APPLICATIONS OF COMPUTER SIMULATION MODEL IN DEVELOPING MICROWAVE ASSISTED THERMAL PROCESSING

By

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APPLICATIONS OF COMPUTER SIMULATION MODEL IN DEVELOPING MICROWAVE ASSISTED THERMAL PROCESSING

Abstract

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Microwave heating is a novel technology that has advantages in reducing heating time and improving food quality. A 915 MHz single-mode microwave assisted thermal sterilization (MATS) system was developed at Washington State University with ultimate goal of industrial applications. This research addresses several engineering issues in future scaling-up of the MATS technology.

A major challenge in developing microwave thermal processing has been non-uniform heating patterns which can result in cold and hot spots. The non-uniform heating pattern is caused by the uneven electric field distribution. In this study, computer simulation method was used to analyze the electric field distribution and its components in each direction within a MATS system. The dominant electric field component was in y direction which could be reformed by adjusting the dimensions of Ultem window and horn applicator in y direction or placing metal/Ultem bars within the horn applicators.

In developing a microwave assisted thermal process, time-temperature profile at the cold spot is recorded to establish the process schedule to control most heat resistant food pathogens. Compared with fragile fiber-optic sensor, a mobile metallic temperature sensor is more suitable for continuous moving packages. However, interaction might occur between the metallic temperature sensor and the electromagnetic field. Thus another main objective of this work was to study the performance of a mobile metallic sensor within microwave environment. Results showed that a mobile metallic temperature sensor
could be used for temperature measurement in the MATS system with suitable probe orientation. Certain
design features, such as round probe tip and thinner probe diameter, could improve the sensor accuracy
used in microwave environment.

Dummy loads provide consistent dielectric properties for power delivery and system stability
tests of a microwave heating system in production. The low cost bentonite water paste with high thermal
stability was used to develop reusable dummy load for industrial microwave heating systems. Dielectric
properties of bentonite pastes of various compositions were measured over 300 to 3000 MHz and 20 to
120 ºC. Vegetable oil and salt were used to adjust the dielectric constant and loss factor of bentonite
 pastes to match dielectric properties of different food materials.
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CHAPTER ONE

FUNDAMENTALS OF MICROWAVE THERMAL PROCESSING

1. Introduction

Thermal processing is the most widely used technology in food industry to ensure food safety and extend the product shelf-lives. In thermal processing, sufficient thermal treatment is applied to inactivate pathogens and spoilage microorganisms. Different thermal processing such as pasteurization and sterilization can be selected based on the intended purpose and the severity of a thermal treatment. However, thermal treatments can also induce partial destruction to the nutritional and sensory attributes of food quality. Opportunities for development of high quality food products in conventional thermal processing is limited by the low heat transfer rate from the heat source of hot water or steam to the slowest heating point of the food. Therefore, recent emphasis of research has been placed on development of new technologies that have the potential to substantially improve the quality.

Microwave heating is a novel technology that holds the potential to produce high quality shelf stable food products due to its unique volumetric heating. In microwave heating, alternating electromagnetic (EM) waves go through food materials and the EM fields directly interact with the inside polar molecules and ions of food materials. Heat is generated rapidly as a result of internal molecular friction while the molecules attempt to align themselves with the oscillating electric field at a rate of microwave frequency. The generated heat is converted from microwave energy. The characteristics of microwave energy in air and food materials and the principles of microwave thermal processing will be discussed in chapter one.

2. Electromagnetic basics

2.1 Microwave
Microwaves are EM waves within a frequency band of 300 MHz to 300 GHz (DeCareau, 1985). The corresponding wavelength is from 1 m to 1mm, respectively. The EM waves are classified based on frequency and wavelength. The relationship between frequency and wavelength is
\[ c = \lambda f \] (1)
where \( c \) is the speed of light, in free space \( (c=3.0 \times 10^8 \text{ m/s}) \), \( \lambda \) is the wave length (m) and \( f \) is the frequency (Hz) of EM waves.

Higher frequency is associated with higher energy of a photon according to quantum mechanics (Mehra and Rechenberg, 2001). Microwaves at lower frequency range belong to non-ionizing of electromagnetic energy. They have lower photon energy than that of infrared and visible light. The region of microwaves in EM spectrum is shown in table 1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Wavelength (cm)</th>
<th>Frequency (Hz)</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>&gt;100</td>
<td>&lt;3\times10^8</td>
<td>&lt;10^{-5}</td>
</tr>
<tr>
<td>Microwave</td>
<td>100–0.1</td>
<td>3\times10^8-3\times10^{11}</td>
<td>10^{-5}-0.01</td>
</tr>
<tr>
<td>Infrared</td>
<td>0.1–7\times10^{-5}</td>
<td>3\times10^{11}-4.3\times10^{14}</td>
<td>0.01–2</td>
</tr>
<tr>
<td>Visible</td>
<td>7\times10^{-5}-4\times10^{-5}</td>
<td>4.3\times10^{14}-7.5\times10^{14}</td>
<td>2–3</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>7\times10^{-5}-10^{-7}</td>
<td>7.5\times10^{14}-3\times10^{17}</td>
<td>3\times10^{3}</td>
</tr>
<tr>
<td>X-Rays</td>
<td>10^{-7}-10^{-9}</td>
<td>3\times10^{17}-3\times10^{19}</td>
<td>10^{3}-10^{5}</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>&lt;10^{-9}</td>
<td>&gt;3\times10^{19}</td>
<td>&gt;10^{5}</td>
</tr>
</tbody>
</table>

Microwaves are extensively used in communications and radar detections. The thermal effect of microwave was found in 1945 by a radar engineer ‘Percy Spencer’. Only few selected frequency bands are allowed for industrial, scientific, and medical (ISM) applications to avoid interference with radio frequency of communication systems such as mobile phones and radar transitions. Frequency bands for ISM may vary with different countries. In US, there are two frequency bands allocated by Federal
Communications Commission (FCC) for ISM applications, 915±13 MHz and 2450 ±50 MHz (Metaxas and Meredith, 1993).

2.2 Governing equations of electromagnetic waves

EM waves have two components: electric field component (\(\vec{E}\)) and magnetic field component (\(\vec{H}\)). In general, these two components are vector quantities that have both magnitude and direction. EM wave is a transverse wave; the directions of field components are perpendicular to the direction of energy and wave propagation. The traveling EM waves in media are governed by the physical laws of Maxwell’s equations. The differential form of Maxwell’s equations describe and relate the electric and magnetic field vectors, current and charge densities at any point in space at any time. The differential form of Maxwell’s equations is shown below (Balanis, 1989):

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} = \mu \frac{\partial \vec{H}}{\partial t} \tag{2-a}
\]

\[
\nabla \times \vec{H} = \sigma \vec{E} + \frac{\partial \vec{D}}{\partial t} = \vec{j} + \varepsilon \frac{\partial \vec{E}}{\partial t} \tag{2-b}
\]

\[
\nabla \cdot \vec{D} = \rho \tag{2-c}
\]

\[
\nabla \cdot \vec{B} = 0 \tag{2-d}
\]

Table 2 lists the connotations of each symbol. Each of them is a function of space coordinates and time, for example, \(\vec{E} = \vec{E}(x, y, z; t)\).

Table 2. Descriptions of the symbols in Maxwell’s equations

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>type</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\vec{E})</td>
<td>Electric field intensity</td>
<td>Vector</td>
<td>Volts/meter (V/m)</td>
</tr>
<tr>
<td>(\vec{H})</td>
<td>Magnetic field intensity</td>
<td>Vector</td>
<td>Amperes/ meter (A/m)</td>
</tr>
<tr>
<td>(\vec{D})</td>
<td>Electric flux density</td>
<td>Vector</td>
<td>Coulombs/ square meter (C/m²)</td>
</tr>
<tr>
<td>(\vec{B})</td>
<td>Magnetic flux density</td>
<td>Vector</td>
<td>Weber/ square meter (Wb/m²)</td>
</tr>
<tr>
<td>(\vec{j})</td>
<td>Volume current density</td>
<td>Vector</td>
<td>Amperes/ square meter (A/m²)</td>
</tr>
</tbody>
</table>
Some of the above variables are related as \( \vec{B} = \mu \vec{H}, \vec{D} = \varepsilon \vec{E}, \vec{J} = \sigma \vec{E} \). The constitutive parameters \( \varepsilon, \mu \) and \( \sigma \) are permittivity, permeability and conductivity, respectively, which reveal the electric and magnetic properties of the material. In free space, the values of permittivity and permeability are \( \varepsilon_0 = \frac{1}{36\pi} \) F/m and \( \mu_0 = 4\pi \times 10^{-7} \) H/m, respectively. The conductivity in free space is zero.

Eq. (2-a) is referred to Faraday’s law which states that the electric field intensity around a closed contour is equal to the changing rate of the magnetic flux through the surface enclosed by the contour. Eq. (2-b) is called Ampere’s law which states that the circulation of the magnetic field intensity around a closed contour is equal to the net current passing through the surface enclosed by this contour. Eqs. (2-c) and (2-d) are the Gauss’s law in electric and magnetic field, respectively. It illustrates that the net electric flux out of a close surface is equal to the net charge density enclosed. The net magnetic flux through a surface is always zero since the magnetic charge does not exist (Balanis, 1989).

### 2.3 Boundary conditions

The differential form of Maxwell’s equations is valid only if the field vectors are continuous functions of position and time and these functions have continuous derivatives. Along the boundaries that the electrical properties of the involved media are not continuous, the field vectors are also discontinuous. The boundary conditions describe these vectors’ behavior across the interface of media (medium 1 and medium 2) with different electrical properties:

\[
\hat{n} \times (\vec{E}_2 - \vec{E}_1) = 0
\]  

(3-a)
\[ \vec{n} \times (\vec{H}_2 - \vec{H}_1) = \vec{j}_s \]  
\[ \vec{n} \cdot (\vec{D}_2 - \vec{D}_1) = q_s \]  
\[ \vec{n} \cdot (\vec{B}_2 - \vec{B}_1) = 0 \]

where \( \vec{j}_s \) is the induced electric current density due to the existence of source or charges; \( q_s \) is the surface charge density at the boundary plane. Eqs. (3a-d) is the general form of boundary conditions which can be modified for different media. For example, if the two medias are both dielectric materials without source and having constitutive parameters of \( \varepsilon_1, \mu_1, \sigma_1 \) and \( \varepsilon_2, \mu_2, \sigma_2 \), respectively. The boundary condition can be written as:

\[ \vec{n} \times (\vec{E}_2 - \vec{E}_1) = 0 \]  
\[ \vec{n} \times (\vec{H}_2 - \vec{H}_1) = 0 \]  
\[ \vec{n} \cdot (\vec{D}_2 - \vec{D}_1) = \vec{n} \cdot (\varepsilon_2 \vec{E}_2 - \varepsilon_1 \vec{E}_1) = 0 \]  
\[ \vec{n} \cdot (\vec{B}_2 - \vec{B}_1) = \vec{n} \cdot (\mu_2 \vec{H}_2 - \mu_1 \vec{H}_1) = 0 \]

For two adjacent dielectric materials without source, Eq. (4-a) and Eq. (4-b) sate that the tangential component of electric and magnetic field intensity across the interface is continuous; Eq. (4-c) and Eq. (4-d) indicate that the normal component of electric and magnetic flux density across the surface is continuous. However, the normal component of electric and magnetic field intensity are not continuous.

### 2.4 Wave equations

Wave equations for electric field and magnetic field in uniform medium could be derived from Eqs. (2a-d). A uniform medium has properties of linear (constitutive parameters are independent of the applied field), homogeneous (constitutive parameters are independent of position), isotropic (constitutive parameters are not dependent on direction that EM wave applied) (Guru & Hiziroglu, 2004).

In uniform medium without net charge density and current density, Eq. (5-a) and (5-b) are obtained by applying curl operator on each side of Eq. (2-a) and (2-b).

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

(5-a)
\[ \nabla^2 \vec{H} = \mu_0 \frac{\partial \vec{H}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \]  

(5-b)

Assuming the electrical and magnetic field intensity is sinusoidal and time harmonic. Then the above equations are written as:

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

(6-a)

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

(6-b)

\[ \vec{E}(x, y, z; t) = \text{Re}[\vec{E}(x, y, z)e^{j\omega t}] \]  

(6-c)

\[ \vec{H}(x, y, z; t) = \text{Re}[\vec{H}(x, y, z)e^{j\omega t}] \]  

(6-d)

\[ \gamma^2 = j \mu \sigma - \mu \varepsilon \omega^2 = (\alpha + j\beta)^2 \]  

(6-e)

where \( \vec{E} \) and \( \vec{H} \) stand for the corresponding complex spatial form of electric and magnetic field intensity which are functions of only position. The absolute values of \( \vec{E} \) and \( \vec{H} \) are the amplitudes of the time varying fields of \( \vec{E} \) and \( \vec{H} \); \( \omega = 2\pi f \) is the angular frequency of the waves (rad/s); \( j = \sqrt{-1} \) is the imaginary number unit; \( \gamma \) is propagation constant of the EM waves, \( \alpha \) and \( \beta \) are both real and positive numbers. For simplicity, suppose the electrical field intensity only has component in x direction \( E_x \) with amplitude of \( E_{x0} \) and it propagates in +z direction; the magnetic field intensity only has a component in y direction \( H_y \) with amplitude of \( H_{y0} \) and it propagates in the same +z direction. The differential equations of (6-a) and (6-b) could be solved as:

\[ E_x(z) = E_{x0}\exp(-\gamma z) \]  

(7-a)

\[ H_y(z) = H_{y0}\exp(-\gamma z) \]  

(7-b)

When a time harmonic electric field with an angular frequency \( \omega \) is applied to a dielectric material, the field intensity may dissipate due to polarization mechanisms. The permittivity \( \varepsilon \), which is referred as dielectric properties of the dielectric materials, is a complex quantity.

\[ \varepsilon = \varepsilon' - j\varepsilon^* \]  

(8)

\( \varepsilon' \) related to the ability of material to store electric energy due to electric polarizations; \( \varepsilon^* \) describes the ability of materials to dissipate energy due to continuous polarization within time-harmonic field.
Apply complex permittivity to Eq (6-e):

\[ \gamma^2 = j\mu\sigma - \mu\omega^2(\varepsilon' - j\varepsilon^*) = j\mu\omega\sigma_e - \mu\omega^2\varepsilon' = (\alpha + j\beta)^2 \]  

(9-a)

\[ \sigma_e = \sigma_s + \omega\varepsilon^* = \sigma_s + \sigma_a \]  

(9-b)

\[ \sigma_a = \omega\varepsilon^* \]  

(9-c)

In which, \( \sigma_e \) is the equivalent conductivity, \( \sigma_a \) is called alternating conductivity; \( \sigma_s \) is static field conductivity (Balanis, 1989). Derived from Eq. (9-a), the real, positive numbers of \( \alpha \) and \( \beta \) are:

\[ \alpha = \omega \sqrt{\frac{\mu\varepsilon'}{2}} \sqrt{1 + \left( \frac{\sigma_a}{\omega\varepsilon^*} \right)^2} - 1 \]  

(10-a)

\[ \beta = \omega \sqrt{\frac{\mu\varepsilon'}{2}} \sqrt{1 + \left( \frac{\sigma_a}{\omega\varepsilon^*} \right)^2} + 1 \]  

(10-b)

The real part \( \alpha \) regarded as the attenuation constant (Np/m), represents the dissipation rate of wave amplitude. The disappeared energy is absorbed by media and generates heat. The imaginary part \( \beta \), which is referred to phase constant (rad/m), describes the propagation of the wave. Both of the two constant are functions of media constitutive parameters.

### 2.5 Energy and Power

Energy of propagating EM waves is described by a Pontying vector (Balanis, 1989):

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

(11)

For time harmonic EM waves, the averaged Pontying vector in one time period is equal to:

\[ P_{av} = \frac{1}{2} \text{Re}(\vec{E} \times \vec{H}^*) \]  

(12)

In which \( \vec{H}^* \) is the conjugate of \( \vec{H} \). The averaged dissipated power in a unit volume is:

\[ P_{dv} = \frac{1}{2} \sigma_e |\vec{E}|^2 = \frac{1}{2} \left( \sigma_s + \omega\varepsilon^* \right) |\vec{E}|^2 \]  

(13)

In which \( |\vec{E}| \) is the amplitude of the time varying field \( \vec{E} \). In general, an equivalent constant electrical field \( \vec{E} \) is substitute for \( |\vec{E}| \) in the expression of averaged power. The equivalent constant electric
field $E$ could generate the same amount of heat with $\vec{E}$ during one period ($T = 1/f$). The relationship among $E$, $\vec{E}$ and $|E|$ could be expressed as

$$\frac{E^2}{T} = \frac{\int_{0}^{T} |\vec{E}|^2}{T} = \frac{\int_{0}^{T} |\text{Re}[\mathbf{E}(x, y, z)e^{j\omega t}]|^2}{T} = \frac{1}{2} |E|^2$$  \hspace{1cm} (14)

### 2.6 Penetration depth of power

For time harmonic EM waves propagating in $+z$ direction with components of $E_x$ and $H_y$, the power density could be derived from Eq. (12):

$$P_{av}(z) = \frac{1}{2} \text{Re} (\mathbf{E} \times \mathbf{H}^*) = \frac{1}{2} E_{x0} * H_{y0} e^{-2az}$$  \hspace{1cm} (15)

Derived from Faraday’s law of time-harmonic field:

$$E_{x0} = \sqrt{\frac{\mu}{\epsilon}} H_{y0} - \eta H_{y0}$$  \hspace{1cm} (16)

Where $\eta = \sqrt{\mu/\epsilon}$ is known as the intrinsic wave impedance of a material. Substitute $E_{x0}$ from Eq. (16) in Eq. (15):

$$P_{av}(z) = \frac{1}{2\eta} E_{x0}^2 e^{-2az}$$  \hspace{1cm} (17)

In lossy material, attenuation constant $\alpha$ is not equal to zero. A fraction of microwave energy is converted into heat. The power stored in EM wave attenuates exponentially with the distance it passes through. Power penetration depth is defined as the distance which EM wave travels to reduce its power to $1/e$ ($e=2.718$) or 36.9% of its original magnitude (Metexas and Meredith, 1993). Figure 1 shows the EM power attenuation in a lossy material.
Penetration depth for a lossy material could be derived from Eq. (17):

$$d_p = \frac{1}{2\alpha} = \frac{1}{\omega \sqrt{\frac{2\mu \varepsilon}{\varepsilon + (\frac{\varepsilon}{\alpha \omega \gamma})^2}}} \quad \text{(18)}$$

The dielectric materials, such as food, are good insulators without static conductivity. The loss factor is dominated by the alternating conductivity that is contributed by dielectric loss factor (Balanis, 1989). The penetration depth of food materials is shown as:

$$d_p = \frac{1}{2\alpha} = \frac{1}{2\pi f \sqrt{\frac{2\mu \varepsilon}{\varepsilon + (\frac{\varepsilon}{\alpha \omega \gamma})^2}}} \quad \text{(19)}$$

2.7 Transmission and reflection

Reflection and transmission occurs when EM wave travel across the interface of two different media. Figure 2 illustrate a EM wave traveling from medium 1 ($\varepsilon_1$, $\mu_1$, $\eta_1$) to medium 2 ($\varepsilon_2$, $\mu_2$, $\eta_2$). The traveling wave is called incident wave before it reaches to the interface. When the incident wave encounters the interface, part of the wave is reflected by the interface, the remaining transmits into the medium 2 which are called as reflected wave and transmitted (refracted) wave, respectively.
The reflection coefficient ($R$) and transmission coefficient ($T$) are shown below

$$R = \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_t}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t} \quad (20-a)$$

$$T = \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t} \quad (20-b)$$

This phenomenon obeys Snell’s law (Mudgett, 1985). For reflection, the incident angle is equal to reflected angle. For transmission (refraction), the relationship between incident angle and refraction angle is shown in Eq. (21-b):

$$\theta_i = \theta_r \quad (21-a)$$

$$\sqrt{\varepsilon_1 \mu_1 \sin \theta_i} = \sqrt{\varepsilon_2 \mu_2 \sin \theta_t} \quad (21-b)$$

If the incident wave travels from one medium to another medium with an incident angle of $0^\circ$ (i.e. perpendicular penetration), the reflected angle is also equal to $0^\circ$. As a result, the reflected wave has a $180^\circ$ out of phase with the incident wave at the reflected surface. Compared with the incident wave, the reflected wave travels in opposite direction and the amplitude is determined by the reflection coefficient
Take the simplified EM wave in Eq. (7-a) for example, the wave only has $E_x$ and $H_y$ component traveling in $+z$ direction. Assume the two media are both lossless. The incident and reflected electric field equations can be written as:

$$E_i(z; t) = \text{Re}[E_{x0}e^{-\gamma z} * e^{j\omega t}] = \text{Re}[E_{x0}e^{-j\beta z-j\omega t}] = E_{x0}\sin(-\omega t - \beta z) \quad (22-a)$$

$$E_r(z; t) = \Gamma E_{x0}\sin(-\omega t + \beta z) \quad (22-b)$$

The superposed wave equation is:

$$E_s(z; t) = E_{x0}\sin(-\omega t - \beta z) + \Gamma E_{x0}\sin(-\omega t + \beta z) \quad (23-a)$$

$$= \Gamma E_{x0}(\sin(-\omega t - \beta z) + \sin(-\omega t + \beta z)) \quad (23-b1)$$

$$+(1 - \Gamma)E_{x0}\sin(-\omega t - \beta z) \quad (23-b2)$$

The wave equation of Eq. (23-b1) is a superposition of two waves travelling with same frequency ($f = \omega / 2\pi$), amplitude ($\Gamma E_{x0}$) and opposite travelling direction. It has a filed pattern that appears to be stationary which is called standing wave. Applying the following trigonometric identical equation to Eq. (23-b1),

$$\sin(x) + \sin(y) = 2\sin(\frac{1}{2}(x + y))\cos(\frac{1}{2}(x - y)) \quad (24)$$

It transforms to:

$$\Gamma E_{x0}(\sin(-\omega t - \beta z) + \sin(-\omega t + \beta z)) = 2\Gamma E_{x0}\sin(-\omega t)\cos(\beta z) \quad (25)$$

The wave equation of (25) implies that for a standing wave, at any fixed point ($z_0$) the field intensity is alternating with time. However, the amplitude is fixed by the position ($\cos(\beta z)$). At some fixed positions ($\cos(\beta z) = 0$) the field intensity is always zero. The position with zero amplitude is called a node and the position with maximum amplitude is called an anti-node. The distance between two adjacent nodes or anti-node is equal to half wavelength.

From Eq. (23-a) to (23-b2), the superposition of the incident wave and its reflected wave is a combination of a standing wave with amplitude of $2\Gamma E_{x0}$ and a travelling wave with amplitude of $(1 - \Gamma)E_{x0}$. The reflected coefficient $\Gamma$ determines the dominant field pattern to be a standing wave or a travelling wave. When the EM wave travels from air to metal with incident angle of $0^\circ$, almost all the
wave will be reflected to make \( I \) is equal to 1. A standing wave with amplitude of \( 2E_{x_0} \) will form as shown in Figure 3.

![Figure 3: Illustration of a standing wave oscillating with time and position](image)

2.8 Propagation mode in waveguide and cavity

The propagation mode of EM waves in homogeneous medium obeys the wave equations (5-a) and (5-b). Assume the propagation direction is along z axis. The following three configurations can be obtained from the solutions of wave equations (Dibben, 2001):

Transverse electromagnetic (TEM\(^z\)): Components of both electric and magnetic fields in the propagation (z) direction are equal to zero, \( H_z = E_z = 0 \).

Transverse magnetic (TM\(z\)): the magnetic field component in the propagation (z) direction is equal to zero, \( H_z = 0 \).

Transverse electric (TE\(z\)): the electric field has no component in the propagation (z) direction, \( E_z = 0 \).

