and cooling.
**** Data logged using Ellab™ sensor positioned at the cold spot of actual middle part of salmon packed in 8oz tray with Alfredo sauce.

Figure 13: Temperature profiles and sterilization values at the cold spot with ±10%, ±30%, and ±50% variation in dielectric constant
Table 11. Summary of final temperature and rate of heating at the cold spot, and sterilization value in cases of ±10% and ±20% variation in loss factor

<table>
<thead>
<tr>
<th>Case</th>
<th>Final Temperature at Cold Spot* (°C)</th>
<th>%Δ**</th>
<th>F_o *** (min)</th>
<th>%Δ**</th>
<th>Average Heating rate (°C/s)</th>
<th>%Δ**</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% Higher Loss Factor</td>
<td>119.2</td>
<td>+0.4</td>
<td>0.251</td>
<td>+10.8</td>
<td>0.254</td>
<td>+0.95</td>
</tr>
<tr>
<td>30% Higher Loss Factor</td>
<td>119.3</td>
<td>+0.4</td>
<td>0.254</td>
<td>+12.1</td>
<td>0.255</td>
<td>+1.0</td>
</tr>
<tr>
<td>10% Higher Loss Factor</td>
<td>119.1</td>
<td>+0.2</td>
<td>0.241</td>
<td>+6.2</td>
<td>0.253</td>
<td>+0.6</td>
</tr>
<tr>
<td>Average Dielectric Property</td>
<td>118.8</td>
<td>0.0</td>
<td>0.227</td>
<td>0.0</td>
<td>0.252</td>
<td>0.00</td>
</tr>
<tr>
<td>Actual Measurement****</td>
<td>118.7</td>
<td>-0.1</td>
<td>0.250</td>
<td>+10.0</td>
<td>0.267</td>
<td>+5.8</td>
</tr>
<tr>
<td>10% Lower Loss Factor</td>
<td>118.4</td>
<td>-0.3</td>
<td>0.207</td>
<td>-8.6</td>
<td>0.250</td>
<td>-0.8</td>
</tr>
<tr>
<td>30% Lower Loss Factor</td>
<td>117.1</td>
<td>-1.4</td>
<td>0.152</td>
<td>-33.2</td>
<td>0.243</td>
<td>-3.6</td>
</tr>
<tr>
<td>50% Lower Loss Factor</td>
<td>113.7</td>
<td>-4.3</td>
<td>0.081</td>
<td>-64.3</td>
<td>0.225</td>
<td>-10.8</td>
</tr>
</tbody>
</table>

*Temperatures correspond to the final temperature at the cold spot at the end of the fourth cavity

**Percent change in reference to the average dielectric property; “+” higher than reference, “-” lower than reference

***Sterilization value includes heating portion only (i.e., from initial temperature of 72°C up to the final temperature of cold spot at the end of the fourth cavity) and does not include preheating, holding, and cooling.

**** Data logged using Ellab™ sensor positioned at the cold spot of actual middle part of salmon packed in 8oz tray with Alfredo sauce.

Figure 14: Temperature profiles and sterilization values at the cold spot with ±10%, ±30%, and ±50% variation in loss factor
3.8. Verification of location of cold spot obtained from computer simulation model and chemical marker method

The computer simulated heating pattern using dielectric and thermal property of salmon fillet and Alfredo sauce compared very well with the heating pattern of the selected S2-WPG processed in MATS (Figure 9 and Figure 11). However, a discrepancy was detected between the location of the cold spot determined by computer simulation method (Table 9) and chemical marker method using S2-WPG (Table 8). Although there was no difference along the z direction, there was a 10.4 mm, and 15.6 mm difference along the x, and y direction, respectively (Figure 15).

Figure 15: Comparison of the location of cold spot determined by (a) chemical marker method using S2-WPG formulation and (b) computer simulation method using dielectric and thermal property of salmon.

