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Modeling of Susceptor Assisted Microwave Heating in Domestic Ovens

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Abstract: Susceptors are used in microwavable food packages to facilitate preferential heating. Modeling of susceptor assisted microwave heating in domestic ovens was performed using radio frequency and heat transfer modules of COMSOL Multiphysics 4.2. Two different approaches (domain discretization and transient boundary condition) were studied for taking into the account of discretizing thin susceptor film in the computational domain. Simulated temperature profiles were compared with microwave heating of 1% gellan gel cylinder placed with a susceptor film on top. There was good agreement between the experimental and simulated spatial temperature profiles. Error value of a point transient temperature profile was 1.51°C. The transient boundary condition approach was found to be better considering the computational time of 1 h compared to 5 h in domain discretization method. We also studied a method to model shielding effect of microwavable package and discussed its heating pattern.

Keywords: Susceptor, Heat transfer model, COMSOL 4.2, Model food, Validation**.**

1. Introduction

Susceptors, very thin metallic microwave absorbing films, are used in microwaveable food packaging. They tend to heat up very rapidly during microwave heating and this effect is used to overcome two major issues faced in microwave ovens; 1) lack of browning and 2) lack of crispiness. While susceptors are being widely used, there is still a lack of scientific knowledge about their interaction with microwaves. Modeling of their interaction with microwaves is an opportunity to bridge the knowledge gap and optimize their role in microwaveable food packaging.

A few researchers have attempted to numerically model susceptor assisted microwave heating (Celuch et al. 2008; Perry and Lentz, 2009; Soltysiak et al. 2008). Celuch et al. (2008) and Soltysiak et al. (2008) used FDTD based numerical software to solve the susceptor assisted microwave heating in water placed in a simple cavity. For susceptor material, they created 1-mm thick layer of surrogate materials whose properties were adjusted to mimic the susceptor film. The authors studied the effect of conductance on power absorption in water, but they did not validate their approach by experimental methods. Perry and Lentz (2009) discussed about science of susceptor heating in microwave oven, but did not develop a model. Our research group is interested to take leap forward and develop a computer model for simulating susceptor assisted microwave heating of foods in domestic ovens.

The main objective of this study was to develop a computer model to simulate microwave interaction with food and active package. The model was further experimentally validated with a model food. The second objective was to develop a model for shielding effect in microwave package and validate with a model food.

2. Materials and Methods

2.1. Governing Equations

Electromagnetic field (**E**) at any point in the computational domain is governed by set of Maxwell's equations. The combined wave form of Maxwell's equation is expressed as (COMSOL, 2011):

$$\nabla\times\mu_r^{-1}(\nabla\times\mathbf{E})-\left(\frac{2\pi f}{c}\right)^2\left(\epsilon_r-i\,\epsilon''\right)\mathbf{E}=0 \quad (1)$$

where f is frequency (2.45 GHz), c is the speed of light (3×10^8 m/s), and ϵ_r and μ_r are relative dielectric constant, and permeability of the medium respectively.

Electromagnetic power dissipation density (Q) is the function of frequency and loss factor (ϵ'') and electric filed strength.

$$Q = 2\pi f \epsilon_o \epsilon'' \mathbf{E}^2 \quad (2)$$

Dissipated power is diffused in the material and governed by Fourier's heat transfer equation.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + Q \quad (3)$$

where ρ is the density (kg/m^3), C_p is the specific heat capacity at constant pressure (J/kg °C), k is the thermal conductivity (W/m °C), and T is the transient temperature (°C).

2.2. Boundary Conditions

The wall of the oven was assumed to be a perfect electrical conductor, where electric field strength (**E**) is zero. The magnetron feeds the electromagnetic wave through the waveguide into the cavity. The magnetron power source was included as coaxial feed as shown in Fig 1. In this study, we studied two methods 1) domain discretization, and 2) transient boundary condition for discretizing the susceptor film. Simulated temperature profiles of these two methods were compared with the experimental profile to identify the best method for further development.