However, the TEM\(^z\) mode does not satisfy the boundary condition of the waveguide wall. Figure 4 illustrates the dimension of a rectangular waveguide that transmitting EM energy in positive z direction.
Considering a TE\textsuperscript{z} mode as an example, the solutions of EM waves are (Balanis, 1989):

\[ E_x^+ = A_{mn} \frac{\beta_y}{\epsilon} \cos(\beta_x x) \sin(\beta_y y) e^{-j\beta_z z} \]  
\[ E_y^+ = -A_{mn} \frac{\beta_x}{\epsilon} \sin(\beta_x x) \cos(\beta_y y) e^{-j\beta_z z} \]  
\[ E_z^+ = 0 \]  
\[ H_x^+ = A_{mn} \frac{\beta_x \beta_z}{\omega \mu \epsilon} \sin(\beta_x x) \cos(\beta_y y) e^{-j\beta_z z} \]  
\[ H_y^+ = A_{mn} \frac{\beta_y \beta_z}{\omega \mu \epsilon} \cos(\beta_x x) \sin(\beta_y y) e^{-j\beta_z z} \]  
\[ H_z^+ = -j A_{mn} \frac{\beta_x^2 + \beta_z^2}{\omega \mu \epsilon} \cos(\beta_x x) \cos(\beta_y y) e^{-j\beta_z z} \]

In which

\[ \beta_x^2 + \beta_y^2 + \beta_z^2 = \beta^2 = \frac{\omega^2 \mu \epsilon}{a^2} \]  
\[ \beta_x = \frac{n \pi}{a} \]  
\[ \beta_y = \frac{n \pi}{b} \]  

Where \( E_x^+ \), \( E_y^+ \), \( E_z^+ \), \( H_x^+ \), \( H_y^+ \) and \( H_z^+ \) represent the electric and magnetic field intensity in each spatial component within the rectangular coordinate system; the superscript (+) indicates that the EM wave is propagating in +z direction; \( \beta_x \), \( \beta_y \) and \( \beta_z \) are the components of phase constant \( \beta \) (Eq. 10-b) in
each coordinates direction; \( a \) and \( b \) represent the dimension of the waveguide in \( x \) and \( y \) direction; \( m \) and \( n \) are integer numbers which are not zero at the same time in a solution \((m \neq n=0, 1, 2, \ldots)\); \( A_{mn} \) is the amplitude constant of the solution corresponding with \( m \) and \( n \). From physical standpoint, the propagating EM wave (in \( z \) direction) forms standing wave in \( x \) and \( y \) direction. The integer number \( m \) and \( n \) indicates the number of semi-sinusoidal variations (anti-node) in the \( x \) and \( y \) directions, respectively. Figure 5 displays the electric field distribution of some TE modes with different semi-sinusoidal combinations (\( m \) and \( n \)).

![Electric field distribution of some TE\( mn \) modes: A: \( m=3, n=0 \); B: \( m=3, n=1 \); C: \( m=3, n=2 \); D: \( m=3, n=4 \)](image)

Figure 5: Electric field distribution of some TE\( mn \) modes: A: \( m=3, n=0 \); B: \( m=3, n=1 \); C: \( m=3, n=2 \); D: \( m=3, n=4 \)

Solution with different values of \( m \) and \( n \) leads to different modes. With a given mode, there is a matching cutoff frequency \((f_c)\) for each waveguide. The EM waves cannot propagate in the wave guide if it has a frequency lower than the cutoff frequency. The cutoff frequency could be derived from:

\[
(f_c)_{mn} = \frac{1}{2\pi \sqrt{\mu \varepsilon}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}
\] (28)
In a waveguide, the transmitted microwave of a mode with lowest frequency is called the dominant mode. The dominant TE10 mode is always the normal operation mode of a rectangular waveguide for power transmission.

Resonant cavity is a common applicator of microwave for heating purpose. The typical example is domestic microwave oven. Similar to the microwaves in a waveguide, there exist different resonant modes in a cavity. There are three integer parameters (m, n and p corresponding three directions) to determine a specific mode with its matching resonant frequency (Metaxas and Meredith, 1993).

\[
\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{c}\right)^2 = \omega^2 \mu \varepsilon
\]  

(29)

The dimension of the cavity is \(a \times b \times c\) in \(x, y\) and \(z\) directions, respectively. If the dimension of a resonant cavity can only support one mode at the operating frequency band, it is called as a single model cavity; otherwise it is a multi-mode cavity. Table 3 shows the possible modes that exist in an empty multimode cavity of dimension 360×350×260 mm\(^3\).

Table 3. Resonant models in an empty multimode cavity with dimension of 360×350×260 mm\(^3\) (Chan and Reader, 2000)

<table>
<thead>
<tr>
<th>Calculated modes</th>
<th>Mode type</th>
<th>Calculated frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m    n  p</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 5 2</td>
<td>TE</td>
<td>2.4327</td>
</tr>
<tr>
<td>0 4 3</td>
<td>TE</td>
<td>2.4351</td>
</tr>
<tr>
<td>4 1 3</td>
<td>TE, TM</td>
<td>2.4398</td>
</tr>
<tr>
<td>5 3 0</td>
<td>TE</td>
<td>2.4471</td>
</tr>
<tr>
<td>2 0 4</td>
<td>TE</td>
<td>2.4626</td>
</tr>
<tr>
<td>4 4 1</td>
<td>TE, TM</td>
<td>2.4586</td>
</tr>
</tbody>
</table>
From Table 3, the resonant frequencies of different modes are very close to each other. The mode type of one microwave heating system is determined by the system dimension and the frequency (or wavelength) of the microwave source. In a multimode cavity such as domestic microwave oven, the electrical field distribution is random with the changing frequencies. The total field pattern is the combination of all the possible modes which is hard to be determined. Furthermore, when a load is placed in the cavity, the resonant frequency and field pattern will be changed and intensifies the complexity. Figure 6 shows some snapshots of frequencies for a domestic microwave oven. The frequency of empty oven is changing with time within a band. However, when a glass of water was placed in, the frequency variation is turbulent. This result implies that multi-mode cavity could not generate a stable electrical field distribution and heating pattern. For industrial microwave heating, a single-mode cavity is recommended to obtain a stable and repeatable heating pattern. The frequency of 2450 MHz is not suitable for single-mode cavity design because the cavity dimension is limited to the corresponding short wavelength. For industrial application, 915 MHz single mode microwave heating cavities are more suitable to provide predictable heating patterns.
Figure 6: Snapshots of frequency variations in a domestic microwave oven. A: empty cavity; B: with a glass of water

3. Microwave thermal processing

Microwave energy has been widely used in food processing such as for tempering frozen fish and meat, precooking bacon, blanching vegetables, dyeing, baking (Ahmed and Ramaswamy, 2007). Domestic microwave oven has become a household necessity appliance in modern fast pace life due to its advantage in convenience cooking. Besides these applications, microwave thermal processing (i.e. pasteurization and sterilization) is attractive in producing high quality food products due to its fast heating rate.

The design of a thermal process is based on the destruction kinetics of concerned microorganisms. There is an argument between thermal and non-thermal effect of microwave heating in inactivating microorganisms. Potential theories to explain non-thermal effect of microwaves on bacteria were summarized by Knorr et al. (1994). However, the opponents refute any molecular effects of microwave using experiments results and classical axioms of physics and chemistry (Stuerga and Gaillard, 1996, Ponne, 1996; Tang and Chow Ting Chan, 2007). The conclusive effect of microbial inactivation in microwave heating is thermal effect. The microbial inactivation kinetics for microwaves is essentially the same as that of conventional thermal processing. Thus, only thermal effect is taken into account in designing a microwave thermal processing while any non-thermal or enhanced thermal effects can be considered as added safety with respect to microorganism lethality. Hence, the principles for
designing a conventional thermal processing design are also suitable in the design of a microwave thermal process. This has been the basis for developing a microwave thermal process.

3.1 Principle of thermal processing of food

Thermal processing has been extensively used in the food industry since it was first developed by Nicolas Appert and the following commercialization. A review on the history of thermal processing science and technology was reported by Goldblith (1971; 1972). The main purposes of industrial thermal processing are to inactivate pathogens and spoilage microorganisms.

Mathematical models have been used in designing industrial thermal processes to ensure the safety of the products and for shelf-life extension (Holdsworth, 1985). A thermal process is established based on the kinetics information for the most heat resistant microorganisms and heating rate for each specific product. The general sterilization process for low acid food is designed to sterilize Clostridium Botulinum (C. Botulinum). Low acid food is defined as foods that have equilibrium pH value greater than 4.6 and a water activity greater than 0.85 (Awuah and Ramswamy, 2007). Within a pH value of 4.6 or lower environment, the C. Botulinum will not grow to produce toxin. However, for low acid foods (pH>4.6), attention is given to C. Botulinum which has highest heat resistance and continue to thrive under anaerobic condition. Industrial processing requires commercial sterility which is defined based on thermal lethality value of C. Botulinum. The thermal lethality value is calculated by combination of the time-temperature history at cold spot location and the kinetic data of C. Botulinum. There are two key parameters which describe the thermal inactivation kinetics of microorganisms called as D and z values. The D value is defined as the heating time (min) that inactivates 90% of existing microbial population at a fixed temperature. The z value represents the temperature increment (°C) that results in 90% reduction of the D value. The basic mathematical model for lethality value was developed by Ball and Olson (1957):

\[
F = \int_0^t 10^{\frac{T-T_{ref}}{z}} \, dt
\]  

(30)

where \( t \) is the processing time (min), \( T \) (°C) is the temperature at time \( t \), \( T_{ref} \) is the reference temperature (°C), \( F \) is the equivalent lethality value (min) at the reference temperature. The standard sterilization
value for low acid food is defined as $F_0$ while the standard reference temperature is 121.1 °C (250 °F) and the $z$ value is 10 °C for the target microorganism of *C. Botulinum*. A minimum value i.e. $F_0$ is required for a successfully sterility. For low acid food $F_0$ should be equal or greater than 3 min which is the time for 12 decimal reduction (12D, i.e. population reduced to 1 in $10^{12}$) based on the kinetic data for *C. Botulinum* (Brown, 1991). However, for the actual process design both public health and spoilage organisms need to be taken into account.

The concept of $F$ value could also be applied to other thermal processing with different reference temperature as $F_{ref}$ value. Pasteurization is another type of thermal processing that can be evaluated by the thermal lethality model. Pasteurization is done to minimize public health hazards and food spoilage microorganisms and extend useful shelf life of foods by relatively mild heat treatments. The temperature for pasteurization treatment is generally below 100 °C. For pasteurized chilled food products that stored and retailed at low temperature (<4°C), 6D reduction is generally required for human pathogen such as *Listeria monocytogenes*. To achieve this treatment, an equivalent F value of 2 min at temperature of 70 °C is required, $F_{70} = 2$ min (Holdsworth, 1997). However, specific process is designed for the specific food and related target microorganism. For example, milk and whole egg are pasteurized to provide 12D and 6D reduction in population of *Coxiellaburnetti* and *Samonellaseftenberg*, respectively (Harper, 1976; Hammid-Samini and Swartzel, 1984).

### 3.2 Optimization of thermal processing

Thermal processing has the tendency to bring irreversible changes to the nutritional and sensory quality of foods such as vitamins, color and texture. Similar to the kinetic data of microorganisms, D and $z$ values of nutrients could also be defined to describe their degradation during thermal process. Mansfield (1962) defined the concept of C (cook) value to evaluate quality degradation of food in a thermal processing:

$$C = \int_0^t 10^{\frac{T-T_{ref}}{z_c}} dt$$  \hspace{1cm} (31)
where C is the C value (min), $T_{ref_c}$ and $z_c$ are the reference temperature (°C) and z value (°C) of the most cook labile food component, respectively. The reference cook value $C_0$ is defined by choosing $z_c = 33.1$ °C and $T_{ref_c} = 100$ °C. Eqs. (30) and (31) indicate that different time-temperature combinations will lead to different F and C values. The general z values for nutrients degradation have a range of 25-45 °C which is normally greater than microbial inactivation of 7-12 °C (Awuah and Ramswamy, 2007; Holdsworth, 1985). Higher z values of nutrients suggest that they are less heat sensitive than microorganisms. Such difference in heat resistance between nutrients and bacteria provides a theoretical basis to optimize the thermal process for producing high quality safety food products. High temperature short time (HTST) process was developed to improve thermal processed food quality under the condition of a sufficient F value (Lund, 1977; 1982). HTST process is the basic conception to optimize thermal processing process. Numerous processing models and packaging techniques have been developed to optimize food quality in conventional thermal processing (Simpson et al., 2004; Silva et al., 1994; Chen and Ramaswamy, 2002a, 2002b, 2002c; Noronha et al., 1996; Balsa-Canto et al., 2002a, 2002b). However, the successful optimization process for solid and semi-solid food products is limited by the low heat penetration rate. Smout et al. (2003), suggested that for industrial retort the non-uniformity improvement in quality varies a lot among different containers. It might be impossible to optimize such a process because the non-uniform temperature distribution in a retort will go beyond the uniformity improvement in the optimizing process.

Novel technology such as microwave heating can offer fast heating rate to overcome the limitation of traditional heat transfer (Guan et al., 2002; Ohlsson, 1987; 1992). Such technology has the potential to provide thermal process for producing high quality food products without compromising food safety to satisfy the demands of market. However, the design of a new thermal processing process should base on the basic rules to meet the primary requirement of safety.

3.3 Factors affecting microwave heating
In a microwave heating process, many factors affect the microwave energy dissipation and the heating behavior of food materials.

The averaged dissipated power in a unit volume is described in Eqs. (13-14) which could be described as

\[ P_d = \omega \varepsilon_0 \varepsilon_r^* E^2 = 2\pi f \omega \varepsilon_0 \varepsilon_r^* E^2 = 5.56 \times 10^{-11} f \varepsilon_r^* E^2 \] (32)

The temperature increase \( \Delta T \) derived from dielectric heating can be calculated from (Nelson, 1996):

\[ \rho C_p \frac{\Delta T}{\Delta t} = 2\pi f \varepsilon_0 \varepsilon_r^* E^2 = 5.563 \times 10^{-11} f \varepsilon_r^* E^2 \] (33)

where \( C_p \) (Jkg\(^{-1}\)C\(^{-1}\)) and \( \rho \) (kgm\(^{-3}\)) is the specific heat and density of the food material, respectively; \( E \) (Vm\(^{-1}\)) is the equivalent constant electric field intensity, \( f \) (Hz) is the frequency of microwave, \( \Delta t \) (s) and \( \Delta T \) (°C) is increment of time and food temperature. Values of specific heat and density of different foods, and heat transfer calculations within microwave heated foods can be found elsewhere (Singh & Heldman, 2001).

The parameters that may affect the temperature increment \( \Delta T \) include physical (\( \rho \)) and thermal properties \( (C_p)\) of food material, microwave frequency \( (f)\), dielectric properties of food material \( (\varepsilon_r^*)\) and electric field intensity \( (E)\). The temperature distribution inside microwave heated food is governed by both the thermal properties of the food and the distribution of the microwave energy dissipation.

**Frequency**

There are two microwave frequencies allocated for industrial application, 915 and 2450 MHz. From Eq. (33), heat generation inside food is proportional to the frequency of applied microwave. In addition, frequency is a key parameter that affects the penetration depth of microwave energy (Eq. 19). Dielectric properties of food materials are also dependent on frequencies which indirectly affect the heating rate. The temperature distribution within food sample depends on the inside electric field distribution. Frequency (wavelength) determines the electric field distribution mode in a given microwave heating cavity.
**Electric field distribution**

Alternating electric field is the source of microwave heating where the heating rate was proportional to the square of electric field intensity. Non-uniform electric field intensity results in uneven temperature distribution within food materials. Furthermore, the uneven heating pattern will be intensified in long time microwave heating because temperature increase is proportional to the square of electric field intensity (Eq. 33). The uneven heating pattern of food is the major challenge to commercialize microwave heating process in food industry. The design of a uniform electric field distribution is based on fully understanding the propagation mode within the microwave heating cavity.

**Shape and position of food**

Electric field distribution can be affected by the shape and position of food sample. The presence of food in microwave heating cavity changed the previous boundary conditions. In general, electric field intensity is higher at sharp edges. This is the reason for overheating at edges. A uniform heating pattern could be obtained by matching the shape and size of food sample to the electric field distribution.

**Dielectric properties of food**

Dielectric properties of food material determine its ability to store and absorb microwave energy. They are the most important properties of food in microwave heating. The dielectric properties of a food material have two components (Eq. 8), dielectric constant $\varepsilon_r$ and dielectric loss factor $\varepsilon''$ which indicate the ability of food material to store and dissipate microwave energy, respectively. The dissipated power in per unit volume is directly related to the loss factor (Eq. 33). However, dielectric constant can also affect the power dissipation in microwave heating. The dielectric constant is a key parameter in power penetration depth (Eq. 19). The instantaneous electric field intensity within food will be affected by the dielectric constant. The dielectric properties are affected by food components, especially water and salt content. High water content increases dielectric constant and more salt content could result in high loss factor. Besides components, dielectric properties of food change with microwave frequency and temperature. Generally, the dielectric constant decreases with increasing frequency and temperature.
However, loss factor increases with increasing temperature. The mutual effect between temperature and dielectric properties could lead to temperature runaway at higher electric field intensity domain.

**Thermal properties of food**

Thermal properties do not affect the microwave energy absorption of foods. However, at the same power level, temperature increase rate is affected by the density and specific heat of food. Microwave power should be adjusted based on the thermal properties of different food materials. Food materials with large difference in specific heat should not be heated in the same microwave heating system without special measure to the easily heated portion of the food, such as partial shielding or lower intimal temperature. Otherwise the food with lower specific heat will be over heated before the other one receiving enough heat. For multi-component foods, attention should be paid to avoid large difference in specific heat among different components. Density variation among different food is not as big as the variation on specific heat and it has little influence on microwave heating. In addition, the thermal conductivity of food may also affect the microwave heating in heating uniformity of food. However, its influence is limited by the short heating time.

**3.4 Industrial application of microwave thermal process**

Microwave heating has been successfully applied in food industry for many processes due to its advantages in reducing processing time and improving product qualities (Ahmed and Ramaswamy, 2007). Recently, more emphasis is placed on applications of microwave heating in commercial thermal processing to satisfy the increasing demands of high quality shelf stable food. Although domestic microwave ovens are the dominant application of 2450 MHz microwave, it is also used in industrial systems. The information of commercial scale of 2450 MHz microwave sterilization systems were reported in literature i.e. OMAC (Harlfinger, 1992) and Berstorff (Schlegel, 1992). Several 2450 MHz systems are used in commercial production of shelf stable packaged foods outside US such as Tops Foods (Olen, Belgium) in Europe and Otsuka Chemical Co. (Tokushima, Japan) in Japan. However, in the US for low acid food, the commercial application of microwave thermal sterilization must receive the FDA
and/or USDA FSIS acceptance as a reliable procedure to ensure microbiological safety. Till now, there is no commercial microwave sterilization operation in North America. Over the past 10 years only Washington State University (Pullman, WA) reported the research on microwave sterilization of packaged foods.

A 915 MHz single-mode microwave assisted thermal sterilization (MATS) system was developed by the advanced thermal processing research team at Washington State University (Tang et al., 2006). It could be a prototype developing a continuous microwave sterilization systems for commercial sterilization of food packed in polymeric containers. In October 2009, after rigorous review by the FDA, the microwave sterilization process for homogeneous mashed potato has been accepted. It was recognized as the first FDA approved microwave process for commercial sterilization of low acid food in the United States. The primary key to gain the FDA acceptance is the particular design of the system and critical procedure for establishing of the processes schedule. This could provide a guideline for designing industrial scale microwave thermal processing.

(1) Single mode design of the microwave heating system. A 915 MHz single mode microwave heating cavity is the key part of MATS system to provide predictable and reproducible heating patterns in foods. Computer simulation models developed based on finite difference time domain (FDTD) method were used to assist the design (Pathak et al., 2003; Chen et al., 2007; 2008).

(2) Determination of cold spot location. Experimental tests are essential to validate results from computer simulation models and confirm the actual heating pattern. Chemical marker (M-2) combined with computer vision method was developed to verify the simulation results to confirm the cold spot location (Pandit et al., 2006; 2007). Furthermore, temperature measurements at cold spot domain were carried out using fiber optic sensors and mobile data tracers. More than one cold spots may occur inside a microwave heated food sample. The coldest spot would be confirmed through multiple temperature measurements at all the possible cold spot locations.
(3) Design of the process schedule. The time-temperature history at cold spot was used to establish the process schedule based on the kinetics study of target microorganism. The processing parameters such as microwave power, moving speed of food packages are decided after several tests.

(4) Microbial validation. Once a process was scheduled, lethality rate needs to be verified through inoculated pack studies using *Clostridium* supergenes as surrogate.

In addition to food safety, product quality and production rate are the substantial factors for the adoption of microwave technology at industrial scale. To improve production and energy efficiency, higher power microwave would be applied. However, high microwave power may enhance the non-uniform heating pattern. Thus, the major challenge to commercialize this technology is to design a uniform heating pattern. Heating pattern in microwave heating is governed by electric field distribution. A coupled EM and heat transfer computer simulation model could assist the analysis of electric field distribution and the effects of different parameters such as cavity dimension, shape and size of food.

Besides heating pattern design, temperature measurement in high power microwave heating system is another problem needs to be solved. Fiber optic sensors are not suitable for temperature measurement in moving samples within high pressure chamber. The mobile data tracer packaged within food is a good alternative. However, within high electric field environment, the influence of the sensor’s metallic surface on electric field distribution and measurement accuracy should be revealed before application.

The mechanism of microwave power delivery is different from traditional thermal processing. The dielectric properties of food will affect the efficiency of power delivery. Use of calibrated sample is essential in the system design and further stability test. A reusable dummy load will save cost and time during these tests especially for industrial scale system with high capacity.

4. Conclusion

Electromagnetic theories govern the microwave heating processes in food materials. The mode type in a microwave heating cavity is determined by its dimension and the frequency of applied
microwaves. A single-mode microwave heating system could avoid the influence from frequency shifts of the microwave source and provide a repeatable heating pattern. Only thermal effect of microwave heating is considered in designing a microwave thermal process while any non-thermal effect is considered as an added up safety. Thus in designing, microwave thermal processing follows the same rule as that in conventional thermal processing. In the USA, FDA has accepted the first microwave assisted thermal processing based on the MATS system developed at Washington State University. The procedure for developing MATS system could be expanded to industrial scale microwave heating processes with high microwave power and production rate. However, certain potential problems may be encountered in scaling up MATS system. In this research the following concerned subjects will be studied: uniform electric field distribution and heating pattern design, influence and accuracy of metallic temperature sensor, and calibration of dummy load.
5. References


CHAPTER TWO

NUMERICAL SIMULATION OF MICROWAVE HEATING

1. Introduction

Microwave heating occurs between alternating electromagnetic waves at microwave frequency (300 MHz~300 GHz) and dielectric materials. In microwave heating, electromagnetic energy is converted into heat due to the friction among molecules of the dielectric material. It is a complex physical process governed by fundamental theories of electromagnetic and heat transfer. Mathematical models have been always used to analyze and design microwave heating processes. Analytical and numerical methods are used to understand the behaviors of these mathematical models. The analytical method is used to gain some information about microwave propagation modes and power distribution for simple models such as rectangular applicator or waveguide (Wang, 1978; Watanable et al., 1978; Zhu and Chen, 1988). The analytical solutions provide a quick and easy method to analyze the influence of individual parameters which can be easily deduced. It plays an important role in initial testing of a new design of simple models. However, in analytical method the model is always oversimplified which cannot represent the actual process. For mathematical models that are too complex to analytically solve, numerical method is a good alternative to give numerical solutions (Zaritzky and Campanone, 2005; Rattanadecho and Klinbun, 2011). However, the numerical method requires a large amount of computation which needs special program or software to implement. The rapid growth of powerful computers accelerates the development of numerical method in solving microwave heating problems.

Computer simulation models are established based on fundamental theories and physical model of the microwave heating system to gain new insights. Numerical method is the fundamental of a computer simulation model. It determines the accuracy and computation speed of the simulation model. Different numerical methods may be used in different software design. Besides numerical method, boundary condition is another key parameter can affect model accuracy. When a simulation model is established, the simulation results need to be verified by the physical model it simulated. Experimental
validation is a significant step in development of computer simulation models. Modification of the simulation model may be desirable to match the experimental results and obtain a reliable and robust model. Once the simulation model was validated and proved to be reliable, it can be modified to optimize the current microwave heating process and explore the potential problem in developing new systems. However, the new developed model should follow the same numerical method and boundary conditions as the validated model.

2. Numerical methods

Numerous methods have been developed to numerically solve related electromagnetic problems. Niziolek (2009), reviewed most commonly used numerical methods for computational electromagnetic and pointed out the main strengths and weakness of given methods such as finite difference time domain (FDTD) method, finite element method (FEM), transmission line matrix (TLM) and method of moments (MOM). However, in simulating microwave heating problems, FEM (Silvester and Ferrari, 1997, Jin, 2002) and FDTD (Yee, 1966; Taflove, 1988) are the two most popular methods.

2.1 Finite element method (FEM)

The finite element method divides the computational domain into a union of subdomains typically quadrilaterals or triangles in two dimensions and tetrahedral or hexahedra in three dimensions (Dibben, 2001). This type of decomposition without regular grid is very flexible for simulating complex geometries. Curved boundaries can be easily modeled with a series of curvilinear elements rather than with staircase approximation in regular grid system. The implement scheme for a FEM is describe below:

1. Divide the solution domain into a collection of small subdomains by taking the nodes as vertexes.

2. Interpolation solutions with unknown coefficients are used to approximate the solutions at each node.

3. Substitute each of the interpolated solution to the original partial differential equations.

4. Assemble the differential equations with approximated solution for the entire solution domain.
5. Solve the obtained algebraic equations using standard tools such as iterative and direct solver methods.