Because the purpose of S2-WPG is a model food for salmon fillet computer simulated identification of cold spot and chemical marker method identification of cold spot using WPG should be comparable. Using P1, P2, P3, and P4 location as described in Figure 15, the procedure described in Section 2.10 using actual food samples (salmon in Alfredo sauce packed
in a 8-oz flexible pouch) was conducted. However, only half of the four points in Figure 15 (a) and Figure 15 (b) were tested. Since the heating pattern is symmetrical, with the point of symmetry at the center of the $xy$ plane, the other half of the four points in Figure 15 (a) and Figure 15 (b) were expected to have the same or approximately the same temperature as the other half to satisfy the symmetry of the heating pattern.

Table 12. Heat penetration test for the identified cold spot of chemical marker method on S2-WPG (P1 and P2), and computer simulation method (P3 and P4)

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>P1</th>
<th></th>
<th></th>
<th>P2</th>
<th></th>
<th>P3</th>
<th></th>
<th>P4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 1</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>5.8°C</td>
<td>5.7°C</td>
<td>5.6°C</td>
<td>5.6°C</td>
<td>5.2°C</td>
<td>4.9°C</td>
<td>5.2°C</td>
<td>4.9°C</td>
<td></td>
</tr>
<tr>
<td>Temperature at the entrance of heating section</td>
<td>72.6°C</td>
<td>72.6°C</td>
<td>72.3°C</td>
<td>72.1°C</td>
<td>72.5°C</td>
<td>72.6°C</td>
<td>72.6°C</td>
<td>72.6°C</td>
<td></td>
</tr>
<tr>
<td>Sterilization value at the end of holding section</td>
<td>20.8min</td>
<td>12.3min</td>
<td>8.5 min</td>
<td>9.2 min</td>
<td>20.3min</td>
<td>23.5min</td>
<td>48.6min</td>
<td>34.8min</td>
<td></td>
</tr>
</tbody>
</table>

Table 13. Heat penetration test ($F_0$ in min) for the neighboring point of P2

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Left</th>
<th>Right</th>
<th>front</th>
<th>back</th>
<th>up</th>
<th>down</th>
<th>middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>15.4</td>
<td>18.9</td>
<td>10.9</td>
<td>17.7</td>
<td>13.6</td>
<td>22.5</td>
<td>11.1</td>
</tr>
<tr>
<td>Test 2</td>
<td>21.6</td>
<td>14.8</td>
<td>16.0</td>
<td>21.9</td>
<td>10</td>
<td>10.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Test 3</td>
<td>21.4</td>
<td>15.7</td>
<td>13.5</td>
<td>22.0</td>
<td>10.4</td>
<td>12.5</td>
<td>7.1</td>
</tr>
<tr>
<td>Test 4</td>
<td></td>
<td>15.1</td>
<td>16.3</td>
<td>10.3</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>test 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.3</td>
</tr>
<tr>
<td>Average / min</td>
<td>19.5 min</td>
<td>16.5 min</td>
<td>13.5 min</td>
<td>19.2 min</td>
<td>12.6 min</td>
<td>14.0 min</td>
<td><strong>9.1 min</strong></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.5</td>
<td>2.2</td>
<td>2.6</td>
<td>3.4</td>
<td>3.0</td>
<td>5.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 12 suggests that P2, which is the cold spot identified by the chemical marker method, received the least sterilization value ($F_0 = 8.5$ min). Therefore, this location should be the real cold spot. This was verified by the heat penetration test on the neighboring points of P2.
following the procedure described in Section 2.10 of Figure 6. Table 13 indicates that P2 has the lowest sterilization value ($F_o = 9.1$ min) among all other neighboring points, and was therefore verified as the real location of cold spot.