2.2.1. Domain Discretization

The physical thickness of the metal film of the susceptor is very small (often below 1 µm). It is possible to discretize such thin films in computational domain as it would result in large computational time and convergence can be an issue. Thus coarse discretization of the susceptor needs to be provided. To validate this approach, a thin sheet of 1 mm aluminum was placed and discretized above the top of the gel cylinder.

2.2.2. Transient Boundary Condition

In COMSOL Multiphysics, transition boundary condition is used on interior boundaries to model a sheet of a medium that should be geometrically thin but not electrically thin. It represents a discontinuity in the tangential electric field. Mathematically, it is described by a relation between the tangential electric field ($\mathbf{E}_t$) discontinuity and the induced surface current density (J_S) (COMSOL, 2011):

$$J_S = \frac{(Z_S \mathbf{E}_{t1} - Z_T \mathbf{E}_{t2})}{Z_S^2 - Z_T^2} \quad (4)$$

$$Z_S = \frac{-j\omega\mu}{\varphi} \frac{1}{\tan(\varphi d)} \quad (5)$$

$$Z_T = \frac{-j\omega\mu}{\varphi} \frac{1}{\sin(\varphi d)} \quad (6)$$

$$\text{where } \varphi = \omega \sqrt{\left(\epsilon + \frac{\sigma}{j\omega}\right)\mu}$$

where indices 1 and 2 refer to the different sides of the layer, Z is the impedance (Ω/m), σ is the electrical conductivity (S/m) of the susceptor film of thickness, d in m.

2.3. Geometric Model

Geometric model was developed for a 700 W microwave oven (Sharp Electronics Corp., New Jersey, USA). The model consisted of an oven cavity, a magnetron, a turntable, a waveguide, crevices and a metal bump. The microwave feed port was located on top of one side of the microwave oven cavity. In this study, we included magnetron as coaxial power source. The geometric model of the microwave oven is shown in Fig 1.

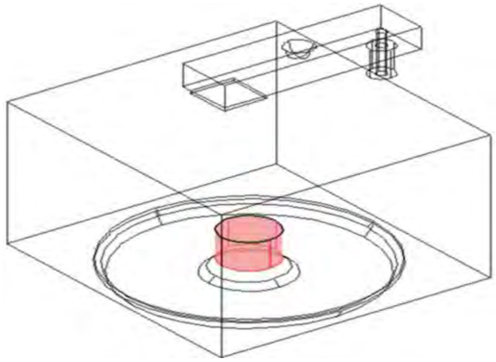

Fig 1. Geometric model of the microwave oven.

2.4. Meshing Scheme

To resolve a wave propagation properly, it is necessary to use about 10 linear (or five 2nd orders) elements per wavelength in the material (COMSOL, 2011). Following these guidelines and performing mesh independent study it was found that maximum 6 mm element size in gel domain and 38 mm in the air are sufficient. For susceptor of 1 mm thickness, 0.5 mm maximum element size was assigned so that at least two layers of elements are in the susceptor domain. The entire discretized domains consisted of ~366,000 tetrahedral elements in which 163, 116 were in the susceptor and gel domain as shown in Fig 2. Interestingly without 1 mm susceptor domain, in transient boundary condition method, the total tetrahedral elements in the gel domain were only ~7,900. As including a small complex domain in the computational area, we need to assign a small size elements accordingly which will eventually affects elements size and number of elements of other domains in the computational area.

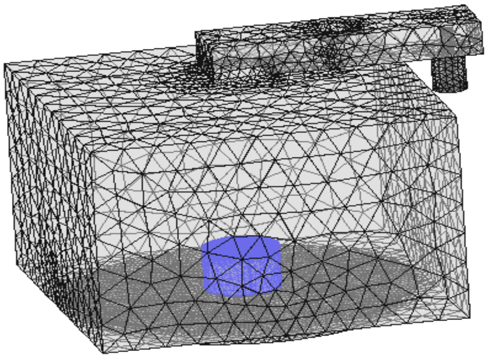

Fig 2. Meshed geometric model of the oven.