The advantages of FEM in terms of mesh type includes: accurate representation of complex geometry, inclusion of inhomogeneous materials and capture of local effects.

The most representative commercial software of FEM is COMSOL. The implementation of FEM requires relatively more computer memory and simulation time due to the unavoidable matrix operation. The FEM is mainly used for simulating system with small size such as domestic microwave oven. For pilot plant or industrial scale system FDTD method is more suitable.

2.2 Finite Difference Time Domain method

The FDTD method is the most popular method in obtaining numerical solution of electromagnetic problem. The FDTD method is a special application of finite difference method (FDM) in solving time differentiated Maxwell’s curl equations. The FDM was first developed by Thom (Thom and Apelt, 1961) to solve hydrodynamic problems. The core of FDM is based on subdividing the whole domain into a number of cells by grids. Then finite difference approximations are applied at the nodes of the grids to replace the differential equations. The value at one node is calculated based on the values at its adjacent nodes. The algorithm of FDTD method can be summarized as follows:

1. Discretize space and time in the way that the electric and magnetic fields are staggered in both space and time. Use finite differences to replace all the original derivatives

2. Solve the resulting difference equations to obtain update equations for future (unknown) magnetic and electric fields in terms of past (known) fields.

3. Evaluate all the magnetic fields of one time-step in the future first and then evaluate the electric fields.

4. Repeat the evaluating procedures until the fields have been obtained over the desired duration.

In brief, FDTD method is a time-marching procedure that simulates the continuous electromagnetic waves in a finite spatial region while time-stepping continues until desired simulation
time is achieved or the interested stable field pattern is established (Taflove, 1998). The typical software
developed based on FDTD method is QuickWave.

3. Implementation of FDTD method on Maxwell’s equations

3.1 Finite difference method

The computer simulation models in this thesis are built up through the commercial software of
QuickWave which is developed based on FDTD method. The basic implementation of FDTD method will
be introduced in this section. FDTD is a special application of FDM in solving time differentiated
Maxwell’s curl equations. The finite differences approximation of a differential equation is derived from
its Taylor series expansions. For the function $f(x)$ expanded at the point $x_0$ with a step of $\pm \delta/2$:

$$f \left( x_0 + \frac{\delta}{2} \right) = f(x_0) + \frac{\delta}{2} f'(x_0) + \frac{1}{2!} \left( \frac{\delta}{2} \right)^2 f''(x_0) + \frac{1}{3!} \left( \frac{\delta}{2} \right)^3 f'''(x_0) + \cdots,$$

(1-a)

$$f \left( x_0 - \frac{\delta}{2} \right) = f(x_0) - \frac{\delta}{2} f'(x_0) + \frac{1}{2!} \left( \frac{\delta}{2} \right)^2 f''(x_0) - \frac{1}{3!} \left( \frac{\delta}{2} \right)^3 f'''(x_0) + \cdots,$$

(1-b)

Where the primes indicate the differentiation and the exclamation points is the factorial notation.

Subtracting Eq. (1-b) from Eq. (1-a) and then dividing by $\delta$ yields:

$$\frac{f(x_0 + \frac{\delta}{2}) - f(x_0 - \frac{\delta}{2})}{\delta} = f'(x_0) + \frac{1}{2!} \left( \frac{\delta}{2} \right)^2 f''(x_0) \cdots,$$

(2)

Thus the left side term is equal to the derivative of the function at the point $x_0$ (i.e. $f'(x_0)$) plus a term
depending on $\delta^2$ and infinite number of hidden terms which depends on higher power of $\delta^2$. The
relationship is often reorganized to:

$$\frac{df(x)}{dx} \bigg|_{x=x_0} = \frac{f(x_0 + \frac{\delta}{2}) - f(x_0 - \frac{\delta}{2})}{\delta} + O(\delta^2)$$

(3)

Where $O(\delta^2)$ indicates all the terms that are not explicitly shown with a lowest order of $\delta^2$. If $\delta$ is
sufficiently small, a reasonable approximation to the derivative would be obtained by the central
difference

$$\frac{df(x)}{dx} \bigg|_{x=x_0} \approx \frac{f(x_0 + \frac{\delta}{2}) - f(x_0 - \frac{\delta}{2})}{\delta}$$

(4)
Since the lowest power of $\delta$ being neglected is second order, the central difference is said to have second-order accuracy. Higher order central difference can be constructed with more sample points to obtain more accurate approximation.

For the electromagnetic problems, the FDTD method employs finite differences as approximations to both the spatial and temporal derivatives that appear in Maxwell’s equations (Yee, 1966; Taflove, 1980).

3.2 Yee Algorithm

The FDTD algorithm was first reported by Kane Yee in 1966 with a second-order central differences. The core of Yee algorithm is based on discretizing space and time to distribute the electric and magnetic fields staggered in both space and time. Then replace the derivatives in Ampere’s and Faraday’s laws with finite differences to obtain the unknown (future) fields in terms of known (past) fields. The electric and magnetic field could be updated in stagger iteratively until the fields have been obtained over the desired duration.

For simplicity, one-dimensional FDTD algorithm is presented to show the implementation of the algorithm. Assume that the electric field only has a $y$ component, then Faraday’s law can be written:

$$\mathbf{E} = \nabla \times \mathbf{H} = \left[ \begin{array}{ccc} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ 0 & 0 & \frac{\partial}{\partial z} \\ 0 & E_y & 0 \end{array} \right]$$

For simplicity, one-dimensional FDTD algorithm is presented to show the implementation of the algorithm. Assume that the electric field only has a $y$ component, then Faraday’s law can be written:

$$\mathbf{E} = \nabla \times \mathbf{H} = \left[ \begin{array}{ccc} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ 0 & 0 & \frac{\partial}{\partial z} \\ 0 & E_y & 0 \end{array} \right]$$

Since it has only $x$ component on the right side of the equation, $H_x$ must be the only non-zero component of time varying magnetic field. $H_y$ and $H_z$ may be non-zero, but they are not time-varying (static). Consider the time-varying component only, the Ampere’s law can be written:

$$\mathbf{E} = \nabla \times \mathbf{H} = \left[ \begin{array}{ccc} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ 0 & 0 & \frac{\partial}{\partial z} \\ H_x & 0 & 0 \end{array} \right]$$

From Eq. (5) and (6), two scalar equations are obtained:
The Eq. (7-a) expresses the temporal derivative of the magnetic field in terms of the spatial derivative of the electric field. It will be used to update the magnetic field in time and the Eq. (7-b) will be used to update the electric field in time because it shows the temporal derivative of the electric field in terms of the spatial derivative of the magnetic field. A leap-frog method will be applied to repeat the process to update the magnetic field and then the electric field in time.

Finite differences will be used to replace the derivatives in (7-a) and (7-b). Before this, space and time need to be discretized. The fields are sampled in space and time by the following notation to indicate the location:

\[ E_y(z, t) = E_y(m\Delta z, n\Delta t) = E_y[m, n] \quad (8-a) \]

\[ H_x(z, t) = H_x(m\Delta z, n\Delta t) = H_x[m, n] \quad (8-b) \]

where \( \Delta x \) is the spatial step size between sample points and \( \Delta t \) is the temporal step size. The index \( m \) is the spatial step indicating the spatial location, while the index \( n \) corresponds to the temporal step. The arrangements of the magnetic and electric field nodes are shown in Figure 1.

The electric fields are shown as circles and the magnetic fields are shown as triangles. Assume that all the fields below the dashed line are known (past) while the fields above the dashed line are future i.e. unknown. The FDTD algorithm provides a way to obtain the future fields from the past fields.

In Figure 1, consider Faraday’s law Eq. (7-a) at the space-time point \([(m + \frac{1}{2})\Delta z, n\Delta t]\):

\[ \mu \frac{\partial H_x}{\partial t} \big|_{(m+\frac{1}{2})\Delta z, n\Delta t} = \frac{\partial E_y}{\partial z} \big|_{(m+\frac{1}{2})\Delta z, n\Delta t} \quad (9) \]
The temporal derivative at the left side of equation will be replaced by finite difference including \( H_x[m + \frac{1}{2}, n + \frac{1}{2}] \) and \( H_x[m + \frac{1}{2}, n - \frac{1}{2}] \), while the spatial derivative at the right side of the equation will be replaced by finite difference including \( E_y[m + 1, n] \) and \( E_y[m, n] \). The following equation is derived:

\[
\frac{H_x[m+1/2,n+1/2] - H_x[m+1/2,n-1/2]}{\Delta t} = \frac{E_y[m+1,n] - E_y[m,n]}{\Delta z}
\]  

(10)

Solve Eq. (10) for \( H_x[m + \frac{1}{2}, n + \frac{1}{2}] \):

\[
H_x[m + \frac{1}{2}, n + \frac{1}{2}] = H_x[m + \frac{1}{2}, n - \frac{1}{2}] + \frac{\Delta t}{\mu} (E_y[m + 1, n] - E_y[m, n])
\]  

(11)

This equation is an updating equation for \( H_x \). It is a general equation that can be applied to any magnetic field node. The future value of \( H_x \) is obtained by its previous value and the adjacent electric fields. It shows that the future value of \( H_y \) depends only on its previous value and the neighboring electric fields. When all the magnetic field nodes were obtained by applying Eq. (11), the time has advanced a half time step. The dividing line between future and past is updated in Figure 2.
Consider Ampere’s law Eq. (7-2) at the space-time point \((m\Delta z, (n + 1/2)\Delta t)\) (Figure 2):

\[
e \frac{\partial E_y}{\partial t} |_{m\Delta z, (n+1/2)\Delta t} = \frac{\partial H_x}{\partial z} |_{m\Delta z, (n+1/2)\Delta t}
\]  

(12)

The temporal derivative at the left side of equation will be replaced by finite difference including \(E_y[m, n + 1]\) and \(E_y[m, n]\), while the spatial derivative at the right side of the equation will be replaced by finite difference including \(H_x[m + 1/2, n + 1/2]\) and \(E_y[m - 1/2, n + 1/2]\). The following equation is derived:

\[
e \frac{E_y[m, n+1] - E_y[m, n]}{\Delta t} = \frac{H_x[m+1/2, n+1/2] - H_x[m-1/2, n+1/2]}{\Delta z}
\]  

(13)

\(E_y[m, n + 1]\) will be obtained by solving Eq. (13)

\[
E_y[m, n + 1] = E_y[m, n] + \frac{\Delta t}{e\Delta z} (H_x[m + 1/2, n + 1/2] - H_x[m - 1/2, n + 1/2])
\]  

(14)

This equation is the updating equation for \(E_y\). The future value of \(E_y\) is given by its previous value and the adjacent magnetic fields. Same as the updating equation of \(H_x\), it is a general equation than
can be applied to any electric field node. After all the electric field nodes were obtained by applying Eq. (14), the time will advance another half step. In this manner, repeat the process for updating magnetic field and then electric field, the fields over desired duration could be evaluated. Same node arrangements could be expanded to a volumetric solution domain to implement FDTD algorithm in three dimensional spaces (Taflove and Hagness, 2005).

In FDTD simulations, the temporal step should be kept small due to stability constraint. For the mesh grid in three dimensions, $\Delta t$ is governed by the Courant condition which relates the time step required for stability to the spatial meshes. Based on the way fields propagate in an FDTD grid, it seems logical that energy should not be able to propagate any further than one spatial step for each temporal step. The ratio between the distance of the energy can propagate in a single temporal step to the spatial step is called Courant number $S$.

$$S = \frac{c \Delta t}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}} \leq 1$$ (15)

where $c$ is the speed of light and $\Delta x$, $\Delta y$ and $\Delta z$ are the size of the grid spacing in the x, y, and z directions, respectively. It has been proved that the optimum ratio for the Courant number (in terms of minimizing numeric errors) is also the maximum ratio.

4. Procedure to establish a computer simulation model

There are many commercial programs available for solving microwave heating problems, such as professional software of COMSOL and QuickWave. The software with friendly user interface is always preferred for researches in microwave heating. However, the numerical method used in different software may be different. For COMSOL, FEM is used while FDTD method is adopted for QuickWave. The selection of software for numerical solution of microwave heating problem is based on the dimension of physical model, platform for running the model, accuracy and time consumption.

4.1 Parameters setting
Once the software is selected, the parameters are needed to be set and tested to establish a computer simulation model. These parameters include but not limited by mesh size, boundary condition, dielectric properties and thermal properties of food, power setting, and moving speed of food.

Discretization of the solution domain is the first step for numerical solution of a model. The mesh size determines the accuracy and stability of the numerical model. Generally, the software allows user to define the maximum mesh size and it will automatically set the mesh size based on the mesh setting and the boundaries of the model. For FDTD method, the general mesh size is set by following the rule of 10 cells per wavelength (Taflove, 1998). The mesh size in dielectric materials should be redefined since the wavelength of microwave reduced a lot compared with that in air. The wavelength in food is about $\frac{1}{\sqrt{\epsilon}}$ of that in air (Wappling-Raaholt et al., 2002). The symbol $\epsilon$ is the permittivity of food. Besides that, refinement may be applied at some boundary area to improve the accuracy and stability of the model. Sensitivity studies for mesh size are required to find a suitable grid while balancing the accuracy and calculation time.

Boundary condition for both electromagnetic field propagation and heat transfer should be defined. For microwave heating in waveguide or domestic microwave oven, the metal boundary is always set as perfect electric conductor (PEC) (Klinbun et al., 2011). That is because metal has very high electric conductivity and microwave cannot go through. However, for some open end in physical model, the perfect matched layer could be used to perform as an absorbing boundary condition (ABC) (Chen et al., 2007). The ABC and PEC are the two commonly used boundary condition for electromagnetic wave. The boundary conditions for heat transfer are defined based on the physical model. For example, the boundary condition between solid food and flowing water should be defined as convective boundary condition. The heat transfer coefficient between water and the surface of food should be defined.

The dielectric properties and thermal properties of food change with temperature. The coupled data should be updated during the implementation of numerical calculation. Accurate measurements of
these properties changing with temperature provide support for developing accurate computer simulation models.

For physical model with moving or rotating food samples, discretization of moving step and rotating step with corresponding heating time should be fixed. Sensitivity study of moving step or rotation step must be done to confirm the best step size.

4.2 Experimental validation

Experimental test is an indispensable procedure to validate and improve the simulation model. For a new microwave thermal process, which ensures adequate thermal lethality of target microorganism, it is essential to confirm the cold spot of processed food products, because the process design is based on the time temperature history recorded at the cold spot location. Thus, heating pattern should be identified first to find the cold spot location. Surface temperature distribution could be obtained through viewing the infrared energy using a thermographic camera (Bows and Joshi, 1992). However, the limitation of this type of camera is that food should be taken out to perform the measurement. Temperature may change during this procedure. To measure the internal temperature distribution within food, food should be cut to expose the inside surface. Beside infrared camera, thermal paper (Bradshaw, et al., 1996) or magnetic resonance imaging (Schwarzmaier and Kahn, 1995) are also used in visualizing the microwave heating pattern. Thermal paper can only measure heating pattern of empty microwave oven while magnetic resonance imaging is very complex and expensive. Recently, chemical marker method developed by the U.S. Army Natick Research Center has been reported to be an effective technique to assess heating pattern in microwave processed food (Kim and Taub, 1993; Parash et al., 1997). In the presence of excess source of either the protein or ribose/glucose precursor in food materials, the formation of intrinsic chemical marker follows first-order reaction. Correlation can be developed between the marker yield and time temperature history in food system (Zhang et al., 2001; Lau et al., 2003). However, the analysis of marker yield required high performance liquid chromatograph (HPLS) which is complex and expensive. Computer vision method was developed to rapidly display the heating pattern (Pandit et al., 2006, 2007a).
In computer vision method, yield of chemical marker was used as a coloring agent and digital images of the processed food were analyzed. Computer vision combined with chemical marker was proven to be a rapid and reliable method to effectively identify the cold spot location of microwave processed foods (Pandit et al., 2007b).

Once the cold spot location was determined temperature sensor was used to record the time temperature profile. In a microwave heating environment, an effective temperature measurement device should not disturb the EM field or be affected by the EM field (Datta et al., 2001). The fiber-optic temperature sensors are commonly used in microwave heating measurements (Kyuma et al., 1982; Tang et al., 2008). But the fiber-optic sensors require light sources that are heat sensitive and expensive. In addition, the long fragile optical fibers are not suited for the temperature measurement in moving samples. Although temperature sensors with metal components may interact with EM field which affect the sensor accuracy, many attempts have been made to modify metallic thermocouples for temperature measurements in microwave environments (Van de Voort et al., 1987; Ramaswamy et. al., 1991). Ramaswamy et al., (1998) reported that metallic thermocouples could be used in microwave ovens with adequate accuracy (errors <2 °C) by proper design of the shield isolation and body insulation. For moving samples, a mobile metallic temperature sensor was reported to be used in continuously moving microwave heating system (Luan et al., 2013). The orientation of the sensor should be selected based on the electric field distribution in the microwave heating system to decrease the influence caused by the interaction between EM field and metallic probe. The study of metallic temperature sensor used in microwave heating will be presented in Chapter 4 and Chapter 5.

5. Application of computer simulation model in microwave heating

5.1 Domestic microwave oven design

The majority of computer simulation models developed for microwave heating is for domestic microwave ovens. Because the domestic microwave oven is the largest application of microwave heating.
It is easier to simulate the small size domestic oven and to carry out the experimental validation compared to the industrial systems.

In earlier studies coupled electromagnetic and heat transfer studies were carried out in simpler one or two dimension plane waves (Smyth, 1990; Ayappa et al., 1991) and cavities (Clemens and Saltiel, 1995; Soriano et al., 1998) to provide qualitative results on heating patterns.

Three dimension simulation models coupled electromagnetic propagation and heat transfer were explored to gain more into microwave heating (Ma, et al., 1995; Torres and Jecko 1997). Computer simulations models are used to study the factors that influence heating pattern and uniformity in microwave oven such as of dielectric properties (Peyre et al, 1997; Zhang and Datta, 2000), food shape (Chamchong and Datta, 1996; Zhang and Datta, 2005), size (Vilayannur et al., 1998) and location (Wappling-Raaholt, and Ohlsson, 2000). Besides these factors, some additional techniques are also simulated to study their influence on heating uniformity of food, such as mode stirrers (Geogre and Bergman, 2006; Plaza-Gonzalez et al., 2004), turntable (Geedipalli, et al., 2007) and feed designs (Kubota and Kashiwa, 1997).

The domestic microwave oven is improved by those techniques in terms of heating uniformity. However, the basic design of a microwave oven (i.e. a single microwave feed and a rectangular box) has not changed since its presence. At least for now, it is unlikely to change. Heating uniformity improvement is still the first challenge. The possible use of computer simulation model is to study the changes in feed, stirrer positions and loading conditions to find the optimized design or minimize the number of prototypes.

5.2 Industrial microwave oven design

The design cost of industrial microwave heating system always takes a large proportion of the total cost compared with domestic oven. That’s because only a few systems of a given design may be manufactured. For this reason, the use of computer simulation model can significantly reduce the design cost by minimizing the number of possible prototypes that needs to be manufactured. Generally, smaller
pilot plant system is constructed first during the design of industrial scale system. The principle of the design will be tested first through pilot plant system before the scaling up. However, the potential problems in the scaled-up version may not be present in the pilot prototype. Numerical solutions from computer simulation could help to identify these potential problems. Computer simulation model based on numerical method could be used to simulate the pilot plant version. Validation and improvement will be done for the established simulation model through the pilot plant system. The validated model can be used to assist the industrial scale system.

There are very few computer simulation models developed for industrial microwave heating system. Burfoot et al. (1996), developed a numerical model pasteurization of prepared meals in a industrial system with microwaves at 896 MHz using FDTD method. The temperature distribution within processed food could be identified by this model. However, the predicted temperatures had big difference from the measured results. More accurate simulation model is required to assist further study. Sundberg, et al. (1996), analyzed the design of industrial microwave ovens using FDTD method. Two different applicators are analyzed numerically and experimentally. Valuable insight into the modes of operation could be successfully revealed. However, there is no further report for the application of these models.

A 915 MHz single model microwave assisted thermal sterilization (MATS) system was developed at Washington State University with the ultimate goal of industrial application. The MATS system is a plot plant system. Since its inception, several MATS processes for different foods in either rigid trays or flexible pouches were developed by the WSU research team and accepted by the United States Food and Drug Administration (FDA) or the United States Department of Agriculture Food Safety and Inspection Service (USDA, FSIS). Computer simulation played an important role during the MATS system design and improvement. Pathak et al. (2003), established a computer simulation model to capture the overall behavior of electric field distribution in a rectangular waveguide terminated into an oversize cavity box. A 915 MHz single mode electric field pattern could be achieved by proper dimension selection of the oversize cavity box. It could be used as an applicator for heating large volume food material. The electric field distribution within the cavity box could be adjusted by changing the
dimension. The uneven power deposition profile at food surface was greatly reduced by immersing the food in water. Chen, et al. (2007, 2008) developed simulation models for 915 MHz single mode microwave heating system. Moving sample was first simulated in the latest model. Good agreement between simulation results and experimental validation were observed. The validated model was used to study the influence of power input and space between packages on heating uniformity. Resurreccion, et al. (2013) expanded the previous simulation model (Chen et al., 2008) to a four cavity pilot plant microwave heating system. Accuracy was improved through setting the parameters of mesh size, moving step, boundary condition and new algorithm in coupling heat transfer. An updated new version of the software helps to achieve these improvements. This model was applied to predict the influence of frequency shift and dielectric properties variations on the heating patterns of the MATS system (Resurreccion, 2012).

6. Future application for computer simulation

The major challenge in microwave heating is the non-uniformity heating pattern which leads to cold and hot spot. The non-uniform heating pattern was caused by the uneven electric field distribution. The heating uniformity will deteriorate when microwave power is increased. That’s because the energy absorbed by food is proportional to the square of the electric field intensity. Furthermore, dielectric loss factor of food materials increase with increasing temperatures which make the hot spot received more energy than cold spot and worsen the non-uniformity. For industrial application, high power microwave source is desirable to satisfy the desirable production. A uniform heating pattern is prerequisite for industrial scaling up. Although, previous computer simulation models were proved to have good results compared with experiments, the application of these models for further study were very few. No study was done to reveal how the electric field distribution formed and gave rise to the current heating pattern.

In the following study, computer simulation will be used to visualize the electric field distribution within the MATS system. The electric field components in different directions will be revealed to analyze the reason of current field pattern. Based on the analysis, techniques which can affect field distribution
and improve uniformity will be explored. The results will provide guidance on designing commercial microwave heating system with uniform heating pattern.
7. References


CHAPTER THREE

ELECTRIC FIELD DISTRIBUTION ANALYSIS AND HEATING PATTERN DESIGN OF MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEM THROUGH COMPUTER SIMULATION METHOD

Abstract

The goal of this study was to analyze the electric field distribution within a microwave assisted thermal sterilization (MATS) system through computer simulation method. The electric field components in each direction were analyzed to reveal the formation of the heating pattern. Results showed that for a TE10 source of microwave, the dominant electric field component was consistent when microwaves propagate from the waveguide to horn applicator and the microwave heating cavity. The heating pattern within MATS system was determined by the electric field distribution of the dominant component. Changing the dimension of horn applicator and cavity aperture along the dominant field direction brought different heating patterns which could be used to improve heating uniformity. Besides that, the electric field distribution could also be affected by metallic bars within the horn applicator near to the cavity. The accessory of metallic bars was a good technique to adjust heating pattern and was easy to realize. The heating uniformity in MATS system could be improved by adjusting electric field distributions in the dominant component direction. Furthermore, designing the dimension of food to match the electric field distribution also improved the heating uniformity.

1. Introduction

Microwave heating has been widely accepted in domestic usage and is gaining attention in industrial applications. Microwave heating offers a much faster heating rate than conventional heating. It can provide high temperature short time (HTST) process (Lund, 1977; 1982) for solid and semi-solid food products to improve the quality.
However, the major challenge in commercialization of microwave heating is the non-uniform heating pattern caused by the uneven electric field distribution. Hot spot and cold spots occur at high and low electric field intensity locations, respectively. Temperature difference between hot and cold spot is intensified by higher microwave power and longer microwave heating time. It is due to the fact that microwave energy absorbed by food is proportional to square of the electric field intensity and also dielectric loss factor of food increases with increasing temperatures. The temperature within food continuously increases as long as microwave power is applied. Hence, thermal runaway might occur at the hot spots (Datta, 2001). A thermal process is designed to ensure that the temperature at the cold spot reaches the required level for a certain amount of time to achieve necessary microbial lethality. However, if the temperature difference between cold and hot spot is large, the temperature at the hot spot may be unacceptable when the temperature at the cold spot reached the required level. This high temperature at the hot spot degrades the food quality in the adjacent domain and can result in high inner pressure which in worst case might lead to breakage of the food package. Thus one of the main factors for the quality evaluation of a microwave heating system is its ability to provide a uniform heating pattern of the food load. For a given microwave heating system, the general way to improve heating uniformity is to lower microwave power and increase heating time. This method provides more time for heat transfer from hot area to the adjacent domain. However, it is not a practical option for industrial applications which need high production to reduce cost. It is better to design a system with uniform heating pattern based on the electric field distribution.