Although the computer simulation model gave a good match in terms of heating pattern, it failed to accurately identify the location of cold spot comparable to the identified cold spot identified by chemical marker method. Some reasons for the mismatch on the location of cold spot could be the following:

- In MATS-CSM the dielectric and thermal property of salmon precooked at 72°C was used. However, the simulation model does not consider possible change in moisture content during thermal processing, for example, when salmon in Alfredo sauce pouches are inside the heating section in MATS, which could cause change in dielectric and thermal property of salmon. According to Kong et al. (2008), the cook-loss (i.e., percent weight reduction of the cooked sample compared with raw sample) for salmon after heating at 121°C for the first 20 min is 19.1%, which is mostly due to water loss. Although microwave heating in MATS as depicted in computer simulation takes only 3 min, a significant amount of water (approximately 7 to 10%) was lost, which can change the dielectric and thermal property of salmon fillets.

- Accompanied by cook-loss is the shrinkage of muscle of salmon fillet. This can also happen to S2-WPG which causes the cold spot illustrated in Figure 15 (a) to be closer to each other than the one suggested by MATS-CSM in Figure 15 (b). Although there was no quantification done on how much water was lost in S2-WPG during processing in MATS, the fact that it identified the cold spot properly (i.e., it was verified through heat penetration test using actual salmon fillet in the section reflected in Tables 12 and 13) means that the water
loss and shortening of S2-WPG is comparable to salmon fillet. One of the limitations of MATS-CSM is a constant computational volume during simulation. Any change in computational volume (i.e., change in number of declared Yee’s cell) will cause error in the simulation.

- Possible presence of micro bubble causing electric field distribution to change in S2-WPG [Figure 15 (a)]. The presence of micro bubbles was not considered in MATS-CSM

4. Conclusion

With the aid of MATS-CSM, this study was able to accomplish and conclude the following:

- S2 formulation of WPG (S2-WPG) is the appropriate model food for salmon fillet.
- The thickness of S2-WPG formulation (12 mm, 14 mm, and 16 mm) processed in MATS has no effect on heating pattern and location of cold spot.
- The heating pattern of S2-WPG was described by three zones: cold area 1, cold area 2, and hot area, within which temperature distribution is relatively uniform.
- Heating pattern is not affected by the different levels of variation of dielectric property but the intensity of temperature of heating pattern is directly proportional to the variation in dielectric property.
- The intensity of temperature of heating pattern is more sensitive to variation in dielectric constant, as compared to variation in loss factor.
- Variation in dielectric property does not affect the location of the cold spot except for positive variation in dielectric constant. This might be due to different amplitude of standing wave within the food as a result of interaction between oppositely directed microwave irradiating from top and bottom surface of the food.

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• The change in the final temperature, sterilization value, and rate of heating at the cold spot is directly proportional to the variation in dielectric property of salmon.

• It was verified that the cold spot suggested by S2-WPG through the chemical marker method was the real cold spot. The cold spot suggested by MATS-CSM was not equal to the cold spot suggested by S2-WPG because of some limitations of the computer simulation model.

5. References


CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

The Microwave Assisted Thermal Sterilization (MATS) system for microwave sterilization of food has been identified as the next frontier of novel food processing (Brody, 2012). After receiving FDA acceptance for processing both homogeneous (e.g., mashed potato) and heterogeneous food (e.g., salmon in Alfredo sauce, and chicken and dumpling stew), several major US food processing and packaging companies have joined force with Washington State University (WSU) team to commercialize the technology. The microwave consortium II was formed that comprises of those companies and led by the microwave sterilization group of WSU. We are now at the final stage of developing a commercial scale MATS. The commercial scale will have a higher throughput to meet industrial needs of bulk production of shelf stable packaged food. It is expected that a functional commercial prototype of MATS will available at the end of 2012.