2.5. Simulation Strategy

Eqns.1 - 3 were solved using radio frequency and heat transfer modules of COMSOL Multiphysics 4.2. To study the effect of conductance on the heating pattern of gel, electrical conductivity of susceptor film was parametrically swept from 0.001 to 0.1 S/m. Both physics (electromagnetism and heat transfer) were solved for fully coupled approach using segregated steps. Monochromatic frequency of 2.45 GHz was used as input to the model. Table 1 summarizes various material properties used in the simulation.

Table 1. Material properties used in model.

Properties	Gellan gel	Glass
Specific heat, kJ/kg °C	4.16	0.55
Density, kg/m^3	1010	2050
Thermal conductivity, W/m °C	0.53	0.1
Dielectric constant	-0.23T+81.103	4
Loss factor		0

2.6. Experimental Study

A homogeneous, gellan gel cylinder (80 mm × 50 mm) was prepared and used for model validation. The model food was subjected to microwave heating for 30 s while the food was stationary on the turntable. A susceptor film laminated on the paper and PET film was cut to size of gel diameter and placed on top of the gel as shown in Fig 3. Four point temperatures were recorded using fiber-optic sensors (4-channel reflex signal conditioner, accuracy ±0.8°C, Neoptix Inc., Quebec, Canada). Immediately after completion of the heating, temperature profiles were recorded at three layers (bottom, middle and top) using thermal imaging camera (SC640, accuracy ±2°C, 640× 480 pixels, FLIR systems, Boston, MA).

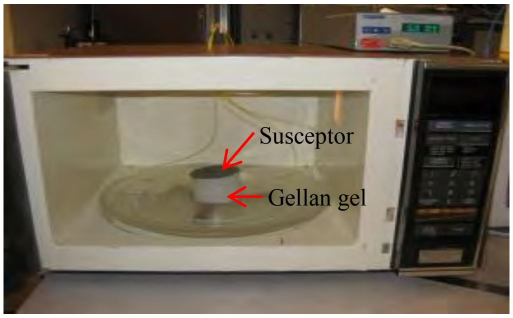

Fig 3. Gel cylinder with susceptor on top.

3. Results and Discussion

3.1. Simulated and Experimental Profile

The electrical conductance value of 0.01 S was chosen to see the model effect of susceptor film on heating patterns. Spatial simulated temperature profiles of the gellan gel cylinder at three layers (z = 0, 25, and 50 mm) obtained by two methods (domain discretization and transient boundary condition) were compared with experimental heating profiles and shown in Fig 4. It shows that the simulated temperatures were lower than the experimental temperatures; however the heating patterns are very close at all three layers. In the top layer, simulated profile of heating pattern (hot and cold spot) was similar as to the experimental profile. The variation in maximum temperature of the top layer profile could be attributed to not providing the inward heat flux term in between the susceptor and gel interface.

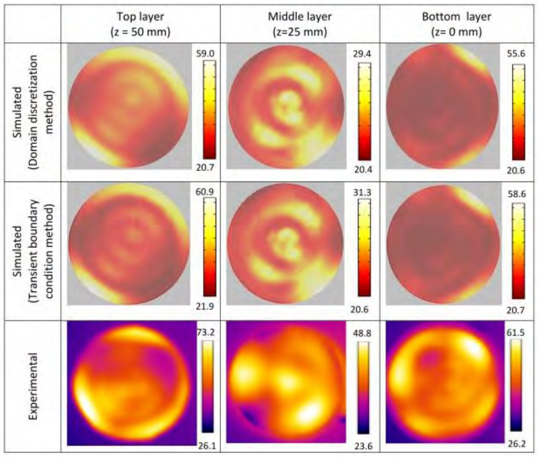

Fig 4. Comparison of simulated and experimental temperature (°C) profiles at three layers.