As described in Chapter one, there are two types of microwave heating cavities categorized by type of the microwave propagation mode: multi-mode cavity and single mode cavity. Domestic microwave ovens are the most common multi-mode microwave heating equipment. The heating pattern in a domestic microwave oven is influenced by many factors (Vadivambal and Jayas, 2010) such as dielectric properties, shape, size and location of food. To improve heating uniformity in domestic microwave ovens, some intuitive techniques were used such as mode stirrers (Geogre and Bergman, 2006; Plaza-Gonzalez et al., 2004), variable frequencies (Bows, 1999) turntable (Geedipalli et al., 2007).
Applications of mode stirrer and variable frequencies changed the resonant mode randomly to achieve a statistical uniformity of electric field distribution. Similar to mode stirrer, turntable attempted to change the position of food to gain statistical uniformity during microwave heating. These techniques could improve the overall heating uniformity of food in a domestic microwave oven. Besides, combined heating by infrared and hot air is another method to improve heating uniformity (Datta and Rakesh, 2013). But due to various parameters involved, heating is difficult to control. For multi-mode microwave heating cavity, the heating pattern is affected by the inside microwave propagation mode that changes with microwave frequencies. The heating pattern in such cavities is unpredictable due to the frequency shift of the microwave source. The methods described above for improving heating uniformity are based on probabilistic design other than mode design. The improvement of heating uniformity is random and dependent on the properties of the food load. The cold spot location is not fixed and it is impossible to design a microwave thermal process without a confirmed cold spot location. Thus multi-mode microwave heating cavity is not appropriate for industrial thermal processing of food.

Single mode cavity design is a suitable option for industrial microwave heating to provide repeatable heating pattern. A 915 MHz single model microwave assisted thermal sterilization (MATS) system was developed at Washington State University to study the feasibility of microwave thermal processing and explore the potential problems in industrial scaling up (Tang et al., 2006). The MATS system is a pilot plant system which includes four sections i.e. preheating, microwave heating, holding and cooling. They are arranged in series representing the four sequential processing steps. In October 2009, the first filing for a MATS processing of mashed potato was accepted by FDA. It was identified as the first FDA approved microwave process for commercial sterilization of low acid food in the United States. The success has accelerated the initial steps towards commercialization of this technology. For industrial scale microwave heating, much higher power is required to improve productivity. However, heating uniformity may deteriorate with increasing microwave power. It is essential to design a suitable heating pattern for higher power microwave heating system. Since the heating pattern is governed by electric field distribution within a microwave heating cavity, a uniform electric field distribution should
lead to a uniform heating pattern. It is important to understand the electric field distribution within the current MATS system. This could help in exploring techniques for improving uniformity of electric field distribution.

The objective of this study was to analyze the electric field distribution within the MATS system and evaluate parameters that affect microwave heating patterns using computer simulation method. Based on the influences of parameters on electric field distribution and heating pattern, techniques for improving heating uniformity were investigated to assist the design of industrial microwave heating systems.

2. Electric field analysis for single mode MATS system

2.1 Physical model

Figure 1 shows the four sections of the MATS system at Washington State University.

![Figure 1: Sketch of microwave assisted thermal sterilization (MATS) system](image)

Food products in pouches or trays are transported sequentially through preheating, microwave heating, holding and cooling section. In operation the four sections are filled with water at set temperatures i.e. 72, 123, 123 and 23 °C, respectively. Packaged food products are immersed in water throughout the process. Each section has a separated water supply system to control the temperature. In the preheating section, the food is heated and equilibrated to highest possible temperature that does not degrade the food quality. In the microwave heating section the temperature of food products is increased rapidly to 121.1 °C. After then, holding section inactivates the pathogens over selected thermal treatment
duration. Lastly the temperature of food is reduced quickly to room temperature (i.e. 23 °C) in the cooling section. Among these four processes, the microwave heating is the key to reduce heating time and improve the food quality.

The microwave heating section consists of four connected microwave heating cavities. Figure 2 shows a typical microwave heating cavity and the attached waveguide components through which microwave power is delivered from the generator to the cavity. Each cavity has two windows (top and bottom) made from high temperature resistant polymer (Ultem® 1000). Microwaves are delivered to the heating cavity through the Ultem windows that are connected to two identical horn shape applicators on the top and bottom. The horn applicator is a tapered shape parallelogram with wide end connected to the window and narrow end connected to a standard WR975 waveguide having an inner cross sectional dimension of 247.7 mm by 123.8 mm. The microwaves are directed from a generator to a tee junction that splits the microwave power equally to the top and bottom horn applicators. In each side, two connected E-bend waveguides directed the microwave to the narrow end of the horn applicator. Several standard WR975 rectangular waveguides components are used to connect the generator and the tee junction. E-bend or H-bend waveguide is used to change the direction of propagating microwave. In Figure 2, an H bend waveguide is shown to change the microwave propagating from x to y direction.
2.2 Computer simulation model for electric field distribution analysis

Computer simulation model was developed using the commercial software QuickWave version 7.5 (QW3D, Warsaw, Poland) based on the physical model of MATS. As shown in Figure 2, only one microwave heating cavity with attached waveguide component was built up in this research to study the microwave propagation mode from waveguide to the microwave heating cavity.

Since the waveguide components from the generator to the tee junction was flexible in practical installation, the microwave input ports (source) could be set at location before the tee junction. In the simulation model, the port was located 200 mm before the H-bend (Figure 4). Snapshots of electric field at several cross sections of the waveguide were analyzed in this chapter to track the electric field propagation mode. In a rectangular waveguide with a lateral dimensions a and b (a>b), as shown in Figure 3, the dominant propagation mode of electromagnetic (EM) wave was TE10 mode. The symbol TE indicated that the electric field component was perpendicular to the propagation direction (i.e. z direction in Figure 3A). The symbols 1 and 0 in a mode type denoted the number of semi-sinusoidal variations in x and y direction, respectively (Figure 3B). For a TE10 mode propagating in the coordinate system
described in Figure 3A, the electric field had no component in z (Ez) and x (Ex) direction. The component in y direction (Ey) formed a standing wave in x direction with one semi-sinusoidal variation.

Figure 3: Rectangular waveguide (A) and its dominant mode (B). For TE10 mode, Ez=0, Ex=0. The electric field component in y direction (Ey) formed a standing wave in x direction with one semi-sinusoidal variation.

3. Electric field distribution analysis

3.1 Electric field distribution in waveguides

Natural biological materials, such as food, interact with only the electric part of the electromagnetic field (Mudgett, 1986). Thus electric field distribution is of the most concern. The electric field distributions at different cross sections of the waveguide components, horn applicator and microwave heating cavity will be analyzed in this section.

Waveguide is a structure used to direct microwave. The cross section of waveguide is consistent. Theoretically the propagation mode or electric field distribution at different cross section should be the same. Figure 4 shows the positions of cross sections selected for electric field distribution analysis. Cross section 1 was located at the interface between exit of the H-bend and the start of the tee junction. Cross section 2a and 2b were located at the beginning of E-bend. At the connection of the two E-bend
components were the cross section 3a and 3b. Cross section 4a and 4b were selected at the interface between the waveguides and the horn applicators.

![Diagram of microwave waveguide system with cross sections labeled]

Figure 4: Positions of the microwave source port and the cross sections for electric field analysis

Figure 5 summarizes the snapshots of electric field distributions and the components in each direction at the microwave source port and each cross section within the waveguide. A sinusoidal microwave source with TE10 mode source was set at the port. Electric field had component only in z direction (E_z). The components in x (E_x) and y (E_y) direction were zero. At cross section 1, the electric field distribution and component did not change after propagating through the H-bend waveguide. However, the electric field intensity in z direction (E_z) was totally converted to E_y at the cross section 2a and 2b when the microwave propagated through the tee junction waveguide. After then the E-bend waveguide converted E_y to E_z. At cross section 3a and 3b, E_y was equal to zero and E_z was the only non-zero component. Through another conversion of E-bend, the non-zero electric field component at cross section 4a and 4b was E_y. The H-bend only changed the propagating direction of microwave other than the electric field direction. However, the tee junction and E-bend could change the direction of electric field. The propagation mode of microwave i.e. TE10 was consistent throughout the waveguide. There was only one non-zero electric field component at each cross section which was along the narrow side of the
rectangular waveguide. But the uniformity of the electric field along the narrow side may be affected by irregular waveguide component such as tee junction (cross section 2a and 2b).

Figure 5: Snapshots of electric field distribution and each component at different cross sections of the waveguide. The location of each cross section was described in Figure 4.

3.2 Electric field distribution in horn applicator and microwave heating cavity

Not all the waveguide components were essential in a computer simulation model since it had no influence on the propagation mode of the microwave. The dimension of the physical model was significantly reduced by excluding the waveguide components which saved the computer memory and calculation time. Figure 6 shows a simplified model with only a short waveguide, horn applicators and the microwave heating cavity. The microwave source port was set 200 mm higher than the horn applicator to provide sufficient long waveguide for reference plane of the source while the reference plane of the source should be at least 150 mm distance from the port.
Figure 6: Microwave heating cavity with only horn applicators and short waveguides

Figure 7 illustrates the snapshots of electric field distribution in front view (x-z plane cross section, middle layer in y direction) and side view (y-z plane cross section, middle layer in x direction) of the microwave heating cavity and horn applicators. The TE10 propagation mode was clearly shown from the front view and side view within the waveguide. As shown in Figure 7A, from front view the electric field intensity had one semi-sinusoidal variation in x direction. Uniform electric field intensity was observed in y direction (Figure 7B).
However, along the propagating direction of the microwave (z direction), the electric field distribution was changed with the increasing dimension of the horn applicator. The electric field distribution was not in standard TE10 mode any more within the horn applicator and the microwave heating cavity. Electric field distribution and the components in each direction at x-y plane were analyzed at the cross section described in Figure 7A. Marked by the red double head arrows, cross section 1a and 1b was located at the wave crest of the microwave snapshot within the waveguide. Cross sections 2a and
2b were selected at the adjacent wave crest within the horn applicators. The distance between section 1a/1b and 2a/2b was 212.6 mm which was close to the half wavelength of 915 MHz in WR 975 waveguide i.e. 218.7 mm. At the open ends of the horn applicators were cross section 3a and 3b. Cross section 4 was located in the middle of the microwave heating cavity. There are three standing waves within the microwave heating cavity in the z direction. The distance between the first and third anti-node was 57.4 mm which was close to the wavelength of 915 MHz microwave in the water with dielectric constant and loss factor of 55.8 and 2.9, respectively, i.e. 58.6 mm.

Snapshots of the electric field distribution and each component in the cross sections (described in Figure 7A) are summarized in Figure 8.

Figure 8: Snapshots of electric field distribution and each component at the cross section of x-y planes described in Figure 7A.
From the waveguide to the microwave heating cavity, there was no change observed in the dominant electric field component (i.e. $E_y$). However, when microwave propagated through the horn applicator, the electric field distribution in $y$ direction was not as uniform as it was in the waveguide, especially near the edge of the horn applicator. At cross section 3a and 3b, the field pattern seemed to be a TE11 mode. However, it was actually not while $E_y$ is the only dominant component. Because the electric field component in $x$ direction ($E_x$) should have similar field intensity to $E_y$ in a TE11 mode. Furthermore, at the middle of the microwave heating cavity, staggered electric field intensity was observed in the $y$ direction (section 4 in Figure 8). Since the propagating direction for a TE mode was perpendicular to the electric field component (i.e. $E_y$) direction, this type of field distribution was not caused by standing wave which only formed in the propagating direction. Possible reason for this type of electric field distribution was due to the dimension variation from the horn applicator to the microwave heating cavity. Boundary condition was changed during the dimension variations.

Electric field distribution determines the heating pattern of the food. However, the presence of food could also affect the electric field distribution. When food was present, the electric field distribution might be different from that in an empty cavity without load. A snapshot of the electric field distribution with food at the middle of the microwave heating cavity is shown in Figure 9. $E_y$ was still the dominant component at the middle layer of the microwave heating cavity. The electric field distribution within food was similar to that in the empty cavity, i.e. there were two high field intensity bands in $y$ direction. But the continuity of the electric field distribution in $x$ direction was cut by the presence of food. Non-uniform heating pattern was due to the uneven electric field distribution in $y$ direction. A uniform design of electric field distribution in $y$ direction is the solution to obtain a good heating pattern.
Figure 9: Snapshots of electric field distribution and the components in each direction at the middle layer of the microwave heating cavity. The results for empty cavity and the cavity with food load were listed at the left column and right column, respectively.

4. Heating pattern design

4.1 Heating pattern in MATS system

Computer simulation model for the MATS system was developed by Ressecssion et al. (2013). Only the horn applicators and microwave heating cavities were built up (Figure 10). In the MATS system the electric field distribution in each cavity is different to design a relative uniform heating pattern. There were different Ultem walls (9.5-12.7 mm) installed on the side of the microwave heating cavity. The electric field distribution within each microwave heating cavity was analyzed by Ressecssion et al. (2013).
Figure 10: Computer simulation model for microwave heating section of the MATS system. It consists of four heating cavities and attached horn applicators, (a) location of microwave input ports (eight ports in the model), (b) direction of movement of pouches, and (c) location of the pouches (from Resurreccion, et al., 2013).

The heating pattern of this model was verified using a whey protein gel containing D-ribose. Heating pattern of whey protein gel (95×140×16 mm$^3$) was displayed through chemical marker and computer vision method (Pandit et al., 2006; 2007) (Figure 11). Further study proved that in single model MATS system, the variation of dielectric properties of food had no influence on the overall heating pattern. In other words, the electric field distribution and heating pattern in MATS system is robust to dielectric properties of food (Resurreccion, 2012). However, the final temperature of food may be different when the dielectric properties change.

In, Figure 11, hot and cold spot areas were staggered in y direction and uniform in x direction. The electric field distribution in y direction gave rise to this type of heating pattern since food moved in x direction. $E_y$ is the dominant electric field component in the microwave heating cavity (Figure 9).
Figure 11: Heating pattern comparison between (a) simulation results and (b) experimental results (from Resurreccion et al., 2013). The dimension of whey protein gel was 95×140×16 mm³.

The design of Ultem walls on the side of the cavity was to create different heating patterns within different microwave heating cavities. However, installation of the Ultem wall on the side of the microwave heating cavity is very difficult and not easy to adjust. Because the MATS system is a closed and pressurized system, it is difficult to open the door of each cavity to adjust the Ultem wall. Thus, Ultem wall is not a good technique for heating pattern design in industrial scale MATS systems. Based on the analysis of the electric field distribution and each component on different cross sections, the dimension variation from the horn applicator and Ultem window to the microwave heating cavity may lead to the non-uniformity of electric field distribution in y direction. Techniques that influence the electric field distribution in y direction could be used to adjust the heating pattern.

4.2 Computer simulation model for heating pattern design

The major difference among the four microwave heating cavities in MATS system is the inner design of the Ultem walls (9.5-12.7 mm in thickness along y direction). A computer simulation model for one cavity without Ultem wall was used to study the influences of different parameters, such as
dimension of Ultem window and horn applicator, metal bar within the horn applicator, on electric field distribution and heating pattern of food. This model was called the original model.

All the parameters of the original model were similar to the four cavity MATS system. The temperature (123 °C) and dielectric properties of water were set as constant. The power setting was 6.4 KW with a conveyor speed of 17 mm/s. The continuous movement was simulated through 10 discrete moving steps. At each moving step position, the food sample was heated for 4 s. The initial temperature of food was 72 °C. The model food of whey protein gel S1 was used as food sample with dielectric properties shown in Table 3.1.

Table 1. Dielectric properties of whey protein gel S1 used in simulation model

<table>
<thead>
<tr>
<th>WPG formulation</th>
<th>Temperature, °C</th>
<th>Dielectric at 915 MHZ</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dielectric</td>
<td>Loss</td>
</tr>
<tr>
<td>S1</td>
<td>20</td>
<td>50.94 ± 1.44</td>
<td>17.50 ± 1.49</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>50.75 ± 0.62</td>
<td>20.49 ± 1.02</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>49.69 ± 0.33</td>
<td>23.84 ± 1.22</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>48.42 ± 0.56</td>
<td>28.87 ± 0.77</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>49.96 ± 0.38</td>
<td>34.10 ± 3.02</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>45.85 ± 0.25</td>
<td>39.25 ± 3.48</td>
</tr>
</tbody>
</table>

In following studies, all the parameters in the new computer simulation models about food, water, mesh size, boundary condition are the same.

4.3 Sensitivity study of the dimension of the horn applicator

The dimension variation of horn applicator brought non-uniformity of electric field distribution in y direction (Figure 7). The influence of horn applicator dimension on heating pattern was studied in this section. Detailed structure at the connection part between the Ultem window, horn applicator and microwave heating cavity is shown in Figure 12.
The window has a staircase structure with two rectangular solid of different size. The smaller one (Part A) has a dimension of $557.2 \times 185.7 \times 12.7$ mm$^3$ in x, y and z direction respectively. The dimension of the bigger one (Part B) is $608.6 \times 236.5 \times 12.7$ mm$^3$. The wide end of the horn applicator is connected to Part B of the window and they have the same size in x and y direction (i.e $557.2 \times 185.7$ mm$^2$). This type of installation gives the cavity an aperture of $608.6 \times 236.5$ mm$^2$ for the microwave transition. The cavity has an inner width and height of $247.7$ mm and $81.0$ mm in y and z direction, respectively. In x direction, the cavity is connected with other cavities or other sections of the system.

The dimension of the wide open end of the horn applicator and the Ultem window Part A is $557.2 \times 185.7$ mm$^2$ in x and y direction, respectively. In this simulation the size in y direction was adjusted to change the electric field distribution in the microwave heating cavity, from the current $185.7$ mm to a size of $198.4$, $174.4$, $161.7$, $149.2$, $136.5$, $123.8$ mm, respectively. To distinguish the different designs, these computer simulation models were numbered sequentially from narrow to wider with a name of Horn width. For example, the model with $123.8$ mm horn width has a name of Horn width 1. By that analogy, the names of different models are summarized in Table 2.
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Size of horn width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn width 1</td>
<td>123.8</td>
</tr>
<tr>
<td>Horn width 2</td>
<td>136.5</td>
</tr>
<tr>
<td>Horn Width 3</td>
<td>149.2</td>
</tr>
<tr>
<td>Horn width 4</td>
<td>161.9</td>
</tr>
<tr>
<td>Horn width 5</td>
<td>174.6</td>
</tr>
<tr>
<td>Horn width 6 (original model)</td>
<td>185.7</td>
</tr>
<tr>
<td>Horn width 7</td>
<td>198.4</td>
</tr>
</tbody>
</table>

The dimension of Ultem window Part B that connected to the microwave heating cavity was constant in these models i.e. 608.6×236.5 mm². The front view of the simulation models and the side views of Horn width 1 and Horn width 6 are shown in Figure 13. The only difference among the simulation models from Horn width 1 to Horn width 7 was the dimension of horn applicators and Ultem window Part A in y direction. They have the same dimension in x direction (front view).
Figure 13: Front view and side views of the simulation models with different dimensions of horn applicator in y direction. A: front view of the models, all the simulation models have the same dimension in x direction (front view), B: side view of Horn width 6 (185.7 mm), C: side view of Horn width 1 (123.8 mm).

The simulation results of heating patterns for these models are summarized in Figure 14. Top view (x-y plane) of the temperature distribution in the middle layer in z direction represented the heating pattern of food. The cold spot was located in this layer, and hot water heating had lowest influence on this layer.

From Horn width 2 to Horn width 7, all the simulation models had a similar general heating pattern of staggered hot and cold area in y direction. There were two parallel strips of cold spot area along x direction at the top and bottom edges of foods. Two parallel hot spot strips were distributed in the middle of the foods. Between the two hot spot area, there was a moderate hot area. The intensity of the moderated hot area increased with decreasing size of the horn applicators from Horn width 7 to Horn width 2. For Horn width 1, two hot spot areas merged in a relatively one large hot area. Results showed that the dimension variation of horn applicator did not have significant influence on the heating pattern of
the food. Possible reason for this observation can be attributed to the consistent dimension of the aperture of the microwave heating cavity. The aperture of the microwave heating cavity was determined by the wider part of the Ultem window (Part B).

![Diagram of horn applicator width](image)

Figure 14: Effect of horn applicator width on heating pattern of food

4.4 Effect of the cavity aperture on microwave heating pattern

To study influence of the dimension of the aperture of the microwave heating cavity on heating pattern of food, computer simulation models were developed based on the previous model of Horn width 1. The width of horn applicator in Horn width 1 was 123.8 mm which was same as the width of the waveguide. The Ultem window Part A had the same width of 123.8 mm and the Ultem window part B had a width of 236.5 mm (Figure 15).
Figure 15: Structure of the Ultem window in simulation model of Horn width 1.

In this simulation, width of the Ultem window Part B was reduced from 236.5 mm to 185.7, 174.6, 161.9, 149.2, 136.5 and 123.8 mm, respectively. The simulation models and the corresponding width of the Ultem window Part B are illustrated in Table 3. The initial ‘Ultem width’ means the width of Ultem window part B and the number from 1 to 8 represents width in ascending order.

Table 3. Name of simulation model with different dimension of Ultem window

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Size of window width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultem width1</td>
<td>123.8</td>
</tr>
<tr>
<td>Ultem width 2</td>
<td>136.5</td>
</tr>
<tr>
<td>Ultem width 3</td>
<td>149.2</td>
</tr>
<tr>
<td>Ultem width 4</td>
<td>161.9</td>
</tr>
</tbody>
</table>
The heating pattern results of these simulation models are summarized in Figure 16. The heating pattern of food was very sensitive to the variation in the size of the Ultem window Part B. Significant changes were observed from simulation model Ultem width 1 to Ultem width 8. Results proved that the aperture of the microwave heating cavity (i.e. the size of the Ultem window Part B) had great influence on the electric field distribution within the microwave heating cavity. But there was no fixed relation between the heating pattern distribution and the size of the Ultem window. Among all the heating pattern results, Ultem width 4 and Ultem width 2 had a complementary heating pattern. The combination of these two heating patterns may result in a uniform heating pattern. Model Ultem width 3 had the most uniform pattern. But there were cold spots on the two edges in y direction. By looking at the complementary heating patterns, the cold edges in Ultem width 3 could be compensated by the edge heating in Ultem width 5. A good heating uniformity could be obtained through combining two staggered heating pattern when food went through these two microwave heating cavities.
Thus based on the above simulation results, it may be concluded that the heating pattern was more sensitive to the dimension of the Ultem window part B compared to the dimension of horn applicator and Ultem window part A. It was complicated to distinguish parameters of staircase design of Ultem window. A better design for the Ultem window was a rectangular shape without staircase. It had a single dimension parameter. Figure 17 shows this type of structure at the connection between horn applicator, Ultem window and microwave heating cavity.
Figure 17: Structure of rectangular Ultem window, Part A and Part B had the same size.

The widths of Ultem window, wide end of horn applicator and aperture of the microwave heating cavity were the same. Effects of the combined parameter on heating pattern were also studied. The simulation models in Table 4 were carried out.

Table 4. Simulation model with different width of Ultem window/horn applicator

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Width of window/horn applicator width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultem horn 1</td>
<td>123.8</td>
</tr>
<tr>
<td>Ultem horn 2</td>
<td>136.5</td>
</tr>
<tr>
<td>Ultem horn3</td>
<td>149.2</td>
</tr>
<tr>
<td>Ultem horn 4</td>
<td>161.9</td>
</tr>
<tr>
<td>Ultem horn5</td>
<td>174.6</td>
</tr>
</tbody>
</table>
The changes in heating patterns with the width of the Ultem window/horn applicator are shown in Figure 18.

There was no regular change in heating pattern with increasing width of Ultem window/horn applicator. However, the heating pattern had significant change from simulation model Ultem horn 1 to Ultem horn 6. Similar heating pattern was observed between Ultem horn 1 and Ultem horn 7 except the temperature level. For the simulation models Ultem horn 4 (w=161.9 mm) and Ultem horn (174.6 mm), the heating patterns are the most uniform.

4.5 Effect of the length of horn applicator on microwave heating pattern
The heating patterns within the microwave heating cavity changed with the width of horn applicator and Ultem window. It is expected that since food sample is moving in x direction, the length of the Ultem window or horn applicator in x direction should not influence the heating pattern. Simulation model Ultem horn1 was modified to verify this. The length of wide end of the horn applicator was reduced from 557.2 mm to 247.7 mm. All other parameters were the same. Modification of the model and the heating pattern results are shown in Figure 19.