MATS technology is a product of over 15 years of research involving many disciplines including food engineering, food science, electrical engineering and mechanical engineering. This Ph. D. studies focused on addressing several scientific challenges including: (1) understanding the effect of dielectric property of both food and circulating water inside the cavity to heating pattern, stability of cold spot, and sterilization value of the food, (2) simulating the effect of frequency shift as a result of continuous used and aging microwave generator using computer models, and (3) minimization of power reflection to improve the overall efficiency of the process with the aid of computer simulation modeling of MATS system, and (4) verification of simulation results with experimental data.
A computer simulation model for MATS was created with added features. The new computer simulation model is now referred to as MATS-CSM which stands for Microwave Assisted Thermal Sterilization Computer Simulation Model. The numerical method used to create MATS-CSM utilizes the Finite-Difference Time-Domain (FDTD) method which is a widely used and accepted method for solving Maxwell equations related to electromagnetic (EM) propagation. Furthermore, the model uses similar finite object generated by FDTD for heat transfer solutions which were coupled with EM solution employing Finite Element Method (FEM) on the governing equations for both conductive and convective heat transfer. Both FDTD and FEM simulation for the modeled computational volume of MATS was executed using a commercial software called QuickWave™ (QWED, Poland). Concept related to EM field propagation, heat transfer, FDTD, and FEM was discussed on the first two chapters of this study.

The coupled EM-heat transfer solution generated by MATS-CSM provided the necessary heating patterns in pre-packaged food processed in MATS with good accuracy. This accuracy was gauged by comparing to experimentally determined heating patterns obtained from computer vision method which employed chemical marker M-2 to correlate the temperature distribution with color intensity. Proper characterization of heating patterns allows for identification of the exact location of the cold spot thereby which in turn used for heat penetration tests on food as an essential step in evaluating food sterility in thermal processes. Furthermore, MATS-CSM is a good tool in studying different variables that may influence heating patterns in food processed in MATS, which would be time consuming and would require considerable amount of resources if done experimentally. This is ideal in an industrial setting since it would potentially reduce cost associated to research and development effort.
One of the drawbacks in Dr. Chen’s computer simulation model is the limitation on the number of steps of moving food. In his study, because of the limitation of the dimension of the cavity in the moving direction of food and because of the non-interchangeability of cell media property, only six (6) time and spatial steps were allowed in a given cavity which essentially provides a lower bound of moving speed that sometimes narrows down its applications. Furthermore, since MATS system consists of four connected cavities, computer simulation model of Dr. Chen needs to be executed four times from which inherent computational error accumulates after every execution thereby affecting the accuracy of simulation. In the new MATS-CSM model, computational volume considers all four cavities of MATS in one model therefore requiring only one execution of MATS-CSM per simulation run. Furthermore, taking advantage of the new movement function in the Basic Heating Module (BHM) of QuickWave™ wherein interchangeability of cell media are allowed, time and spatial step of food in MATS-CSM where significantly increased (i.e., from 6 step to 16 step) considering a practical simulation time and the computational capability of workstation used. Flexibility in the number of moving steps of foods in MATS-CSM allows for simulation of variable moving speeds of food which was one of the recommendations in Dr. Chen’s study.

Changes in operating frequency bandwidth of microwave generator powering MATS as a result of continuous use and subsequent aging of magnetron was discussed in chapter 4. The operating frequency of microwave generator was systematically monitored for a year period and the effect of change in frequency bandwidth was quantified by comparing changes in heating pattern and location of cold spot in food. Although no significant change in heating pattern and location of cold spot considering the measured fluctuation in operating frequency as a function of power setting of microwave generator, it is recommended that a continuous monitoring of
frequency be done on microwave generators of MATS for the purpose of quality control. The use of MATS-CSM in this part of the study was a time and cost effective way of virtually determining the heating pattern of food at different power and frequency setting of the microwave generators. Only several heating patterns at a specific power and frequency setting of microwave generators was needed to verify experimentally (i.e., using chemical marker M-2) the validity of the simulation result.

Another milestone achieved by this study is the reduction of power reflection which was the topic of chapter 5. A three (3)-probe stab tuner was used for impedance matching on MATS reducing the power reflection from 50-60% to <10%. Doing so drastically improves the overall efficiency of MATS. Again MATS-CSM was used as tools for identifying the proper insertion depth combination of the 3-probe tuner. This was done by extracting $S_{11}$ parameter on MATS-CSM at different insertion depth combination of 3-probes.

