Coupled Electromagnetic and Heat Transfer Modeling of Microwave Heating using Finite Difference Time Domain Method

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Introduction

- Non-uniform heating is an issue in microwave heating, especially in frozen foods
- Many frozen microwaveable foods are not-ready-to-eat, meaning that they may have pathogens
- If not properly cooked in all locations, it can result in foodborne outbreaks
- Modeling is a tool for understanding non-uniform heating to improve food safety
Outbreak History

Multistate Outbreak of *Salmonella* Infections Associated with Frozen Pot Pies --- United States, 2007

On June 6, 2007, a cluster of four human *Salmonella* serotype I 4,5,12:i:- infections sharing a pulsed-field gel electrophoresis (PFGE) pattern was identified by the Pennsylvania Department of Health and reported to PulseNet. Initial investigations conducted during June–September 2007 by state and local health departments in collaboration with
Overall Picture

- **Heat transfer model**
  - Getting time – temperature profile

- **Microbial inactivation model**
  - Finding reduction of microorganism

- **Risk assessment model**
  - Identifying variables of interest

- **Developing education material**
  - Creating awareness
Overview of Modeling

- Modeling of microwave heating has been in action for years
- Modeling has been validated most of the time only for subjective comparisons

A computational model for calculating temperature distributions in microwave food applications. Kai Knoerzer et al., 2007.
Objectives

I. Develop a microwave heating (coupled electromagnetic and heat transfer) model for homogeneous food product (Gellan gel)

II. Validating the model with experimental work qualitatively and quantitatively
I. Model development
Numerical Solver

- Quickwave - 3D software
- Solving electromagnetic and temperature field
- Numerical method - FDTD
- Two interfaces – Q-Editor, Q-Simulator
Advantages of FDTD method

- Conformal FDTD algorithm
- Variables solved for space and time
- Computation memory required less

Stair-case mesh

Conformal mesh
Protocol for Model Development

1. Create geometry of microwave oven
   (Cavity, Load, Port, Turntable)

2. Provide electromagnetic variables
   (Frequency, Amplitude, Waveform)

3. Assign thermo-physical properties
   (Specific heat, Thermal conductivity, Density)

4. Assign dielectric properties
   (Dielectric constant, Dielectric loss factor)
Provide meshing condition
(Load-1mm, Cavity-5mm)

Assign boundary condition
(Adiabatic, Convection)

Select simulation parameters
(Heating time, Rotation)

Solving coupled equation
(Maxwell’s EM equations, Heat conduction)
3-D Geometry

- Power source
- Metal bump (ϕ-40 × 16 mm)
- Waveguide (290 × 80 × 40 mm)
- Oven cavity (420 × 395 × 253 mm)
- Turntable
- Load (ϕ-80 × 50 mm)
- Crevice
Model Inputs

- Frequency - Energy cycles per s
- Electric field strength - Signal power magnitude
- Waveform - Sinusoidal or Pulse of spectrum
- Wave mode - TE10 or TEM
Electric Field Strength

- Indirectly measured using power absorbed in the load
- Power measured using IEC 705 standard
- Power absorbed in load – 625 W

\[ P \propto E^2 \]

<table>
<thead>
<tr>
<th>Time avg. power</th>
<th>Time max. power</th>
<th>Electric field strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{avg} = 625 \text{ W} )</td>
<td>( P_{max} = 2 \times P_{avg} )</td>
<td>( E = \sqrt{P_{max}} )</td>
</tr>
</tbody>
</table>

*Reference with Quickwave 3D software manual
Assigned Inputs

- Frequency - 2.45 GHz
- Amplitude (EFS) - 35.35 V/m
- Waveform - Sinusoidal
- Wave mode - TE10 mode
Load Properties

- Temperature dependent dielectric properties
  - Co-axial probe method
- Thermal and Physical properties considered as isotropic (identical in all three directions)
  - KD2 meter, DSC

<table>
<thead>
<tr>
<th>Temperature (degC)</th>
<th>Enthalpy (J/cm³)</th>
<th>EPA</th>
<th>SIGa (S/m)</th>
<th>SpecHeat (j/g°C)</th>
<th>Density (g/cc)</th>
<th>Ka (W/cm°C)</th>
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<td>1.01</td>
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</tr>
</tbody>
</table>
Domain Meshing

A

5 mm

B

1 mm
Boundary Conditions

- Cavity & gel interface
  - Adiabatic

- Gel & glass shelf interface
  - Continuous
Solving Coupled Equation

Power dissipation

Heat equation

Maxwell's equation

Temperature field

EM properties

\[ \oint E \cdot dA = \frac{q_{enc}}{\varepsilon_0} \]
\[ \oint B \cdot dA = 0 \]
\[ \oint E \cdot ds = -\frac{d\Phi_B}{dt} \]
\[ \oint B \cdot ds = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc} \]

\[ \rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \]
II. Validation of model
Model Validation Method

- 700 W rated power microwave oven
- Product not rotated
- Gellan gel product heated for 30 s
- Temperature in product recorded
  - Infrared imaging camera
  - Fiber optic sensors
Gellan gel

- Dissolve 1% gel power in distilled water
- Raise the temperature to 90°C in 15 min
- Add 0.17% CaCl$_2$ salt
Sensors Location

Gellan gel

Dimensions:
- 80 mm in diameter
- 50 mm in height

Locations:
1. 10 mm
2. 20 mm
3. 25 mm
4. 45 mm
Temperature Measurement
Optimization of Modeling

- Electromagnetic steady state iterations

![Temperature vs. Electromagnetic steady state periods graph](image)
Qualitative Validation

<table>
<thead>
<tr>
<th>Collected image position in load</th>
<th>Experimental IR image</th>
<th>Simulated image</th>
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</thead>
<tbody>
<tr>
<td>Top plane (0 mm)</td>
<td><img src="image1" alt="Experimental IR image" /></td>
<td><img src="image2" alt="Simulated image" /></td>
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<tr>
<td>Middle plane (25 mm)</td>
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<td><img src="image4" alt="Simulated image" /></td>
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<tr>
<td>Bottom plane (50 mm)</td>
<td><img src="image5" alt="Experimental IR image" /></td>
<td><img src="image6" alt="Simulated image" /></td>
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</table>

<table>
<thead>
<tr>
<th>Max Temperature °C</th>
<th>Experiment</th>
<th>Simulation</th>
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<tbody>
<tr>
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<td>71.2</td>
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<td></td>
<td>45.6</td>
<td>34.6</td>
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<tr>
<td></td>
<td>54.2</td>
<td>58.2</td>
</tr>
</tbody>
</table>
Quantitative Validation

Sensor 1  RMSE 9.53 °C

Sensor 2  RMSE 0.67 °C
Sensor 1 Temperature Correction

Sensor 1 Corrected RMSE 1.38 °C
Conclusion

- Microwave heating model for homogeneous food product developed

- Heat transfer model validated quantitatively and qualitatively

- Model needs to be fine tuned to match the heating pattern orientation and heating rate
Modeling Issues

- Dynamic nature of magnetron may not be exactly applied in modeling

- Average frequency of 2.45 GHz was used in the model; however, the frequency may vary with time.
Future Work

- Validation of the model will be extended to pixel by pixel of simulation temperature with experiment temperature once frequency and pattern matching optimized.

- Modeling of microwave heating will be performed for not-ready-to-eat foods.
Acknowledgements

- USDA – NIFSI Grant
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  - Dr. Michal Soltysiak
  - Dr. Andzrej Wieckowski
Questions & Comments