Figure 19: Simulation models with different lengths of horn applicator and the related heating pattern results. The length of horn applicator in x direction was change from 557.2 mm to 247.7 mm. A: model Ultem horn 1, B: modified model.

Similar heating pattern was found between the two models except that the temperature level was different. The food processed by the shorter horn applicator had a low temperature. This is reasonable that with same moving speed and distance, food received a shorter microwave heating time when it went through the shorter horn applicator. It revealed that the electric field intensity in x direction was limited
by the length of the horn applicator. However, the length of horn applicator did not affect the heating pattern of food.

4.6 Application of accessory in the horn applicator

In commercial operation, it is not practical to change physical dimension of the windows or the applicators. In spite of the good simulation results obtained in the previous section, it may better to design some accessories which can be easily used to adjust the electric field distribution and the heating pattern in a commercial system with a fixed dimension. In the MATS system, electric field distribution in y direction regulates the heating pattern. As described in previous sections, the width of horn applicator or aperture of the microwave heating cavity influenced the electric field distribution in y direction and changed the heating patterns. To affect the electric field distribution in y direction, a cylindrical metal bar was placed in the horn applicator near the Ultem window. The placement direction and position of the metal bar is shown in Figure 20. The influence of metal bar on electric field distribution and heating pattern is studied in this section.

Figure 20: Cylindrical metal bars in horn applicators
The influence of metal bars on electric field distribution in y direction was revealed from the side view (y-z plane) of the model. To make comparison, the metal bar in the bottom horn applicator was removed. The snapshots of the electric field distribution in top view in the middle layer of the metal bar in z direction and the side view in the middle layer of the cavity in x direction are shown in Figure 21.

![Figure 21: Snapshots of electric field distribution affected by the metal bar in horn applicator. A: top view in the middle layer of the metal bar in z direction, B: side view in the middle layer of the cavity in x direction.](image)

The electric field intensity was enhanced near the surface of the metal bar except for the top and bottom surface surfaces in z direction. It was due to the behavior of EM fields at edges. It was well know
that when a metallic, dielectric or perfectly conducting wedges was illuminated by EM wave, the transverse component may be singular the mathematically sharp edges. However, the components of the electric and magnetic field strength parallel the edges are always finite (Meixner, 1972). Other than mathematically sharp edges, the transverse components were also intensified near the edges. Previous simulation results stated that the dominant electric field component in horn applicator and microwave heating cavity is in y direction. In Figure 21A, the field enhancement occurred near the surface of metal bar along x direction which is transverse to the field component. It was also the reason that the electric field component was not enhanced near the top and bottom surface of the metal bar in z direction. Because that these two surfaces were parallel to the Ey component.

If a conductor is placed in alternating electric field, eddy current may occur in the conductor’s surface which results in generation of heat. However, because the penetration depth of electric field into metal is very small (order of micron or less at microwave frequency), a bulk metal cannot be heated very much (Yoshikawa, 2010). Thus, same as the waveguide and horn applicators, the metal bar will not be heated much.

Besides that, singular electric field intensity at the sharp edges may cause dielectric breakdown or electric discharge. That is the reason of arcing or sparking occurs in microwave oven when a fork is placed in. If electric discharge or dielectric breakdown happens, it may cause damage to the Ultem window that near the metal bar. Electric discharge may happen if the electric field intensity at the surface is strong enough to lead to dielectric breakdown. Thus a smooth surface should be designed for the metal bar to reduce electric field enhancement near the surface. Furthermore, Ramaswamy et al. (1998), reported that electrical discharge at the tip of a thermocouple could be avoided by grounding it to the metallic wall of the microwave oven. Design of grounding connection is a suitable way to avoid electric discharge of the metal bar. Hence, the metal bar should be connected with the inside wall of the horn applicator to avoid electric discharges.
There was a similar design used in rectangular waveguide of a coaxial water dummy load (Figure 22), which has an operation power of 25 kW (Omegaline, model 5725a, Arkansas, USA). It verified that the design of metal bar in microwave horn applicator was practical.

![Metal bar in rectangular waveguide of a coaxial water dummy load](image)

Figure 22: Metal bar in rectangular waveguide of a coaxial water dummy load (Omegaline, model 5725a, Arkansas, USA)

The model of Ultem horn 6 (Figure 18F) was selected to study the influences of metal bars (38.1 mm in diameter) on electric field distribution within the microwave heating cavity. These influences were reflected on the heating patterns (Figure 23). A convergence effect on electric field intensity was brought by the metal bar which caused hot spot at the position of microwave heating cavity below the metal bar. It could be used to adjust the electric field distribution in y direction to improve heating uniformity of food. For example, in Figure 23C the electric field was concentrate at one side of food which lead to a hot spot area at this side. This type of heating pattern could be used to process food with multi-components that having big difference in dielectric properties.
Figure 23: Influences of cylindrical metal bars on heating pattern. The metal bar has a diameter of 38.1 mm.

The effect of cylindrical metal bar on electric field distribution was due to its influence on the continuity of electric field component in y direction other than the reflection to microwaves. Besides metal, other materials might also have similar influence on electric field distribution through changing the boundary conditions in y direction. A rectangular Ultem bar with a thickness of 38.1 mm and width of 38.1 mm was used to replace cylindrical metal bar in the horn applicator in Figure 23. The heating pattern results for the corresponding models are shown in Figure 24.
Figure 24: Influences of rectangular Ultem bars on heating pattern. The Ultem bar had a dimension of 38.1 mm in thickness (z direction) and 38.1 mm in width (y direction).

Similar effect of Ultem bars on heating pattern was observed compared with the metal bars. The Ultem bar in horn applicator also had a convergent effect to electric field distribution in y direction. However, a bigger Ultem bar was required to achieve the same influence on heating pattern.

To test the function of metal/Ultem bars in the horn applicator, two metal/Ultem bars were placed in each horn applicator of the model Ultem width 3 (Figure 16C). The metal bar had a diameter of 25.4 mm and the thickness and width of Ultem bar were both 38.1 mm. The heating pattern of Ultem width 3 was uniform at the middle area besides the two cold spots edges in y direction. Metal or Ultem bars were used to adjust the electric field distribution in y direction to remove the cold edges. Top view of these models and the heating pattern results are shown in Figure 26. The cold spot areas at the edges were
removed by the metal/Ultem bars. They became a relatively hot spot area and the heating uniformity of
the heating pattern was improved. Application of accessories in the horn applicator is a good technique to
adjusting electric field distribution in y direction.

Figure 25: Effect of the metal bars and Ultem bars on simulation model Ultem width 3

4.7 Effect of dimension of the food on heating uniformity

As shown in the previous sections, various heating patterns could be created by changing the
width of horn applicator and Ultem window in y direction. Some of these heating patterns showed that the
energy was focused on the center part of food, such as model Horn width 1, Ultem horn 1, Ultem horn 2,
and Ultem width 3. The dimension of food used in these models is 96×140 mm² in x and y direction.
Cold edges were observed of the food in y direction. It is a good alternative to change
dimension/placement of food to improve the microwave heating pattern. Figure 26 summarizes the results
for these simulation models with different placement of food.
Figure 26: Heating pattern comparison for simulation models with different dimension of food

With the new dimension or placement direction, more uniform heating patterns were obtained. The temperature at cold spot was higher and the temperature at hot spot did not increase. Results indicated that a matched dimension of food with respect to the electric field distribution within the microwave heating system brought good heating uniformity.

5. Conclusion

The heating pattern in the single mode MATS system was investigated through the simulated electric field distributions within the microwave heating cavity. The propagation mode of microwave in standard WR975 rectangular did not change during the delivery from generator to the horn applicator and microwave heating cavity. For a TE10 mode microwave that propagated in z direction, the electric field component in y direction was the only non-zero components. In the horn applicator and microwave heating cavity, electric field distribution in y direction changed with the dimension of these system components. However, the electric field component in y direction was still the dominant component.
There was non-uniform electric field distribution in y direction within the microwave heating cavity. This non-uniform electric field distribution was caused by the dimension variations from horn applicator, Ultem window to the microwave heating cavity, other than the standing waves in y direction. Hot and cold spot areas were brought by the uneven electric field distribution in y direction.

With a fixed dimension of the microwave heating cavity, different heating patterns were obtained by changing the dimension of the horn applicator and the Ultem window. However, the heating pattern of food was more sensitive to the dimension of the Ultem window because it determined the aperture of the microwave heating cavity. There was no regular relationship between heating pattern and dimension of the Ultem window. But the significant changes in these heating patterns provided a data base for designing uniform heating patterns.

A cylindrical metal bar placed within the horn applicator could be used to adjust the electric field distribution in y direction. Stronger electric field occurred at the surface of the metal bar which resulted in converged electric field intensity around the metal bar. A hot spot area occurred when food was placed below the metal bar. Hence, metal bar could be used to increase electric field intensity at cold spot position to improve heating uniformity. Besides metal bar, a rectangular Ultem bar could bring similar effect on electric field distribution and heating pattern. This type of accessories was a good technique to adjust energy distribution in y direction.

Heating uniformity could also be improved by designing the dimension of food to match the electric field distribution within the microwave heating cavity.
6. References


CHAPTER FOUR

USING MOBILE METALLIC TEMPERATURE SENSORS IN CONTINUOUS MICROWAVE ASSISTED THERMAL STERILIZATION (MATS) SYSTEMS

Abstract

The goal of this study was to evaluate suitability of using mobile metallic temperature sensors in continuous microwave assisted sterilization (MATS) systems. A computer simulation model using the finite difference time domain methods was developed to study the influence of microwave field on the accuracy of mobile temperature sensors, ELLAB, in a MATS system in which food packages with embedded sensors traveled on a conveyor belt. Simulation results indicated that the metallic temperature sensors did not change the overall heating patterns within food samples. But when a metallic temperature sensor was placed in parallel to the electric field component within microwave cavities the field intensity had intense singularity at the sensor tip and caused localized overheating. The electric field singularity adjacent to the tip of the metallic temperature sensor can be avoided by placing the sensor perpendicular to the electric field component. The simulated heating patterns and temperature profiles were verified with experimental results. It was evident from both simulated and experimental results that the metallic temperature sensor could be used to capture temperature profile in a MATS system when placed in a suitable orientation.

1. Introduction

Microwaves generate heat through interaction between dielectric materials, such as foods, and alternating electromagnetic (EM) fields. Compared with conventional water or steam heating, microwave volumetric heating has significant advantages in reducing process time and improving food quality (Guan et al., 2002, 2003). A single mode 915MHz microwave assisted thermal sterilization (MATS) system was developed at Washington State University (Pullman, WA) to explore applications of the microwave technology in pasteurization and sterilization processes and collect engineering data for industrial scale-up (Tang et al., 2006). It is a 22 meter long pilot-scale system that includes four sections: preheating,
microwave heating, holding and cooling to simulate continuous industrial processes. Packaged food products are transported continuously through these four sections by a microwave transparent conveyor belt. Microwave heating section is the key part which can elevate the temperature of a food product by more than 50 °C (e.g., from 70 °C to 121 °C) in three minutes. This section has four connected single-mode microwave heating cavities each with a minor different internal configuration to provide complementary field distributions leading to a relative uniform final heating in foods after moving through those cavities at a constant speed.

Knowledge of heating pattern in foods and reliable measurement of temperature histories at desired locations are critical in developing a thermal processing process for production of safe foods. Heating pattern describes the temperature distribution within foods. It is used to evaluate heating uniformity and identify locations of least processed parts within food packages. The temperature profile, also known as time-temperature profile, records the changes in food temperature over processing time to provide data for calculations of projected reduction in targeted food pathogen population or possible thermal degradation of food qualities (Holdsworth, 1985). Temperature profiles are directly measured by temperature sensors at different locations within foods. In conventional thermal processing, the location that gains least heat and shows lowest temperature is called the cold spot. In microwave heating, the temperature distributions at different locations are caused by uneven electric field distributions. More than one cold spots may exist in a microwave heated food product. Likewise, hot spots may also be present at different positions in microwave heated foods. Unlike multi-mode microwave heating systems in which heating patterns are difficult to predict due to the co-existence of several resonant modes within the frequency bandwidth that coincides with the power spectrum of industrial microwave generators (Chan and Reader, 2000), the single mode MATS system can provide a stable and predictable heating pattern (Resurrection et al., 2013). This was verified with an effective method that assesses the heating patterns based on formation of chemical marker (M-2) in model foods during microwave heating (Pandit et al., 2006, 2007a, 2007b; Resurrection, 2013).
Once the heating pattern and cold spots are determined, temperature sensors can then be directly placed at the locations of cold spots to record temperature profiles for developing of thermal process to ensure food safety. Fiber-optic thermometers are the most reliable and accurate means for direct temperature measurements in microwave heating because those sensors do not disturb microwave fields (Kyuma et al., 1982; Wang et al., 2003). In general, thermocouples and other metallic probes are not desirable for accurate temperature measurements in microwave environments due to possible strong interactions between metal parts and microwave fields (Datta et al., 2001). Strong microwave fields can cause electrical discharges and signal perturbations in metallic probes. Furthermore, the microwave fields are also distorted by the presence of metallic probes. In a previous study, to explore the use of thermocouples in microwave environments a thermocouple was shielded with an aluminum tube and grounded to the metallic wall to reduce electrical discharges and signal perturbations (Van De Voort, et al., 1987). Ramaswamy, et al., (1998) also reported effectiveness of several shielding constructions. Reasonably accurate results were obtained through proper designs (shield isolation and body insulation) of the shielding. However, in continuous microwave heating systems, neither the fiber-optic thermometers nor shielded thermocouples are applicable because of the need to connect those sensors to signal conditioning and data acquisition units that only operate in an open ambient environment outside microwave systems. Possible alternatives are mobile (wireless) temperature sensors, such as Tracksense Pro data logger (Ellab Inc., Centennial, CO, USA) and NanoVACQ temperature data logger (TMI-USA Inc., Reston, VA, USA) developed for temperature measurements in continuous conventional thermal processes. In operation, mobile temperature sensors imbedded in packaged foods collect and store temperature data during thermal processes. Afterward, those sensors are removed from food packages, and data downloaded into computers for analyses. A common mobile temperature sensor is composed by two units: a probe for sensing temperatures and a base for storing temperature data (Figure 2). The surfaces of both units are made of a metal sheet used for protecting the inner sensing and data storing elements. In microwave application, the surface protection can act as a shield for microwave energy based on the same principle as for shielded thermocouples reported in previous mentioned two studies. But the
metallic shielding may also create disturbances to microwave field distribution and affect the heating pattern.

In studies of diffraction problems in EM fields, it has been found that the EM field components at sharp edges of diffracting obstacle may runaway to infinity. This irregular sharp increase in EM field intensity is known as a singularity (Bouwkamp, 1946). The EM fields may have singularities at the vicinities of metal-dielectric wedges. However, the field components parallel to the edge are always finite (Meixner, 1972; Bladel, 1985). Egorov et al. (2006) studied the edge effect in microwave heating of conductive plates. It was reported that the overheating in the edge vicinity of thin conducting plates was attributed to the diffraction of EM waves rather than the uneven irradiations. The level of this overheating reached to maximum when wave components were perpendicular to the edge of a plate. No studies have been reported to investigate the behavior of microwave fields diffracted by mobile metallic temperature sensors. Performance of the mobile metallic temperature sensor influenced by the diffracted EM field is also unknown. In this study we developed a computer simulation model to investigate the interaction between mobile metallic temperature sensors and microwave fields in MATS systems.

With the development of powerful computer workstation and professional software, computer simulation has been effectively used to numerically solve microwave heating problems based on different numerical methods. The finite-difference time-domain (FDTD) method is popular in solving coupled EM and heat transfer problems in microwave heating due to less computer memory and simulation time consumptions (Dev et al., 2010, Watanabe et al. 2010). Furthermore, arbitrarily shaped geometries can be simulated after the conformal FDTD method was developed (Holland, 1993). Chen et al. (2007, 2008) developed simulation models for food packages processed in continuously moving microwave heating system based on conformal FDTD method. The system contained two microwave heating cavities which were similar to the cavities in MATS system. Resurrection et al., (2013) developed a computer simulation model (CSM) for MATS systems based on the dimension of the microwave heating section which was called as MATS-CSM. The heating patterns of pre-packaged foods in the MATS system were correctly predicted by the MATS-CSM.
The objective of this study was to develop a computer simulation model for mobile metallic temperature sensors used in a continuous MATS system based on MATS-CSM. Performances of the mobile metallic sensors in a MATS system were investigated at different cold spot locations and in different orientations. Experiment tests were carried out to validate simulation results in terms of heating patterns and temperature profiles of the food samples.

2. Material and methods

2.1. Physical model

A simulation model was developed based upon MTAS-CSM. Only the microwave heating section was simulated in MATS-CSM. This section contains four microwave heating cavities. Each cavity consists of a rectangular box and two identical horn shaped applicators on its top and bottom. Microwave energy is delivered to the applicators by a standard waveguide WR975, through which only TE10 mode is supported. The front and top views of a cavity with the direction of electric field component and its propagating direction are shown in Figure 1. The electric field component is in y direction (Ey) and it propagates in z direction to the load box which is filled with water and packaged foods. The packages are transported in the positive x direction by the conveyor belt immersed in a shin bed (29 mm) of circulating hot water. Hot water is circulating in the opposite (negative x) direction to the moving packages with a speed of 40 L/min. The purpose of water immersion during microwave heating was to reduce edge overheating in packaged foods. A detailed description of the MATS system and its operation are provided in (Resurrection, et al., 2012).
The mobile metallic temperature sensor used in this study for experimental validation was the Tracksense Pro data logger. It consisted of two parts: a cylindrical base, and a long probe (Figure 2). The length and the diameter of the base were 22 mm and 15 mm, respectively. The probe had a diameter of 2 mm and a length of 50 mm. A temperature sensor (PT 1000) was installed in the probe and its sensor element was placed at 3 mm distance from the probe end. Temperatures detected by the probe were stored in the cylindrical base in two seconds interval. The entire surface of this temperature sensor was made of metallic materials. The metallic temperature sensor in the computer simulation model was developed based on the size of this sensor.
Figure 2: Schematic of the metallic temperature sensor. The diameter (D) and length (L) for the sensor probe and base are 2 mm, 50 mm and 15 mm, 22 mm respectively.

The size of the food samples used in this study was $135 \times 95 \times 16$ mm$^3$. The mobile metallic sensor was placed within a food sample and packaged with the food sample. The sensor was placed in different directions to investigate the behavior of diffracted EM field components. The 2-D views of the food samples and the temperature sensors with different placement orientations are illustrated in Figure 3. Alternating electric field with Ey component was the source to heat foods. Magnetic field component was not illustrated since it has no effect on food materials. The placement orientation of a metallic sensor was explained by an orientation angle while keeping the probe end at the same location. The angle ($\varphi$, $0^\circ \leq \varphi \leq 90^\circ$) between the direction of a metallic temperature sensor (along the probe length direction) and the direction of alternating electric field component was called the orientation angle. The orientation angle was defined as $0^\circ$ (Figure 3A1) and $90^\circ$ (Figure B1) respectively when the sensor was parallel or perpendicular to the electric field component.
Figure 3: Placement orientations for the temperature sensors within foods in different views. A1: \( \varphi = 0^\circ \), top view, A2: \( \varphi = 0^\circ \), front view, A3: \( \varphi = 0^\circ \), side view, B1: \( \varphi = 90^\circ \), top view, B2: \( \varphi = 90^\circ \), front view, B3: \( \varphi = 90^\circ \), side view. The orientation angle (\( \varphi, 0^\circ \leq \varphi \leq 90^\circ \)) is the angle between the direction of a metallic temperature sensor (along the probe length direction) and the direction of electric field component. Alternating electric fields were distributed in food with a component of \( E_y \).

2.2. Governing equations for EM field and heat diffusion

A microwave heating process include two thermal phenomena: microwave heating due to EM field propagation and heat diffusion within foods. The fundamental theory for microwave propagation is based on Maxwell’s equations. In this study, EM waves were calculated through the conformal FDTD method based on the integral form of Maxwell’s equations (Balanis, 1989).

\[
\oint E \cdot dl = -\frac{\partial}{\partial t} \iint B \cdot ds
\]  

(1)
\[ \int H \cdot dl = \frac{\partial}{\partial t} \int D \cdot ds + \int (j + j_c) ds \]  \hspace{1cm} (2)

\[ \int D \cdot ds = Q^e \]  \hspace{1cm} (3)

\[ \int B \cdot ds = 0 \]  \hspace{1cm} (4)

Where \( \vec{E} \) is electric field intensity, \( \vec{D} = \varepsilon \vec{E} \) is electric flux density, \( \vec{H} \) is magnetic field intensity, \( \vec{B} = \mu \vec{H} \) is magnetic flux density. \( j_j \) is the impressed (source) electric current density and \( j_c \) is the conduction electric current density. \( Q^e \) is the electric charges in the volume enclosed by surface S. \( \varepsilon \) and \( \mu \) are the permittivity and permeability of the media that EM wave propagate in. In free space, the value of permittivity is \( \varepsilon_0 = 10^9 / 36\pi \) F/m and the value of permeability is \( \mu_0 = 4\pi \times 10^{-7} \) H/m.

Conduction heat transfer takes place inside of foods due to uneven temperature distribution and convection heat transfer exists between food and the hot water. The equation for conduction heat transfer inside of food is (Rakesh et al., 2010):

\[ \nabla (K(T) \cdot \nabla T) + P = \rho C_p(T) \frac{\partial T}{\partial t} \]  \hspace{1cm} (5)

The equation for convection heat transfer between food and circulating water is:

\[ q = hA(T_w - T) \]  \hspace{1cm} (6)

\( K(T) \) is the thermal conductivity of food and \( C_p(T) \) is the specific heat. Both of them are functions of temperature \( T \). \( \rho \) is the density of food. \( q \) and \( h \) are the energy exchange and the heat transfer coefficient between foods and water respectively, \( A \) is the interface area. \( T_w \) is the temperature of hot water and \( T \) is the temperature of food.

In Eq. (5), \( P \) stands for the dissipated power of microwave in a certain volume:

\[ P = 2\pi f\varepsilon_0\varepsilon''|E|^2 \]  \hspace{1cm} (7)
In which, $f$ is microwave frequency, $\varepsilon_r^*$ is the relative dielectric loss factor of dielectric material. $\mathbf{E}$ is the instantaneous electric field vector, $\mathbf{E} = E(x, y, z; t)$.

### 2.3 Development of the numerical models

A commercial EM field solver QuickWave 3D version 7.5 (QW3D, Warsaw, Poland) was used to solve the integral form of Maxwell’s equation. Furthermore, an attached Basic Heating Module of QuickWave (QW-BHM) provides FDTD calculation for heat transfer. The QW-BHM allows modification for dielectric and thermal properties of media varying with temperature, which can perform simulations that are more approximate to the actual microwave process. It also supports load rotation and movement in horizontal direction for simulating moving samples. MATS-CSM was also built based on QW3D. Furthermore, the newly released module of QW3D provides a support for the movement of metal elements which can be used to simulate the mobile metallic temperature sensor in a MATS system.

Temperature dependent dielectric and thermal properties of the simulated foods were saved in a separate file which could be recognized by QW-BHM. The initial temperature of food was set as uniform (72 °C) to simulate the food packages processed by the preheating section of the MATS system. Water temperature was set as a constant of 125 °C to simulate the high speed circulating condition. All water properties were treated as constant.

The microwave heating section in the MATS system had two open ends in x direction which was connected with preheating and holding section. A perfect electric conductor (PEC) boundary condition was recommended for the numerical terminations at these two ends (Chen et al. 2007). The PEC boundary condition was also applied at the two open ends in this study. However, a 300 mm long load box filled with water was applied to each open end of the section to attenuate the intensity of EM field propagating to the PEC ends. The metallic temperature sensor was assumed as PEC to simulate its high conductivity ($\sim 10^{-6}$ S/m). In the QW-BHM, adiabatic conditions were applied at the boundaries between PEC and dielectric materials (foods, water). QW-BHM automatically assumes that there is no heat exchange between PEC and other materials. As a result, the PEC had no temperature evolution through
the simulation process. A constant temperature of a PEC was initially set up at the beginning of the simulation. The temperature of the metallic temperature sensor was set as a constant of 121.1 °C which is the objective temperature in sterilization. Convection heat diffusion occurred at the surface between hot water and the packaged food, the heat transfer coefficient was set as 180 Wm\(^{-2}\)K\(^{-1}\). It was chosen based on the agreement between simulation results and experiment results for hot water heating (Resurrection, 2012).