Due to the increasing demands on shelf stable food packed in pouch for both military ration and general public consumption, the focus of the applied research part of this study was on food packed in flexible pouches. Furthermore, since MATS was FDA already approved for processing homogenous food (e.g., mashed potato) in 2009, this study took the advantage of testing MATS in processing heterogeneous food for the purpose of obtaining FDA acceptance of the system in processing heterogeneous food. For this purpose, salmon (solid part) and commercially available Alfredo sauce (liquid part) was co-packed inside a flexible pouch and was used as heterogeneous food sample. Following the procedure developed in processing homogeneous food in MATS, a processing schedule was developed for salmon in Alfredo sauce packed in flexible pouch considering several critical factors that may affect microwave heating. The critical factors considered were; (1) the effect of precooking on the dielectric properties of
salmon fillet, and (2) effect of intrinsic and inherent difference in dielectric properties of salmon fillet and Whey Protein Gel (WPG) as model food for salmon. For the effect of precooking on the dielectric properties of salmon fillet discussed in chapter 6, dielectric properties of salmon fillet at 915 MHz was determined considering the effect of different precooking conditions. The precooking conditions used in Chapter 6 are similar to the preheating condition of sample in the preheating section of MATS. Using the obtained data in chapter 6, dielectric property of precooked salmon was incorporated in the MATS-CSM model to simulate the heating pattern, location of cold spot, and heat penetration at the cold spot in a sample of salmon in Alfredo sauce packed in flexible pouch in Chapter 7. The dielectric property of precooked salmon was also used as a reference in selecting the appropriate WPG formulation as model food for salmon used in chemical marker method. Chemical marker method was used in conjunction with MATS-CSM simulation in determining heating pattern and location of cold spot in food wherein the result of one method (e.g. MATS-CSM) serves as verification to the other (chemical marker) and vise-versa, making the final result and conclusion drawn from the result more reliable. For the heat penetration test in this study, a remote metallic temperature sensor was utilized (i.e., the Ellab™ temperature sensors). Although a preliminary study was done on metal sensors, it is recommended that a complete study be conducted on the effect of metal sensor inside food packages in electric field distribution and the resulting heating pattern.

The MATS process is not accepted by the FDA for processing heterogeneous food, specifically for salmon in Alfredo sauce packed in flexible pouch as a sample. Due to this success, microwave sterilization group of WSU are testing different food categories with more complex configuration such as; (1) chicken and dumplings in sauce, (2) tortellini in tomato sauce, (3) macaroni and cheese and many others. Most of these samples are formulated by
different food companies that are members of the WSU Microwave Consortium II and are possible adaptors/recipient of the MATS technology. Processing these foods in MATS requires heating pattern and cold spot identification to properly establish the processing schedules. The MATS-CSM developed in this study can be a useful tool in establishing process schedule for different foods in a time and cost effective manner. The flexibility of MATS-CSM allows for modeling of different food combinations and complex configurations with acceptable accuracy and is complementary to the chemical marker method or any other experimental methods for determining heating pattern and location of cold spot. Currently, the MATS-CSM has several versions classified according to different time steps and food configurations. It is recommended to continuously update the versions of MATS-CSM considering other classification such as; (1) different size and configuration of the cavity, (2) different size and shape of the cavity horn applicator, (3) different configuration of Ultem slab and bars on the size of the cavity that controls electric field pattern, (4) different food movement trajectories, and (5) different type, shape and configuration of food packaging (e.g., flexible pouch and rigid trays).

In a related activity, the microwave sterilization group of WSU is currently developing a microwave heating system for food pasteurization purpose. The computer simulation procedures in MATS-CSM are utilized to create a customized computer simulation modeling for the Microwave Assisted Pasteurization System (MAPS). Since this activity is still at its initial stage, computer simulation is mainly used for characterizing EM field distribution for the development and design of microwave cavities and applicator specific for pasteurization purpose. Due to the demonstrated potential of MATS-CSM in food sterilization, it is recommended that computer simulation method also be explored in heating pattern determination for pasteurization of food.