The general size of the FDTD cells occupied by the food sample was the same as the one in MTAS-CSM which had a size of 4×4×1 mm\(^3\) (Resurrection, 2012). However, in this study, the size of the cells in the probe vicinity of the metallic sensor was refined. The sizes of the FDTD cells at the probe end of the temperature sensor are shown in Figure 4. In the top view (x-y plane), if \(\varphi = 90^\circ\), the cell size was 3×3 mm\(^2\) around the probe end, and a 3×2 mm\(^2\) cell was modified to keep the probe occupying a whole cell since its diameter was 2 mm. If \(\varphi = 0^\circ\) the cells occupied by the probe were modified to 2×3 mm\(^2\) and other cells were kept as 3×3 mm\(^2\). In the thickness direction (z-x or z-y plane), a finer mesh was defined. The cell occupied by the sensor probe had a size of 3×0.5 mm\(^2\) and the around ones were 3×1 mm\(^2\). In summary, the cell size in the probe of a metallic temperature sensor was either 3×2×0.5 mm\(^3\) or 2×3×0.5 mm\(^3\) depending on its directions and the cell size in the adjacent food was 3×3×1 mm\(^3\). The same FDTD cell sizes were applied in the simulation models without a metallic sensor to compare the temperature profiles influenced by the sensors.
The power setting for the four microwave heating cavities in the MATS system were based upon previous experience and were set to 6.0, 4.7, 2.8 and 2.7 kW, respectively. Thirty two discrete moving steps were applied to simulate the continuous moving process. As was done in the case of the traveling distance, the total heating time was discretized and averagely distributed into these steps. Sensitivity studies were performed for smaller cell sizes and larger number of moving steps. Results indicated that the simulation models were robust and displayed convergence. Based on the balance between simulation accuracy and time consumption current cell size and moving steps were chosen.

### 2.4 Experimental validation

Experimental tests were carried out through the MATS system to validate the simulation models. Preformed whey protein gel (WPG) was used as model food to provide a homogeneous sample (Lau et al., 2003; Wang et al., 2009). The WPGs were made by mixing 75.4% water, 23.3 % protein, 0.3% salt and 1% D-ribose. The uniform mixture was placed into containers and cooked in an 80 °C water bath for 40 minutes. After cooking, the solidified gels were stored at 4 °C refrigerator for at least 24 hours before the MATS process.

The probe end of a temperature sensor was located within WPG at a local cold spot area predetermined by the computer simulation method. Packaged with Alfredo sauce, a total weight of 215 g
sample was sealed in a pouch which is transparent to microwave. The packaged WPG with temperature sensor was placed in conveyor belt sequence and transported through the MATS system. To eliminate the interference from adjacent sensors, at least two packages without sensors were placed between each package with the sensor. The moving speed of the conveyor belt during microwave heating section was 18 mm/s resulting in a final heating time of 170 seconds. The processed samples were taken out at the end of the cooling section and then analyzed for heating pattern.

3. Results and discussion

3.1 Heating pattern generated from simulation model without sensor

The heating pattern obtained from computer simulation was generated from the temperature distribution in each FDTD cell. By setting different colors to represent different temperature levels, a heating pattern image was obtained. Temperature distribution in the middle layer in z direction can best represent the heating pattern where it received the lowest influence by hot water heating, and cold spots located in this layer due to lowest microwave energy. Each heating pattern generated from a simulation model shown in this study was a top view (x-y plane) of the temperature distribution in the middle layer in z direction. The heating pattern without sensor is shown in Figure 5. A symmetric temperature distribution (in either x or y direction) was shown in the heating pattern. There were two hot spot and three cold spot bands interlaced in y direction except for the edge heating. Six local cold spots (cold spot A1, A2, A3, A4, B1 and B2) and two local hot spots (hot spot A and B) located at these bands vicinities. Based upon the symmetrical characteristic, cold spots A1-A4 were parallel to each other in temperature and the same as cold spot B1 and B2. Cold spots A2 and B2 were used to represent these two different local cold spots and the metallic temperature sensors placed at these locations were simulated.
3.2 Heating patterns and temperature profiles influenced by the metallic sensors

In the simulation models, temperature sensors were placed at cold spots A2 and B2 (Figure 5) with two orientation angles (\( \varphi = 0^\circ \) or \( 90^\circ \)) to study the influences on the heating patterns and temperature profiles. Top view heating patterns of these simulation models are demonstrated in Figure 6. Compared with the heating pattern without sensor in Figure 5, the global distributions of cold and hot spots were not affected by the existence of the temperature sensors. However, there were some minor shifts in local temperature distribution. In Figure 6A and 6C, a relative higher temperature appeared in the y direction close to the edge of the temperature sensor. These local variations were noticeable at the hot spot areas and no visible modification was found in the cold spot area. Influenced by these local variations, there was a little shape change in the hot area close to the sensor. In Figure 6B and 6D, the shapes of hot spot areas were obviously modified by the base part of the metallic sensors. But there was no evident change to the heating pattern caused by the probes. In summary, the existence of the metallic sensor did not affect the general temperature distribution within the model food. However, it can locally increase the temperatures close to its edges that perpendicular to the electric field component and bring
heating pattern changes in the local domain. The localized heating pattern changes were noticeable in the regions close to hot spots and the base part of a metallic temperature sensor. These results indicated that a metallic temperature sensor caused temperature increases at the edges that perpendicular to the electric field component. The temperature increase was enhanced by higher electric field intensity and larger metallic body. In a previous report, EM field components behaved singularities adjacent to the edge of a PEC (Meixner, 1972). But the components parallel to the edge were always finite. The local temperature increase in this study was attributed to the electric field singularity close to the edge of a metallic temperature sensor, although the singularity level in this study was not as high as infinity.

Figure 6: Heating patterns generated from the computer simulation models with the metallic temperature sensors. The sensors in different simulation models either had a different location or a different orientation angle. A: $\varphi = 90^\circ$ at cold spot A2, B: $\varphi = 0^\circ$ at cold spot A2, C: $\varphi = 90^\circ$, at cold spot B2, D: $\varphi = 0^\circ$ at cold spot B2.
To evaluate the accuracy of temperatures detected by the metallic temperature sensor, temperature profiles data at cold spot locations were extracted from simulation results. The 32 simulation steps in each model can provide 32 elements for the temperature profile. Each element was obtained by averaging the temperatures at the probe end vicinity. Since the sensing element of the temperature sensor is 3 mm in length from the probe end, all the FDTD cells within 3 mm from the probe end were used to obtain the average temperature values. To avoid size difference among FDTD cells, the volume-temperature average was conducted by:

$$T_{av} = \frac{\sum_{i=1}^{n} (T_i V_i)}{\sum_{i=1}^{n} V_i}$$

(8)

where $T_{av}$ is the average temperature, $T_i$ is the temperature in a FDTD cell and $V_i$ is the cell volume. The result of a temperature profile for the simulation model without the metallic temperature sensor was extracted from the same FDTD cells to make comparison. The temperature profiles influenced by the sensor conditions (without sensor, $\phi = 0^\circ$ or $90^\circ$) at cold spot A2 and B2 are shown in Figure 7.

In Figure 7, temperature profiles at the cold spot A2 were similar to the profiles at cold spot B2 in general trends. Good agreement in temperature profiles was observed between the one without sensor and the one with a sensor in the orientation of $\phi = 90^\circ$. The results implied that when placing sensors with $\phi = 90^\circ$, the metallic mobile temperature sensor had little influence on the measured temperature profiles. However, fluctuating temperature profiles were obtained for the period of time when foods are traveling directly in high microwave field and when the sensors were placed in an orientation angle of $\phi = 0^\circ$. These fluctuations were unexpected since the temperature at a cold spot should not decrease based upon the heat transfer law. The appearances of fluctuations in a temperature profile implied that, a local hot spot appeared at the tip area of the sensor with $\phi = 0^\circ$, caused by an electric field singularity. The electric field singularity arose while the edge of the probe end was perpendicular to the electric field component.
Figure 7: Comparison of temperature profiles for different metallic temperature sensor conditions within foods: $\varphi = 0^\circ$ (---), $\varphi = 90^\circ$ (---) and without sensor (---). The temperature profiles were obtained from different computer simulation models at cold spot A2 (A) and cold spot B2 (B).

The dissipated microwave power density within a food containing a metallic temperature sensor with $\varphi = 0^\circ$ is shown in Figure 8 to reveal the field singularity. For illustration, three snapshots of the power density were taken at the entrance, center and exit of the second cavity. Higher microwave power density implies stronger electric field intensity. The electric field intensity at the tip of the metallic sensor reached its maximum while the food moved to the center position of the cavity. While travelling through the whole length of this cavity, the electric field intensity at the sensor tip increased from the entrance to the center position and then decreased from the center to the exit position.
Figure 8: Microwave power dissipation within food packages (top view) at different positions of Cavity 2:
A: at the entrance of cavity 2, B: at the center of cavity 2, C: at the exit of Cavity 2.

In summary, when the temperature sensor was entering into a microwave heating cavity with $\phi = 0^\circ$, the electric field singularity and local overheating were enhanced by the increasing electric field intensity as reflected by a sharp temperature increase in the temperature profile. The singularity and local overheating reached maximum when the temperature sensor moved to the center of a microwave heating cavity. When the temperature sensor was leaving the microwave heating cavity, the singularity decreased with reducing electric field intensity and lowered the level of local overheating. Based on the heat transfer law, the energy in the local overheating region will flow to the vicinity region which was shown on the decreased trend of the temperature profile. The same explanation could be applied to the different fluctuation levels of the temperature profiles among the four microwave heating cavities. The fluctuations were dramatic in the first two cavities compared with the last two cavities because that the powers in the first two cavities (6.0 and 4.7 kW) were higher than the other two (2.8 and 2.7 kW). The results agreed with the edge heating of conductive plates in microwave heating that the field singularity or edge overheating reached to maximum when the field component was perpendicular to the edge direction (Egorov et al., 2006). In this study, the good agreement between the temperature profile without sensor...
and the one with $\varphi = 90^\circ$ indicated that the local overheating can be reduced to minimum by orientating the edge parallel to the field component that providing the heat source.

### 3.3 Experimental validation

The cold spot B2 was chosen to carry out experimental validation. B2 had a higher final temperature than cold spot A2 (Figure 7). Probe ends of the sensors were placed at cold spot B2 in two orientations ($\varphi = 0^\circ$ or $90^\circ$) and each was packaged with separated WPG samples (Figure 3). At the end of the experiment, the heating pattern of the WPG was obtained through computer vision method and the temperature profile was retrieved from the temperature sensor. The heating patterns are shown in Figure 9. Similar to heating patterns obtained from simulation results (Figure 5, Figure 6C and 6D), there are three cold spot areas and two hot spot areas alternately distributed in y direction except for edge heating. The influences caused by metallic temperature sensors on heating patterns were the same as simulation results.

![Figure 9: Heating patterns obtained from experimental results with different sensor conditions at cold spot B2. A: without sensor, B: $\varphi = 90^\circ$, C: $\varphi = 0^\circ$. Various colors stand for different temperature levels. Temperatures increase in order with colors changing from blue, green, yellow to red.](image-url)
Besides the heating pattern, temperature profiles recorded by the metallic temperature sensors and the related simulation results are displayed in Figure 10. The variations of temperature in experimental results among replications were caused by possible differences in the tip locations of the temperature sensors. Differences among the tip locations may occurred when the sensors were placed into foods by hand. However, the differences of tip locations can only affect the magnitude of the collected temperature. They cause no changes in the general trend of the temperature profiles. Furthermore, the general trend of the temperature profiles between experiment and simulation results are the same.

![Figure 10: Comparison of temperature profiles for experimental (—) and simulation (——) results at cold spot B2 with different orientation angles of the temperature sensor, A: $\varphi=90^\circ$, B: $\varphi=0^\circ$.](image)

The fluctuant temperature profile was verified by the metallic temperature sensor in experiment test with $\varphi=0^\circ$. The fluctuations were observed in every microwave heating cavity (Figure 10B) and they are noticeable in the first two cavities. The unexpected fluctuations were removed by orienting the metallic temperature sensor to $\varphi=90^\circ$ (Figure 10A). Results verified that local overheating appeared at the tip of a metallic temperature sensor while the edge was perpendicular to the electric field component. The local overheating was caused by electric field singularity and it could be enhanced by higher microwave power which delivered higher electric field intensity. This field singularity could be avoided
by placing the edge of the probe end parallel with the electric field component. The difference in the tip location of the metallic temperature sensor would not influence the general trend of the temperature profile. The temperature profiles in simulation results did not completely coincide with the experimental results especially in the last two cavities. Many parameters in simulation models may lead to the difference, such as the heat transfer coefficient between food and hot water, the dielectric and thermal properties of model foods and ideal assumption of the PEC metallic temperature sensor. Overall, simulation models were proved to be correct with good agreements to experimental results in terms of both heating patterns and temperature profiles. In particular, the trends of the temperature profiles influenced by the metallic temperature sensors were well confirmed by experimental tests.

4. Conclusion

The mobile metallic temperature sensor showed no influence on the general heating pattern of a packaged model food. However, there was a temperature increase at the edge vicinity of the sensor which brought a local modification of heat pattern once the edge was perpendicular to the electric field component. This modification of a heating pattern was noticeable at the domain close to a hot spot area and the region adjacent to the base part of the sensor. The local temperature increase was attributed to the local overheating that caused by an electric field singularity. The level of the field singularity and local overheating can be enhanced by higher electric field intensity. If a field singularity occurred at the probe end of the metallic temperature sensor, the temperature profile at this location displayed fluctuations with varying electric field intensity. A metallic temperature sensor with a small volume is recommended to reduce its influence on the heating pattern. To remove the influence of field singularities on the temperature profile, the metallic temperature sensor should be placed in the orientation that the edge of the probe end was parallel to the electric field component. In conclusion, the mobile metallic temperature sensor can be used in a microwave heating system while a right placement orientation was required to obtain a reliable temperature profile.
Further studies are required to understand the field singularities and local overheating affected by high microwave power used in industrial application and the influences on food safety and quality. This will help to support the application of the metallic temperature sensors in commercial microwave heating system.
5. References


CHAPTER FIVE

PERFORMANCE OF MOBILE METALLIC TEMPERATURE SENSORS IN HIGH POWER
MICROWAVE HEATING SYSTEMS

Abstract

The goal of this study was to investigate the performance of mobile metallic temperature sensors in a packaged food processed in high power microwave assisted thermal sterilization (MATS) systems. A validated computer simulation model based on conformal finite difference time domain (FDTD) method was used to evaluate the influences of the microwave power intensity, probe tip geometry and diameter on the accuracy of the sensors. The simulation results revealed that a higher temperature zone was created near the probe tip. This temperature alteration was caused by the distortion of electric field at the probe tip area. Increasing the microwave power setting of MATS system amplified the temperature alteration. Proper sensor designs could help to reduce the temperature alterations. The flat probe tip was most sensitive to high power setting. Changing the probe tip to a spherical geometry and decreasing diameter of the probe significantly reduced the temperature alteration.

1. Introduction

Microwave heating has been widely used in food industry. In microwave heating, alternating electromagnetic (EM) fields directly interact with polar molecules and ions in food materials to cause volumetric heating that sharply reduces thermal processing time and greatly improves the quality of thermally processed foods (Guan, et al., 2002; 2003). Microwave thermal process holds potential for commercial production of high quality shelf stable food products (Ohlsson, 1987, 1990; Ahmed and Ramaswamy, 2007). In commercial thermal processes, sufficient thermal energy needs to be delivered to inactivate food pathogens and product temperature is the key parameter to ensure food safety. In developing a new thermal process, temperature sensors are placed at target locations (i.e. cold spots) to measure the time-temperature profiles over the processing time. Accurate measurement of temperature history is critical to the design of a thermal process to ensure the processed foods to be safe (Lund, 1977;
Ohlsson, 1980; Holdsworth, 1985; Awuah et al., 2007). If the temperature was overestimated, an insufficient thermal treatment will lead to a food safety problem. On the other hand, underestimated temperatures would cause quality degradation of food products by overcooking.

Appropriate selection of temperature sensors for thermal process development is based on the process conditions and the performance of the sensors such as the requirement of accuracy, response time, cost and stability of calibration (Wang et al., 2003). In a microwave heating environment, an effective temperature measurement device should not disturb the EM field or be affected by the EM field (Datta et al., 2001). The fiber-optic temperature sensors are commonly used in microwave heating measurements (Kyuma et al., 1982; Tang et al., 2008). But the fiber-optic sensors require light sources that are heat sensitive and expensive. In addition, the long fragile optical fibers that connecting sensors in food and the light source outside of the system are not suited for the temperature measurement in moving samples within high temperature pressurized chambers. The above disadvantages make fiber-optic sensors impractical in commercial industry applications.

Temperature sensors with metal components are generally not suitable for microwave heating because metallic materials interact with EM field. The interaction alters EM field distribution and reduces the sensor accuracy. Nevertheless, many attempts have been made to modify metallic thermocouples for temperature measurements in microwave environments (Van de Voort et al., 1987; Ramaswamy et al., 1991; Kermasha et al., 1993). Ramaswamy et al., (1998) reported that metallic thermocouples could be used in microwave ovens with adequate accuracy (errors < 2 °C) by proper design of the shield isolation and body insulation. However, this accuracy is inadequate for developing the commercial thermal processes. Correct measurements of metallic temperature sensors within high power microwave environment may be affected by two sources: the intrinsic accuracy of the sensor type and the interaction between metallic body and the electric field.

A temperature sensor with a higher intrinsic accuracy, such as the resistance temperature detector (RTD), could be used to replace a thermocouple in designing a shield metallic sensor applied in a microwave environment. However, local electric field distortion and enhancement will occur at the
metallic surface especially at the probe tip area (Pert et al., 2001). Temperature alteration may be created by the distortion and enhancement of the electric field which results in incorrect measurement. Other techniques need to be developed to reduce this type of temperature alteration. Luan et al., (2013) studied a commercial mobile metallic temperature sensor (Tracksense Pro data logger, Ellab Inc., Centennial, CO, USA) used in a pilot scale microwave assisted thermal sterilization (MATS) system. Results indicated that at pilot scale power settings (2.7–6 kW), the mobile metallic sensors could be used in microwave heating environment. But to reduce the temperature alteration the sensor probe should be placed perpendicular to the dominant electrical field component. This type of small metallic mobile sensors with build-in memory for storing data can be extremely convenient for use in measuring temperatures inside packaged foods during a continuous commercial process. But in industrial applications a much higher microwave power may be used to meet the requirement for designed production. Possible temperature alterations caused by the electric field distortion around the probe tips were unclear at the high power microwave environment.

Computer simulation methods that numerically solve the coupled Maxwell’s and heat transfer equations are effective tools to assist the microwave heating designs (Dibben, 2001; Pathak et al., 2003; Chen et al., 2007, 2008; Resurrection et al., 2013). An experimentally validated computer model can be used to provide inside information of complicated microwave heating process and facilitate process developments.

A computer simulation model based on conformal finite difference time domain (FDTD) method (Holland, 1993, Yu et al., 2000) was developed and validated in a previous study for the MATS system (Luan et al., 2013). In the current research, the same model was adapted to evaluate the temperature alterations caused by the mobile metallic sensors in a 915 MHz single mode microwave heating system. The results of the study would provide a general guidance for designing appropriate temperature sensors applied in industrial microwave heating systems.

2. Methodology
2.1 Physical model

The microwave heating system we attempted to model in this study was a portion of a pilot scale, 915 MHz, single mode microwave heating system developed by Washington State University (Pullman, WA). This system consisted of four sections: preheating, microwave heating, holding and cooling (Tang et al., 2006).

![Physical model in 3-D view. A: microwave heating cavity, B: electrical field distribution of TE10 model in the rectangular waveguide, C: food with an imbedded metallic sensor.]

Figure 1: Physical model in 3-D view. A: microwave heating cavity, B: electrical field distribution of TE10 model in the rectangular waveguide, C: food with an imbedded metallic sensor.

The microwave heating section that contains four microwave heating cavities was the key unit of the system. Only one microwave heating cavity was simulated to reveal the detailed interaction between EM field and metallic sensors. The selected microwave heating cavity had a rectangular load box and two identical horn shaped applicators on its top and bottom (Figure 1A). A standard waveguide WR975 delivered microwave energy from a generator to the applicators. Within the waveguide only a TE10 microwave propagation mode was supported and transmitted (Figure 1B). The symbols 1 and 0 in a mode type denoted the number of semi-sinusoidal variations in x and y direction, respectively. For a TE10 mode in a rectangular waveguide, the electrical field component only existed in y direction (Ey) and it formed a standing wave in x direction with one semi-sinusoidal variation. Microwaves propagated...
in z direction to the load box which was filled with circulating hot water and food packages. The packages were transported in the negative x direction through a conveyor belt. Both the conveyor belt and packages were immersed in water bed with a thickness of 29 mm. The materials of packages and conveyor belt were not considered in the simulation model since they were both transparent to microwave.

We selected commercial mobile metallic sensors, Tracksense Pro data logger, manufactured by Ellab Inc. (Centennial, CO, USA) for this evaluation. The mobile metallic sensor had two parts: a cylindrical base and a long probe (Figure 1C). The base part had a diameter of 15 mm and a length of 22 mm. A RTD (PT 1000) was installed in a shielding tube (316 stainless steel) 2 mm in diameter and 50 mm in length. The sensor was imbedded in a model food prepackaged in a polymeric pouch that had a dimension of 95×135×16 mm³ in x, y and z direction, respectively. The sensor probe was placed at the validated cold spot location detected using chemical marker method (Pandit et al., 2006, 2007). A previous study revealed that the sensor accuracy was affected by the relative direction between the sensor orientation and electric field component (Luan et al., 2013). In the current study, a similar orientation angle (ϕ) was defined to describe the orientation of a sensor within the x-y plane of food (Figure 2). The orientation angle was defined as zero when the length of sensor from probe to base was along positive y direction. The angle increased with the rotating base in counter-clockwise direction and vice versa. The two particular orientation angles in the previous study (ϕ = 0° and 90°) had the same definition in this orientation angle system. Other than particular orientation angels, a general angle of ϕ = 45° was simulated to identify the best orientation angle for analyzing the temperature alterations affected by different sensor designs and microwave power settings.
Three different geometries of the probe tip were simulated in this study: flat, sphere and truncated cone. Top view (x-y plane) of these probe tips are shown in Figure 3. The sensing element of the metallic sensor was a RTD that shielded by a metallic tube. There was a 3 mm distance between the probe tip and the resistance element of the RTD. To investigate the influence of the probe tip size on temperature alteration, a simulation run for the flat probe tip in 1 mm diameter with the best orientation angle and highest power setting within this study was performed in addition to the simulation for the flat probe tip in 2 mm diameter.
2.2 Numerical model and parameter settings

The computer simulation model used in current research was modified based on the previously validated model which was built using commercial software QuickWave version 7.5 (QW3D, Warsaw, Poland). This model was previously verified using a whey protein gel containing D-ribose (Luan, et al., 2013). The metallic sensors (Ellab) were embedded in whey protein gels at two orientations \( \varphi = 0^\circ \) and \( 90^\circ \). The sensor was placed at the same cold spot location for each sample. Heating pattern of whey protein gel was displayed through computer vision method (Pandit et al., 2006, 2007). The validation results of heating pattern and temperature profiles are shown in Figure 4. Good agreements on heating pattern and temperature profiles between experimental result and simulation results were observed. In current study, all the fundamental parameters such as numerical method, boundary condition and basic assumptions were the same as those for the validated model (Luan et al., 2013). The parameters having
different settings from the validated model were the mesh size and moving step of food package. A finer mesh size and smaller moving step were adopted to improve the simulation accuracy.

Figure 4: Validation results of heating pattern and temperature profile through experimental tests of the protein gels processed by a four cavities microwave heating system. Metallic sensors were embedded in the whey protein gel model food with an orientation angle of $\varphi = 90^\circ$ and $0^\circ$. Heating pattern results were obtained at the exit of the fourth cavity. Temperature profiles were the results of temperature history at the probe tips through the four microwave heating cavities. A1 & A2: experiment and simulation results of heating patterns and temperature profiles for the metallic sensor at an orientation angle of $\varphi = 90^\circ$, $\varphi = 0^\circ$. 
respectively. B1 & B2: experiment and simulation results of heating patterns and temperature profiles for the metallic sensor at an orientation angle of $\varphi = 0^\circ$, respectively, (Modified from Luan et al., 2013).

The mesh size of a general FDTD cell in different materials was set following the rules of more than ten cells per wavelength (Rattanadecho, 2006). However, in the proximity of the metallic probe tip domain (within 3 mm distance from the tip) a much finer mesh size of $0.5 \times 0.5 \times 0.5$ mm$^3$ (Figure 5) was set to reveal detailed information of the electrical field and the corresponding temperature distribution within this area. This arrangement resulted in an overall cell number of $423 \times 92 \times 103$ for the simulation model and a cell number of $54 \times 52 \times 24$ for the food sample. A HP Z800 workstation with a dual processor of X5680, 3.33GHz and a memory of 96GB was used to run the simulation model. Ten discrete moving positions were uniformly distributed in the length of the cavity to simulate the continuous moving process. At each position from entrance to exit of the cavity, food sample was simulated in sequence. It took 2 hours to finish one moving position and 20 hours for a whole run. The power setting of the initial model was 6.0 kW with an overall heating time of 39 s and 3.9 s for each moving position. To study the performance of metallic sensor in high microwave power environment, the simulation model with power settings of 12 kW and 24 kW and corresponding heating time of 19.5 s and 9.75 s were also run. The governing equations for EM field and heat transfer with corresponding boundary conditions were the same as those in Luan et al. (2013). Preliminary convergence and sensitivity tests were conducted to ensure reliable simulation results.
Figure 5: FDTD cell sizes at the probe tip area of a metallic temperature sensor with the orientation angle of $\varphi = 90^\circ$

### 2.3 Data analysis

Once the simulation of each moving position was finished, the temperature distribution within each FDTD cell was saved in a data file as the initial temperatures for next position. The temperature distribution within a food sample at each moving position was extracted from the corresponding 54×52×24 FDTD cells for heating pattern and temperature profile analyses. A heating pattern image of a given cross section of the food sample was generated by setting different colors to represent different temperatures. The image of temperature distribution in middle layer (z direction) of x-y plane was the best illustration of the heating pattern, because the cold spot was located in this layer and it received lowest influence from hot water heating. All the heating patterns shown in this study were the middle layer x-y plane images of the last (10th) moving position.

The time-temperature profile was obtained by extracting the average temperature at the probe tip area from each temperature distribution file. All the FDTD cells within 3 mm distance from the probe tip were used to calculate the average temperature. Each time-temperature profile had ten elements matching ten moving positions. A separated Matlab (Mathworks Inc., MA, USA) script was programed to read the
temperature data file and perform the calculation. The same operation was done for the simulation results of the contrast run that was without sensor to obtain the comparison temperature profile. At each moving position, the temperature difference between the objective run with sensor and the contrast run was the temperature alteration created by a metallic temperature sensor. A temperature difference profile was obtained by collecting the ten temperature alterations at the corresponding moving positions.

3. Results and discussion

3.1 Influence of orientation angle and tip geometry of metallic probes on heating pattern and temperature alterations

The metallic sensors with three different probe tip geometries were simulated at the two particular orientation angles ($\phi = 0^\circ$ and $90^\circ$) to study the influence of tip geometries on heating patterns and temperature alterations at the original power setting of 6 kW. A general orientation angle of $\phi = 45^\circ$ was also studied for the sphere probe tip to reveal the performance of the metallic sensor at a general orientation. The best orientation angle was selected by comparing the heating pattern and temperature alteration results. The heating pattern results are shown in Figure 6.

Compared with the heating pattern without sensor (Figure 6D), a mobile temperature sensor did not change the general cold and hot spot distribution when it was placed at orientation angles of $\phi = 0^\circ$ or $90^\circ$. This result was consistent with the validated model (Figure 4). Similar heating patterns were observed for different tip geometries when the sensors were placed at the same orientation angle such as the results in Figure 6A1, B1 and C1. A distorted heating pattern was observed near the base part of the sensor when it was placed at the orientation of $\phi = 45^\circ$ (Figure 6B3). However, this local distortion did not affect the temperature distribution at the probe tip zone. There was obvious local overheating at the probe tip zone when the sensor had an orientation angle of $\phi = 0^\circ$ (Figure 6A1, B1, and C1) and $45^\circ$ (Figure 6B3). This local overheating was displayed by the simulation model with finer mesh size at the probe tip.
zone. However, no such overheating was observed at the same domain of the metallic sensors with the orientation angle of $\varphi = 90^\circ$.

Figure 6: Heating patterns in the food samples with different sensor conditions at the exit of a 6 kW microwave heating cavity. The sensors with different probe tip geometries were placed at the same location with different orientation angles.

Temperature difference profiles were calculated for the sensors with different tip geometries and orientation angles. These temperature alterations varied with moving positions are shown in Figure 7. All the values of the alterations were above zero which indicated that the metallic sensor created a higher temperature at the probe tip zone. Electric field distortion and enhancement at the probe tip zone caused these higher temperature zones (Pert et al., 2001; Egorov et al., 2006; Luan et al., 2013). With the same orientation angle ($\varphi = 0^\circ$ or $90^\circ$), temperature alterations of different sensor probe geometries had no significant difference. The temperature alterations were reduced by changing the orientation angle from
0° to 45° and 90°. The orientation angle of $\varphi = 90°$ was the best orientation angle for the metallic sensor which was directly perpendicular to the dominant electric field component (y direction). The best orientation angle limited the temperature alterations within a range of 0.6 °C when the sensor in food moved through the 6 kW microwave heating cavity.

The temperature alterations increased first and then decreased with the moving position numbers. This trend can be explained by the electric field distribution in the microwave heating cavity that the highest electric field intensity arose at the middle of the cavity. The results showed that higher electric field intensity at the center of the microwave heating cavity amplified the temperature alteration. Likewise, higher microwave power may also amplify the temperature alteration to a high level although the sensor was at the best orientation.

### 3.2 Influence of power setting on heating pattern and temperature alteration

![Figure 7: Temperature difference profiles for different sensor conditions in 6 kW microwave heating cavity.](image)

The temperature alterations increased first and then decreased with the moving position numbers. This trend can be explained by the electric field distribution in the microwave heating cavity that the highest electric field intensity arose at the middle of the cavity. The results showed that higher electric field intensity at the center of the microwave heating cavity amplified the temperature alteration. Likewise, higher microwave power may also amplify the temperature alteration to a high level although the sensor was at the best orientation.
Simulation runs with higher power settings of 12 kW and 24 kW were carried out for three different metallic sensor tip geometries with the best orientation angle ($\varphi = 90^\circ$). The comparison runs without sensor were also carried out with these two power settings. The overall heating time within each simulation run was reduced accordingly to 19.5 s and 9.75 s, respectively, so that the cold spot temperature reached a proximity value. The heating patterns for 24 kW power setting are shown in Figure 8. Compared with power setting of 6 kW (Figure 6), four times power setting did not change the general heating patterns. Results proved that the heating pattern in a MATS system was stable regardless power settings. However, the overheating in y direction near the sensor surface was more obvious at high microwave power settings. The reason was that the existence of metallic sensor cut off the continuity of electric field component in y direction and led to field enhancement at the metallic surface. Heat dispersion within a short time was not adequate to ease the local overheating intensified by high microwave powers.

Figure 8: Heating patterns in food samples without sensor and with three different probe tips (orientation angle of $\varphi = 90^\circ$) at the exit of the 24 kW microwave heating cavity. A: flat, B: sphere, C: truncated cone, D: without sensor.
Analyses of the electric field component in the middle layer (z direction) of the microwave heating cavity could help to verify this electric field enhancement effect. Two identical microwave heating cavities were built in one simulation run to analyze the distribution of electric field components. Food samples with and without sensor (sphere tip) were placed at the center of each cavity. Combined in one simulation run, the electric fields within the two cavities had the same phase. A snapshot of electric field component distributions at the middle layer of z direction is shown in Figure 9.

Figure 9: Snapshot of electric field component distributions in two 24 kW microwave heating cavities. Food samples with sensor (spherical tip, $\varphi = 90^\circ$) and without sensor were placed at the center position of the left and right cavities, respectively.
The right side cavity was the contrast one without sensor. It was clear that the dominant component of the overall electric field intensity (E) was in y direction (Ey). The electric components in x (Ex) and z (Ez) directions were close to zero. Electric field enhancement was observed near the sensor surface in y direction which was reflected on the heating patterns (Figure 8).

The influences of probe tip geometries and power settings on the temperature difference profiles are shown in Figure 10. The temperature alterations were amplified by increasing the microwave power setting for each type of probe tip geometry. However, the sphere probe tip had the lowest sensitivity to the increased powers. It was reasonable that electric field enhancement was very intensive at sharp edges (Bouwkamp, 1946). The smooth surface of the sphere tip helped to reduce this type of enhancement. The sensor with the truncated cone tip had lower temperature alteration and displayed less sensitivity to power settings compared with the flat tip sensor which also proved that the probe tip with smoother surface is better.

Figure 10: Temperature difference profiles for the three probe tip geometries at different microwave power settings with the probe orientation angle of \( \phi = 90^\circ \). A: flat, B: sphere, C: truncated cone.

The amplification effect of high power setting on temperature alterations could be used in arranging the microwave power distribution of multi-cavity microwave heating systems. A proper arrangement for microwave power distribution could reduce the influence of temperature alterations on the development of a thermal process to meet the academic desired microbial inactivation. For a
microwave heating system with two or more cavities along the moving direction of food packages, a decreasing power setting is desirable to make the larger temperature alteration arise at the first cavity of first few cavities where food temperatures were at a low level. The temperature alterations at a low temperature level had limited influence on evaluation values of microbial inactivation due to the relationship between time-temperature profile and the thermal inactivation of microorganisms (Holdsworth, 1985).

The simulation model was also used to study the influence of heat dissipation on temperature alternations caused by the presence of mobile probe after the food pouches moving out of microwave heating cavities into the holding zone. In the holding zone the microwave power was set to zero, only heat transfer was considered, and the circulating water temperature was set as 125 °C. The temperature difference profiles during microwave heating and holding processes for two sensor tips (flat and sphere) at three microwave power settings are shown in Figure 11. In the holding section, the temperature alterations decreased gradually with holding time. At 10 second after the food pouch moved to the holding section, the temperature alterations caused by the flat sensor in 6, 12 and 24 kW microwave heating process decreased to 0.36, 0.47 and 0.61 °C, respectively. For the sphere sensor, the corresponding temperature alterations were reduced to 0.15, 0.27 and 0.33°C, respectively. These results indicate that lower power setting of the last few microwave heating cavities could reduce the effect of temperature alterations to an acceptable level within a very short holding time. For example, if a 6 kW microwave power setting was used for the last microwave cavity connected to the holding section, the 0.15 °C alternation over a holding temperature of 121.1 °C at the cold spot would only led to an overestimated value of 0.21 min (i.e. 12.6 s) to a $F_0 = 6$ min (thermal lethality to *Clostridium botulinum* at constant temperature of 121.1 °C) when using a probe with spherical tip.
Figure 11: Temperature difference profiles during microwave (MW) heating and holding processes for flat and sphere tips with the probe orientation angle of $\varphi = 90^{\circ}$ at three microwave power settings. A: 6 kW, B: 12 kW, C: 24 kW.

3.3 Influence of probe diameter on temperature alteration

The flat probe tip which was most sensitive to microwave power settings was chosen to study the influence of probe diameter on temperature alterations. Figure 12 shows the temperature difference profiles obtained from the simulation with power setting of 24 kW for flat probe tips with different diameters (1 mm and 2 mm) and probe orientation angle of $\varphi = 90^{\circ}$. The temperature alteration caused by electric field enhancement decreased from more than 1.1 °C to less than 0.2 °C by reducing the probe diameter from 2 mm to 1 mm. The temperature alteration of 0.2 °C in the 24 kW microwave heating cavity even for the worst tip design (flat tip) considered in this study was comparable to the accuracy of RTD (Wang et al., 2003). It was acceptable in commercial thermal processing development.
Figure 12: Temperature difference profiles during microwave (MW) heating process for flat tips with different probe diameters of 1 mm and 2 mm at an orientation angle of $\varphi = 90^\circ$ and 24 kW microwave power setting.

4. Conclusion

Computer simulation results revealed that a higher temperature zone was created at the metallic temperature sensor tip which could cause erroneous temperature readings. These temperature alterations were caused by electric field distortion and enhancement at the probe tip. The temperature alterations were reduced by orienting the sensor probe perpendicular to the dominant electric field component.

At a low microwave power setting of 6 kW for a 915 MHz single mode cavity, there was no significant difference among the temperature alterations of the probes with different tip geometries; however, the temperature alterations were amplified by higher microwave power settings.
Among the three probe tip geometries, the sphere tip with the smoothest surface had the lowest sensitivity to microwave power settings. For the worst case of flat probe tip, which caused the highest temperature alteration, the temperature alteration could be greatly reduced by decreasing the probe diameter from 2 mm to 1 mm. It was suggested that the design of spherical probe tip and thinner probe diameter should improve the accuracy of metallic temperature sensors applied in high microwave power environment.

For a multi-cavity microwave heating system, a decreasing power distribution of the heating cavities along the package moving direction is recommended. This arrangement could reduce the propagating errors from the time-temperature profiles to the estimation of desired microbial inactivation level in designing microwave thermal processes. The dominant electric field component within microwave heating cavity is in \( y \) direction which is the same as the electric field in a waveguide. It implies that in MATS system, the general mode of microwaves did not change when they propagate from waveguide to the heating cavity.
5. References


CHAPTER SIX
DIELECTRIC PROPERTIES OF BENTONITE WATER PASTE CHANGING WITH INGREDIENTS AND TEMPERATURE RELEVANT TO MICROWAVE THERMAL PROCESSING

Abstract

The dielectric properties of bentonite water pastes relevant to microwave thermal processing were measured over 300 to 3000 MHz and 20 to 120 °C. Effects of bentonite content (7.5% to 25%, wb), salt content (0.3% to 1.2%, wb) and vegetable oil content (5% to 15%, wb) were investigated. Regression equations were developed to reveal the influences of temperature and different ingredients on the dielectric properties of bentonite paste at 915 and 2450 MHz. Results illustrated that dielectric properties of bentonite pastes with different ingredients were similar to that of food materials and they have the same response to increasing temperature and frequency. Vegetable oil and salt were good additives to reduce dielectric constant and increase loss factor, respectively. Derived from the regression equations, the influence factor of each ingredient was calculated to reveal its influence on the changing rate of dielectric properties with increasing temperature. The bentonite pastes could be widely used as dummy load material to provide consistent dielectric properties same as the objective food products.

1. Introduction

Microwave thermal processing is a novel technology in food industry that has potential to produce high quality shelf stable food products (Guan et al., 2002; Guan et al., 2003; Ohlsson, 1992) due to its unique volumetric heating. A single model 915 MHz microwave assisted thermal sterilization (MATS) system was developed at Washington State University (WSU) with the ultimate goal aimed toward industrial implementation (Tang et al., 2006). In 2009, a microwave sterilization process based on the MATS system for mashed potato packaged in polymeric trays was accepted by the FDA (Food and Drug Administration). The success has accelerated the initial steps towards commercialization of this technology.
In microwave heating, the dielectric properties of food materials are the principal parameters which describe how materials interact with electromagnetic energy. Dielectric properties have two components: dielectric constant \((\varepsilon')\) and loss factor \((\varepsilon'')\) which describe the ability of a food material to store and dissipate microwave energy, respectively, in response to applied electric field. Food samples with consistent dielectric properties are essential in designing microwave heating systems and the following thermal processes. However, it is difficult to obtain real food or food materials that have certain consistent dielectric properties, because dielectric properties of food materials vary with ingredients (Ryyannen, 1995; Sakai, et al., 2005; Wang et al, 2008). Model food is a better alternative used as dummy load to provide stable homogenous load with consistent and predictable dielectric properties. In previous studies, agar gel (Padua, 1993a; 1993b), whey protein gel (Lau et al, 2003; Wang et al, 2009) and egg white gel (Zhang et al., 2013) have been used to create model foods used in microwave heating research.

Dummy loads, made of model food materials, play an important role in development of microwave heating systems and thermal processes. Calibration dummy loads are often used in the design of microwave heating systems for power delivery tests. In an industrial system, microwave power is delivered through waveguides from a generator to the microwave heating cavity. During the delivery, portion of the energy may be reflected back to the generator. The reflected power level is affected by the waveguide components, possible misalignment and dielectric properties of the loads (Meredith, 1998). To develop a reliable thermal process, steady microwave power delivery is the prerequisite. A standard food sample with consistent dielectric properties is desirable to verify proper installation and operation of a new. Once a good power delivery system is installed and calibrated, a process can then be developed for a specific product. To verify the heating pattern and process parameters such as microwave power setting and conveyor belt speed, numerous experimental tests need to be performed. Preforming these tests with full load of foods will lead to a large amount of waste especially for an industrial system with high production capacity. For a microwave heating system in production, reusable dummy loads with consistent dielectric properties may be used to verify that the process is stable and reliable.
The material used for reusable dummy loads should have the following features: low cost, thermal stability for reuse, homogeneous ingredients, easy to prepare and adjustable dielectric properties to simulate different foods. However, the ingredients of those dummy loads used in previous studies were food materials that have low thermal stability. The dielectric properties may change during thermal treatments. In addition, the procedures to prepare these model foods were time consuming because the materials need to be heated to a certain temperature. These model foods could not be reused.

In traditional thermal processing, bentonite water pastes have been widely used to simulate different kinds of food in retort systems (Hayakawa, 1974; Unklesbay et al., 1981; Peterson and Adams, 1983; Unklesbay et al. 1980). Compared with other models, bentonite water paste is inexpensive, easy to prepare and reusable because of its high thermal stability. Tong and Lentz (1993) measured the dielectric properties of 8% and 10% (bentonite powder concentration, wb) bentonite water pastes at 2450 MHz over a temperature range of -25 to 90 °C. It was reported that bentonite pastes could be good model foods because they have similar dielectric properties as most food materials. However, there was a lack of data at temperatures above 90 °C and at the allocated frequency of 915 MHz for industrial application. In this study, dielectric properties of bentonite pastes were measured over 300 to 3000 MHz and 20 to 120 °C. The response of dielectric properties to temperature at 915 and 2450 MHz were summarized.

Additives were used to adjust the dielectric properties of bentonite pastes to broaden its application range for different kinds of food. Salt is a good additive for adjusting loss factor of model food in previous studies (Sakai, et al., 2005; Wang et al, 2009). In this study, salt was used to modify the loss factor of bentonite paste. Sucrose is always used to reduce the dielectric constant of model food (Sakai et al., 2005; Padua, 1993a, 1993b). However, to obtain desired results high concentration, even up to 40%, of sucrose was always used. High concentrations of sucrose significantly reduce the moisture of model food which may change the response of dielectric constant to increasing temperature. In this study, vegetable oil which has a very low dielectric constant (Ryynanen, 1995) was used to decrease the dielectric constant of bentonite paste. Although the molecules of vegetable oil are hydrophobic, the large basal surface structure of bentonite can act as an emulsion stabilizer for oil and water (Clem and Doehler,
A comparison measurement was carried out to compare the effect of sucrose and oil on dielectric properties of bentonite paste.

The objective of this study was to measure the dielectric properties of bentonite pastes with different ingredients to provide a wide range of data for preparing reusable dummy loads used in the microwave heating processes. The dielectric properties of bentonite water pastes over a wide range of concentrations were measured. Suitable additives were used to adjust the range of these properties. Regression equations were developed to describe the dielectric properties of bentonite pastes affected by ingredients and temperature at 915 MHz and 2450 MHz.

2. Material and methods

2.1 Bentonite powder

Bentonite powder is mainly composed of two basic elements, alumina octahedral and silica tetrahedral. Both silica tetrahedral and alumina octahedral exist with a sheet formation (Figure 1). A bentonite unit consists of two silica tetrahedral sheets and between them is one alumina octahedral sheet. Bentonite is negative in charge balanced by cations such as sodium and calcium. The bentonite lattice Bentonite flakes are superposed loosely in such a way as to make bentonite similar to books of sheets or bundles of needles (Clem and Doehler, 1961). The length and width of these flakes are 10-100 times its thickness. With this structure water molecules can easily enter and separate bentonite flakes and give rise to a great basal surface increase as well as total volume expansion. Water molecules are adsorbed or bounded on the flat basal surface and aligned regularly. These molecules have properties more like bounded water other than free water. When the amount of water is relatively large and bentonite has adsorbed its maximum of water molecules, the additional water takes effects as lubricant.
The two major compositions of bentonite, silica and alumina are both diamagnetic material. Similar to water and fatty substance, this type of material has no magnetic energy absorbed (Kirschvink et al., 1992) when applied to an electromagnetic field.

### 2.2 Preparation of bentonite water paste

Bentonite powder (MP Biomedicals LLC, Solon, OH, USA) and distilled water were used to make pastes. Pastes with bentonite concentrations of 7.5, 15, 20 and 25% (wb) were prepared. Beyond this concentration range, the pastes were either too dilute as liquid solution or too dry to mix uniformly.

A paste with 20% bentonite concentration was used to study the effect of additives. The concentration of water was reduced with the addition of additives to keep the bentonite concentration constant. Four concentration levels of salt were prepared: 0.3, 0.6, 0.9, and 1.2% (wb). The salt was dissolved in distilled water first and then mixed with bentonite powder uniformly.

Bentonite pastes with three concentration levels of vegetable oil were prepared: 5, 10 and 15% (wb). Vegetable oil was first mixed with bentonite powder and then distilled water was added. Pre-experimental results showed that the ratio between oil and bentonite powder (wb/wb) should be less than
one. Otherwise the vegetable oil could not be totally absorbed by bentonite powder resulting in non-
uniform mixture.

To study the interaction effect between additives (i.e. salt and vegetable oil), 20% bentonite paste
with 15% vegetable oil and 1.2% salt content was prepared. Furthermore, 20% bentonite paste with 30%
sucrose and 1.2% salt was also prepared to compare the effect of oil and sucrose on dielectric properties.
Figure 2 shows the appearance of 20% bentonite pastes with different additives.

![Figure 2: 20% bentonite paste with different additives. A: no additive, B: 1.2% salt, C: 15% oil, D: 15% oil and 1.2% salt.](image)

2.3 Dielectric properties measurement

The dielectric properties of prepared bentonite pastes were measured using an open ended
coaxial-line probe connected to a network analyzer (HP 8752C, Hewlett Packard Corp., Santa Clara, CA,
USA) with a setting frequency range of 300 to 3000 MHZ. This frequency range covers the two industrial
application microwave frequencies of 915 MHz and 2450 MHz allocated by US Federal Communications
Commission (FCC). Temperature of the sample was controlled by a custom-built test cell with one oil
circulating heating system. The detailed information of this heating system can be found in Wang et al.
(2003). Each measurement was performed from 20 °C to 120 °C with an increment of 10 °C. At each
temperature level, three replicate measurements were made.

2.4 Data analysis
Dielectric properties of bentonite pastes at 915 MHz and 2450 MHz were plotted against temperatures. Regression equations based on the quadratic polynomial were developed to reveal the response of the dielectric properties to increasing temperatures and the concentrations of each ingredient such as bentonite, salt and vegetable oil. The regression equations were fitted through Matlab (Mathworks, MA, USA). The parameters in the fitted equations (i.e. temperature, bentonite, salt and vegetable oil) were normalized before regression to adjust their values within 0 and 1. After normalization, the coefficients of each parameter in the fitted equation represented the impact factor on the dielectric properties. The formula for normalizing a parameter X is:

\[ X_N = \frac{X - \text{min}(X)}{\text{max}(X) - \text{min}(X)} \]  

(1)

\( X_N \) is the normalized value of the parameter \( X \), \( \text{max}(X) \) and \( \text{min}(X) \) are the maximum and minimum values of the parameter. As long as the upper and lower limits of a parameter were fixed, the original value and normalized value can be switched through Eq. (1).

3. Results and discussion

3.1 Effect of frequency

The dielectric properties of 20% bentonite pastes changing with frequency at three temperatures are shown in Figure 3. Both the dielectric constant and loss factor decreased with frequency. This agrees with the previous observations of food or model food materials such as mashed potatoes (Guan, et al., 2004), Salmon fillet (Wang, et al., 2008) and whey protein gel (Wang, et al., 2009). It is interesting that the dielectric constant increased with increasing temperature below 480 MHz. Above this frequency, dielectric constant decreased with increasing temperature. A similar phenomenon was observed for mashed potatoes (Guan, et al., 2004) and whey protein gel (Nelson and Bartley, 2002).
Figure 3: Change of dielectric properties of 20% bentonite paste with frequency at three temperatures (--- 20 °C, —— 70 °C, ▲ 120 °C). A: dielectric constant, B: loss factor.

3.2 Effect of bentonite concentration

The dielectric properties of bentonite pastes changing with bentonite powder concentration and temperature at frequencies of 915 and 2450 MHz are shown in Figure 4. The dielectric constant of bentonite pastes decreased with increasing bentonite concentration. This decrease was due to the decrease of water content in the paste. Similar to food materials, higher moisture content results in higher dielectric constant. However, the dielectric loss factor increased with increasing bentonite concentration. It was reasonable that higher concentration of bentonite brought higher ion (cation) concentration and increased the loss factor.
At 2450 MHz, although the general trend that loss factor is increases with increasing temperature, there was a broad valley around the temperature 40 to 70 °C (Figure 4D). This was more obvious for pastes with lower bentonite concentrations (7.5%). Similar curves were reported for 8% and 10% bentonite pastes by Tong (1993). This type of valley curve may be caused by the two different loss mechanisms of loss factor: dipole loss ($\varepsilon_d$) from dipole rotation and ionic loss ($\varepsilon_\sigma$) from ionic conductivity. It can be mathematically expressed as (Ryynanen, 1995):

$$\varepsilon'' = \varepsilon_d + \varepsilon_\sigma$$  \hspace{1cm} (2)
with
\[ \varepsilon^* = \frac{\varepsilon}{2\pi f \varepsilon_0} \]
where \( \varepsilon \) is the electric conductivity of the material; \( \varepsilon_0 \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F/m})\) and \( f \) is the frequency of the electromagnetic waves.

The two mechanisms resulted in two different responses to temperature changes (Roebuck and Goldblith, 1972). The loss contributed by dipole rotation of free water decreases with the increase of temperature while ionic loss caused by ionic conductivity increases with increasing temperatures. If one of the two loss mechanisms dominated the contribution, the overall loss factor will have similar trend as the dominant loss in response to increasing temperature. However, if the two mechanisms had parallel contribution, the loss factor the graph may show a valley curve as observed in Figure 4D. Such type of curve could also be found for many food materials containing salt (To et al., 1974).

The dielectric properties of bentonite pastes with different contents of bentonite powder have similar curves to that of food varying with temperatures (To et al., 1974; Ryyannen, 1995; Sakai et al., 2005). However, the trend of dielectric properties changing with bentonite concentration is fixed. A higher bentonite concentration resulted in a lower dielectric constant and a higher loss factor. Pastes with higher dielectric constants and higher loss factors or low dielectric constants and low loss factors could not be obtained by adjusting the bentonite concentrations. Additives are required to obtain a paste with such dielectric properties.

### 3.3 Effect of salt

Figure 5 summarizes the effects of salt on the dielectric properties of 20% bentonite paste changing with temperature. At 915 MHz and 2450 MHz, the dielectric properties had similar responses to increasing salt concentration. The dielectric constant increased slightly with the increasing salt contents. A possible explanation was that salt increased the concentration of cations (Na\(^+\)) in the paste and reduced the binding effect of bentonite to water molecules (Grim, 1978). The reduction in bound water and
increase in free water resulted in a slightly increase in the dielectric constant. The addition of salt sharply increased the dielectric loss factor at both 915 and 2450 MHz.

Figure 5: Dielectric properties of 20% bentonite paste changing with salt contents (— 0, —△— 0.3%, —□— 0.6%, —○— 0.9%, —△— 1.2%) and temperatures. A: dielectric constant at 915 MHz, B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz

It is necessary to point out that different from Figure 4D, in Figure 5D the dielectric loss factor increased with increasing temperatures without fluctuation. This result revealed that at a higher salt content level, ionic loss was the dominant loss mechanism. The increase of ionic loss response to increasing temperature balanced the decrease of dipole loss at the low temperature range. This could also
be verified by the relationship between $\varepsilon^\ast_\sigma$ and the frequency. By taking a logarithm of both side of Eq. (3), one obtains:

$$\log\varepsilon^\ast_\sigma = -\log f + \log \frac{\sigma}{2\pi\varepsilon_0}$$

(4)

From Eq. (4) there is a linear relationship between dielectric loss factor and frequency in a log-log graph if the ionic loss is the dominant contributor to the overall loss factor. The log-log plots of frequency and loss factor of bentonite pastes with different salt contents are shown in Figure 6. At 120 °C, dielectric loss factor decreased linearly with increasing frequency (Figure 6A). It revealed that $\varepsilon^\ast_\sigma$ was the major contributor to the overall loss factor at high temperature. It was due to that the $\varepsilon^\ast_\sigma$ increased and $\varepsilon^\ast_d$ decreased with increasing temperature within the measuring frequency range, i.e. 0.3-3 GHZ. However, at 20 °C (Figure 6B) the linearity was not good at high frequency range (i.e. >2 GHz). It was due to the different repossess of $\varepsilon^\ast_d$ and $\varepsilon^\ast_\sigma$ to increasing frequency. Within the frequency range of 0.3 to 3 GHZ, $\varepsilon^\ast_\sigma$ decreased and $\varepsilon^\ast_d$ increased with increasing frequency. At lower frequency range (< 2 GHz), $\varepsilon^\ast_\sigma$ dominated the composition of the overall loss factor which resulted in a linear curve. However, the linearity was weakened by the increasing $\varepsilon^\ast_d$ at high frequency range (> 2 GHz), which even caused to a slight increase of the overall loss factor. The addition of salt increased the overall loss factor by increasing $\varepsilon^\ast_\sigma$. A better linearity was observed for higher salt contents at 20 °C. The slopes of the linear curves in Figure 6A were calculated to reveal the influence of salt content on $\varepsilon^\ast_\sigma$. From Eq. (4), the slope should be -1 if there was no $\varepsilon^\ast_d$ included. For bentonite pastes with salt content of 0, 0.3, 0.6, 0.9 and 1.2%, the slopes of related curves in Figure 6B were -1.284, -1.156, -1.117, -1.079 and -1.051, respectively. More salt content brought a slope that closer to -1. These slope values indicated that $\varepsilon^\ast_d$ increased with increasing salt contents.
Figure 6: Loss factors of 20% bentonite paste with different salt contents (— 0, —— 0.3%, ▲ 0.6%, □ 0.9%, ▼ 1.2%) changing with frequency in a log-log plot at two temperatures. A: 120 °C, B: 20 °C, the dash lines represent the ideal curve without the contribution of $\varepsilon_d^*$. 

3.4 Effect of vegetable oil

Figure 7 summarizes the effects of vegetable oil on dielectric properties of 20% bentonite paste changing with temperature. At 915 and 2450 MHz, the dielectric constant was significantly decreased by the increasing vegetable oil. This decrease was due to the great reduction in the water content and the binding effect of bentonite to water molecules. The loss factor decreased slightly with an increasing concentration of oil. A possible explanation is that low water content and addition of oil reduced the migration rate of ions.
3.5 Interaction effect between salt and vegetable oil

The addition of salt primarily affected the loss factor and the addition of oil primarily affected the dielectric constant. As a result, the desired dielectric properties could be obtained by adjusting the concentration of the two additives. However, there may be some interaction effect between them. The dielectric properties of 20% bentonite paste with high concentrations of both oil (15%) and salt (1.2%) were compared with the samples without additives and with only one additive (1.2% salt or 15% vegetable oil). These dielectric properties results at 915 MHz and 2450 MHz changing with temperature...
are shown in Figure 8. Compared with samples without additive, the bentonite paste with 1.2% salt and 15% oil showed an obvious decrease in the dielectric constant and a great increase in the loss factor. However, compared with samples containing only one additive (15% oil or 1.2% salt), the addition of salt increased the dielectric constant slightly and the addition of vegetable oil reduced the loss factor slightly. With vegetable oil present, relatively higher salt concentration is required to obtain the same increase level in loss factor. Moreover, more vegetable oil content has to be applied to offset the influence of salt on the dielectric constant.

Figure 8: Dielectric properties of 20% bentonite pastes with different additives (— no additive, ▲ 1.2% salt — 15% vegetable oil, ▼ 1.2% salt & 15% oil, ○ 1.2% salt & 30% sucrose) changing with temperature. A: dielectric constant at 915 MHz, B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz
The dielectric properties of 20% bentonite paste with 30% sucrose and 1.2% salt are also shown in Figure 8. At 915 MHz, the bentonite paste with 15% vegetable oil and 1.2% salt had a lower dielectric constant (Figure 8A) and a much higher loss factor than the bentonite paste with 30% sucrose and 1.2% salt (Fig, 8B). Similar results were observed at 2450 MHz (Figure 8C and D). This result proved that vegetable oil was more efficient in reducing the dielectric constant of bentonite paste with less influence on dielectric loss factor. In addition, the dielectric constant of the paste with 30% sucrose increased slightly at lower temperature range and then decreased with increasing temperatures. That may be caused by the binding effect of high concentration of sucrose to water molecules. This type of trend was also reported for 1% agar gel with 30% sucrose (Sakai et al., 2005).

3.6 Regression equations

To relate the dielectric properties of bentonite pastes with temperature, regression equations of dielectric properties as functions of ingredients and temperatures were developed (Table 1). The value of each parameter (i.e. temperature, bentonite powder, salt and vegetable oil) was normalized within 0 and 1 using Eq. (1) before regression equations were fitted. The influence of each parameter on dielectric properties was reflected by its coefficient in the regression equation. The coefficient of each parameter had a significance of P< 0.01. The non-significant parameter was not included in the equation. The adjusted coefficient of determination ($r^2_{adj}$) of each regression equation was greater than 0.95, which verified that the quadratic polynomial was good enough to fit to the profiles of dielectric properties.
Table 1. Regression equations for dielectric properties of bentonite pastes varying with temperature and different ingredients

<table>
<thead>
<tr>
<th>Parameters: temperature (T) and bentonite concentration (B)</th>
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<tbody>
<tr>
<td>( \epsilon' = 73.96 - 18.25T - 17.15B + 13.16T \times B + 1.312T^2 )</td>
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<tr>
<td>( + 3.178B^2 )</td>
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<tr>
<td>( r^2_{adj} = 0.9984 )</td>
</tr>
<tr>
<td>915 MHz</td>
</tr>
<tr>
<td>( \epsilon^* = 9.020 + 2.982T + 9.743B + 20.66T \times B + 8.222T^2 )</td>
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<tr>
<td>( - 2.487B^2 )</td>
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<td>( r^2_{adj} = 0.9987 )</td>
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<tr>
<td>( \epsilon' = 72.92 - 18.75T - 17.01B + 9.060T \times B + 2.958B^2 )</td>
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<tr>
<td>( r^2_{adj} = 0.9926 )</td>
</tr>
<tr>
<td>2450 MHz</td>
</tr>
<tr>
<td>( \epsilon^* = 10.53 - 9.161T + 3.292B + 10.93T \times B + 8.470T^2 )</td>
</tr>
<tr>
<td>( - 1.911B^2 )</td>
</tr>
<tr>
<td>( r^2_{adj} = 0.9893 )</td>
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<table>
<thead>
<tr>
<th>Parameters: temperature (T) and salt concentration (S)</th>
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<tr>
<td>( \epsilon' = 62.44 - 7.218T + 4.657S )</td>
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<tr>
<td>( r^2_{adj} = 0.9530 )</td>
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<tr>
<td>915 MHz</td>
</tr>
<tr>
<td>( \epsilon^* = 16.63 + 9.082T + 24.51S + 73.17T \times S + 15.48T^2 )</td>
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<tr>
<td>( + 6.294S^2 )</td>
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<td>( r^2_{adj} = 0.9986 )</td>
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<tr>
<td>( \epsilon' = 61.18 - 9.205T + 3.068T \times S - 2.732T^2 + 1.924S^2 )</td>
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<td>( r^2_{adj} = 0.9795 )</td>
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<td>2450 MHz</td>
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<tr>
<td>( \epsilon^* = 12.23 - 3.618T + 6.215S + 26.00T \times S + 10.51T^2 )</td>
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<tr>
<td>( + 5.512S^2 )</td>
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<td>( r^2_{adj} = 0.9981 )</td>
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<th>Parameters: temperature (T) and vegetable oil concentration (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon' = 63.07 - 7.643T - 21.13V + 3.618T \times V + 4.624V^2 )</td>
</tr>
<tr>
<td>( r^2_{adj} = 0.9965 )</td>
</tr>
<tr>
<td>915 MHz</td>
</tr>
<tr>
<td>( \epsilon^* = 13.75 + 20.55T - 4.472T \times V + 6.421T^2 )</td>
</tr>
<tr>
<td>( r^2_{adj} = 0.9959 )</td>
</tr>
<tr>
<td>( \epsilon' = 61.39 - 11.42T - 20.27V + 3.560T \times V + 4.099V^2 )</td>
</tr>
<tr>
<td>( r^2_{adj} = 0.9942 )</td>
</tr>
<tr>
<td>2450 MHz</td>
</tr>
<tr>
<td>( \epsilon^* = 11.53 - 5.395V + 7.413T^2 + 3.151V^2 )</td>
</tr>
<tr>
<td>( r^2_{adj} = 0.9933 )</td>
</tr>
</tbody>
</table>

\(^a\)All the parameters are normalized values within 0 and 1
Based on regression equations, one can find more details of dielectric properties as affected by ingredients and temperatures. When taking the derivation of a regression equation with respect to temperature, the changing rate of the response value (dielectric constant or loss factor) against temperature was revealed. For example, in Table 1 the regression equation of dielectric constant as a function of bentonite concentration and temperature at 915 MHz is:

\[
e' = 73.96 - 18.25 T - 17.15 B + 13.16 B \times T + 1.312T^2 + 3.178B^2
\]  \hspace{1cm} (5)

Taking the derivative with respect to temperature gives:

\[
\frac{d\epsilon'}{dt} = -18.25 + 13.16 B + 2.624 T
\]  \hspace{1cm} (6)

Equation (6) demonstrates that the changing rate (slope) of the dielectric constant in response to temperature was affected by bentonite concentration with a coefficient of 13.16. This coefficient implies the influence of the parameter (i.e. bentonite concentration) on the slope. The influence factor of the parameter was defined as following:

\[
\text{Influence factor} = \frac{13.16}{-18.25 + 2.624 T}
\]  \hspace{1cm} (7)

The influence factor of a variable was used to describe its maximum ability to adjust the changing rate of the response value against temperature. The influence factor of different ingredients for dielectric constant and loss factor are summarized in Table 2. It was observed that the slope value of dielectric constant varying with temperature was more sensitive to bentonite concentration than vegetable oil. However, the slope of loss factor was affected more by salt instead than bentonite. The salt had a significant influence on the slope of loss factor and very limited influence on the slope of dielectric constant. On the contrary, vegetable oil had a big influence on the slope of dielectric constant and a small influence on the loss factor.

<table>
<thead>
<tr>
<th></th>
<th>915 MHz ($\epsilon'$)</th>
<th>915 MHz ($\epsilon''$)</th>
<th>2450MHz ($\epsilon'$)</th>
<th>2450MHz ($\epsilon''$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T=0$</td>
<td>$T=1$</td>
<td>$T=0$</td>
<td>$T=1$</td>
<td>$T=0$</td>
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<td>$T=1$</td>
<td>$T=0$</td>
<td>$T=1$</td>
<td>$T=0$</td>
<td>$T=1$</td>
</tr>
</tbody>
</table>

Table 2. Influence factor of ingredients on the slope of dielectric properties against temperature
To simulate a food material with given dielectric properties, the changing rate of dielectric constant against temperature should be calculated first to determine a suitable bentonite concentration. Then vegetable oil could be used to adjust the value of dielectric constant. Once the dielectric constant over the required temperature range was matched, loss factor could be modified by adjusting salt concentration.

4. Conclusion

The Dielectric properties of bentonite pastes decreased with frequency within the range 300 to 3000 MHz which was similar to those of food materials. At 915 MHz, dielectric constant decreased and loss factor increased, respectively, with increasing temperature and bentonite concentration. At 2450 MHz, similar trend was observed. However, at low bentonite concentration, loss factor decreased first with increasing temperature and then increased. The decrease of overall loss factor at low temperature range (<50 ºC) was due to the decrease of dipole loss. However, the ionic loss increased with increasing temperature. At high temperature range (>50 ºC), the ionic loss became the major contributor of the overall loss factor and an increasing trend was observed.

The addition of salt could greatly increase the dielectric loss factor of bentonite pastes by increasing the ionic loss. The dielectric constant was not affected much by the addition of salt, only slightly increase. The dielectric constant of bentonite pastes were greatly reduced by the addition of vegetable oil. However, vegetable oil had slightly influence on loss factor. Compared with sucrose,
vegetable oil could decrease the dielectric constant to the same level with only half of the sucrose concentration and less effect on the loss factor. Results revealed that salt and vegetable oil were good additives to adjust the loss factor and dielectric constant, respectively. However, due to the interaction effects between the salt and vegetable oil, the effects of salt on the loss factor and oil on the dielectric constant were weakened a little.

Good fitted regression equations were developed to reveal the influence of ingredients and temperatures on dielectric properties of bentonite pastes. Derived from these equations, bentonite had higher impact factor than vegetable oil on the changing rate of dielectric constant against to temperature. However, for loss factor changing with temperature, salt had higher impact factor than bentonite. By selecting suitable additives, bentonite pastes could be used as dummy load for different foods by simulating their dielectric properties changing with temperature.
5. References


CHAPTER SEVEN

CONCLUSIONS

Microwave thermal processing brings significant improvement in reducing heating time and retaining food quality over conventional heating. A 915 MHz single model microwave assisted thermal sterilization (MATS) system was developed at Washington State University to explore the commercialization potential of this technology. Several MATS processes for different foods in either rigid trays or flexible pouches were developed by the WSU research team and accepted by the United States Food and Drug Administration (FDA) or the United States Department of Agriculture Food Safety and Inspection Service (USDA, FSIS). The success of MATS system provides a blueprint for commercialization of microwave thermal processing. However, many potential problems might be encountered during the scaling up of the MATS technology. Compared with pilot plant MTAS system, a much higher microwave power and faster moving speed of conveyor belt will be applied in industrial microwave heating system to improve the production. The major challenge in microwave thermal processing is the non-uniform heating pattern caused by the uneven electric field destitution. Hot spots and cold spots occur at high and low electric field intensity locations, respectively. Temperature difference between hot and cold spot is intensified by higher microwave power. Thermal runaway might occur at hot spot which degrade the food quality at adjacent domain and can result in high inner pressure which in worst case might lead to breakage of the food package. A uniform heating pattern must be designed for industrial scale microwave heating system to satisfy the high microwave power. When the heating pattern is fixed, temperature sensor is used to measure the time-temperature profile at the cold spot location. The thermal processing will be established based on the time-temperature profile to control the most heat resistant food pathogens. Another challenge in scaling up the MATS system is the temperature measurement for the moving sample within the environment of high electromagnetic field intensity, high temperature and pressure. Although the fragile and expensive fiber-optical sensor is immune to electromagnetic field, it is not suitable for moving sample within high temperature and
pressure environment. A suitable temperature sensor needs to be selected in such environment. At last, calibration dummy load with consistent dielectric properties is required in the power delivery test and stability test of a microwave heating system. In this study, these three topics relevant industrial scale microwave heating system were investigated.

The electric field distribution and components in each direction within the MATS system were analyzed through computer simulation method. With a TE10 source of microwave, the dominant electric field component was consistent when microwaves propagated from the waveguide, horn applicator to the microwave heating cavity. The heating pattern within MATS system was determined by the distribution of the dominant electric field component. For a TE10 mode microwave propagating in z direction, the electric field component in y direction was the only non-zero components. In the horn applicator and microwave heating cavity, the electric field distribution in y direction changed with the dimension of these system components. However, the electric field component in y direction was still the dominant component. There was non-uniform electric field distribution in y direction within the microwave heating cavity. This non-uniform electric field distribution was caused by the dimension variations from horn applicator, Ultem window to the microwave heating cavity, other than the standing waves in y direction. Hot and cold spot areas were brought by the uneven electric field distribution in y direction. With a fixed dimension of the microwave heating cavity, different heating patterns were obtained by changing the dimension of the horn applicator and the Ultem window. However, the heating pattern of food was more sensitive to the dimension of the Ultem window because it determined the aperture of the microwave heating cavity. There was no regular relationship between heating pattern and dimension of the Ultem window. But the significant changes in these heating patterns provided a data base for designing uniform heating patterns. A cylindrical metal bar placed within the horn applicator could be used to adjust the electric field distribution in y direction. Stronger electric field was present near the surface of the metal bar which resulted in converged electric field intensity around the metal bar. A hot spot area occurred when food was placed below the metal bar. Hence, metal bar could be used to increase electric field intensity at cold spot position to improve heating uniformity. Besides metal bar, a rectangular Ultem bar
could bring similar influence on electric field distribution and heating pattern. This type of accessories was a good technique to adjust energy distribution in y direction. Besides, heating uniformity of food could also be improved by designing the dimension of food to match the electric field distribution within the microwave heating cavity. These simulation results could be used to assist the design of industrial microwave heating system to obtain acceptable uniform heating pattern at different power settings.

A mobile metallic temperature sensor was used in temperature measurement within MATS system after calibration test through fiber-optic sensors. The mobile metallic sensor could be packaged within food to record the time-temperature profile at cold spot. At the end of the process, it was taken out and data were exported to computer. The interaction between the metallic temperature sensor and electromagnetic field were studied through computer simulation method. The mobile metallic temperature sensor showed no influence on the general heating pattern of a packaged model food. However, there was a temperature increase at the edge vicinity of the sensor which brought a local modification of heat pattern when the edge was perpendicular to the electric field component. This distorted heating pattern was noticeable at the domain close to a hot spot area and the region adjacent to the base part of the sensor. The local temperature increase was attributed to the electric field enhancement near the metallic surface. The level of the electric field enhancement and local overheating were exacerbated by higher electric field intensity. If a strong electric field enhancement occurred at the probe end of the metallic temperature sensor, a higher temperature was recorded. To remove the influence of field enhancement on the temperature profile, the metallic temperature sensor should be placed perpendicular to the electric field component. These results were validated through experimental tests both in heating pattern and temperature profiles. Computer simulation models with finer meshes at the probe tip domain were developed based on the validated model to evaluate the influences of the microwave power intensity, probe tip geometry and diameter on the accuracy of the sensors. Computer simulation results revealed that a higher temperature zone was created at the probe tip of the metallic temperature which could cause erroneous temperature readings. These temperature alterations were caused by electric field distortion and enhancement at the probe tip. Although the temperature alterations were reduced by orienting the sensor
probe perpendicular to the dominant electric field component, they were not totally removed. At a low microwave power setting of 6 kW for a 915 MHz single mode cavity, there was no significant difference among the temperature alterations of the probes with different tip geometries; however, the temperature alterations were amplified by higher microwave power settings. Among the three probe tip geometries, the spherical tip with the smoothest surface had the lowest sensitivity to microwave power settings. Whereas flat probe tip, caused the highest temperature alteration. The temperature alteration could be greatly reduced by decreasing the probe diameter from 2 mm to 1 mm. This suggested that the spherical probe tip with thinner probe diameter should improve the accuracy of metallic temperature sensors applied in high microwave power environment. For a multi-cavity microwave heating system, a decreasing power distribution of the heating cavities along moving direction is recommended. This arrangement could reduce the propagating errors from the time-temperature profiles to the estimation of desired microbial inactivation level in designing microwave thermal processes.

In traditional thermal processing, bentonite water pastes have been widely used for simulating all kinds of food in retort system due to its advantages of low cost and high thermal stability. It is a suitable material for reusable dummy loads in microwave heating system for calibration tests and processing schedule development. However, dummy load material should have similar dielectric properties as the objective food products. The bentonite pastes with different ingredients were measured over 300 to 3000 MHz and 20 to 120 ºC. Within the frequency range, the dielectric properties of bentonite pastes decreased with increasing frequencies which were similar to food materials. At 915 MHz, dielectric constant decreased and loss factor increased with increasing temperature and bentonite concentration, respectively. At 2450 MHz, similar trend was observed. However, at low bentonite concentration, loss factor decreased first with increasing temperature and then increased. The decrease of loss factor at low temperature range (<50 ºC) was due to the decrease in dipole loss with increasing. Besides dipole loss, the other contributor of loss factor ionic loss increased with increasing temperature. At high temperature range (>50 ºC), the ionic loss became the major contributor of loss factor and an increasing trend was observed. The addition of salt could greatly increase the dielectric loss factor of bentonite pastes by increasing the ionic loss. The
dielectric constant was not affected much by the addition of salt, a slight increase was observed. The dielectric constant of bentonite pastes were greatly reduced by the addition of vegetable oil. However, vegetable oil had slight influence on loss factor. Compared with sucrose, vegetable oil could decrease the dielectric constant to the same level with only half of the sucrose concentration and less effect on the loss factor. Results revealed that salt and oil were good additives to adjust the loss factor and dielectric constant, respectively. However, due to the interaction effects between the salt and vegetable oil, the effects of salt on the loss factor and oil on the dielectric constant were weakened a little. Good fitted regression equations were developed to reveal the influence of ingredients and temperatures on dielectric properties of bentonite pastes. Derived from these equations, bentonite had higher impact factor than vegetable oil on the changing rate of dielectric constant against to temperature. However, for loss factor changing with temperature, salt had higher impact factor than bentonite. By selecting suitable additives, bentonite pastes could be used as dummy load for different foods by simulating their dielectric properties and the changing rate with increasing temperature.

In this study, computer simulation models were used to study the electric field distribution and heating pattern design of the MATS system. In future work, the numerical results will be verified through experimental test. Besides heating pattern design, numerous parameters were included within the process schedule of a microwave thermal process, such as moving speed of food, microwave power settings and water temperature. The validated computer simulation model could be used to optimize these parameters in future studies.