In middle layer, a perfect match of simulated and experimental heating pattern can be seen. Bottom layer has slightly different simulated temperature profile compared with the experimental profile. This difference was probably due to heat loss during time lag in acquiring thermal images. A slight deviation in the pattern deviation could be due to fact that the magnetron does not operate at a monochromatic frequency but at a spectrum of frequencies.

Overall, in transient boundary condition method, maximum temperature at all three layers were higher (1 to 3°C) than domain discretization method. Thus, it was inferred that transient boundary temperature profile could be used for simulating active packages.

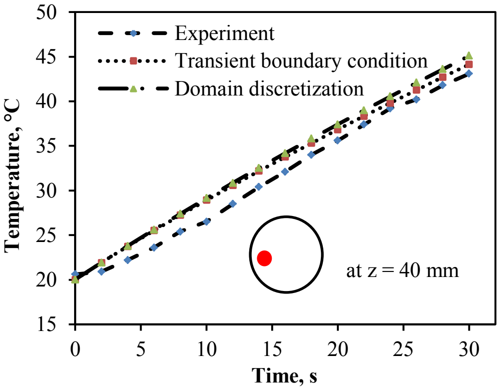

Fig 5. Validated simulated and experimental time-temperature profile at z = 40 mm of transient boundary condition and domain discretization methods (susceptor conductance =0.01 S).

Fig 5 compares the experimental and simulated temperature profiles of transient boundary condition and domain discretization at a point close to the top surface of the gel (z = 40 mm). It shows that transient boundary condition temperature profile is closer to the experimental profile than domain discretization temperature profile. The RMSE error of transient boundary condition is 1.51°C which is less than domain discretization error value (1.91°C). Domain discretization method took about ~5 h to solve the coupled equations compared to only 1 h for transient boundary condition. Thus, transient boundary condition method is best suited for further simulation because of better accuracy and less computational time.

3.2. Effect of Conductance

The electrical conductance of the susceptor film is an important factor in deciding the amount of power absorbed in the food. This material property decides whether the package acts as a susceptor or a shielding to microwave energy.

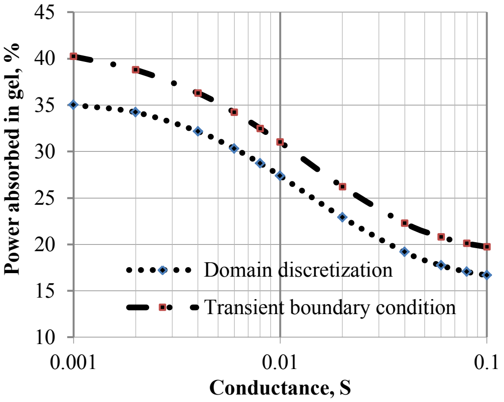

Fig 6. Effect of susceptor conductance on microwave power absorption in the gel.

Fig 6 shows the effect of conductance of the susceptor placed on top of the gel on microwave power absorption of the two simulation methods. Power absorption calculated in domain discretization method follows a similar trend as exhibited by transient boundary condition method. In general, as the conductance increases, the power absorbed in the load decreases and the material starts to behave like a shielding material. From this study, we could suggest that a susceptor's conductance value is in the range of 0.01 to 0.1 S. Conductance value of anything more than 0.1 S will behave as shielding.

The other form of microwave package is the reflector type (shielding). Susceptor and shielding type packages are important to know about their characteristics to microwave heating. As the microwave heating provides non-uniform temperature distribution within a product, susceptors can be used in place where foods heat slowly whereas shielding in place where food heats rapidly. Therefore it is desired to develop the model for shielding type package. The following section discusses about the validation of model for shielding effect.

3.3. Shielding Effect

Shielding type package is used to alleviate the problem of thermal-runaway heating of microwavable food product. Shielding patches are strategically placed on hot spots to modify the field patterns and eliminate these hot areas. To understand microwave interaction with shielding package and food material, a simulation was run with the electrical conductance value of 1 S.

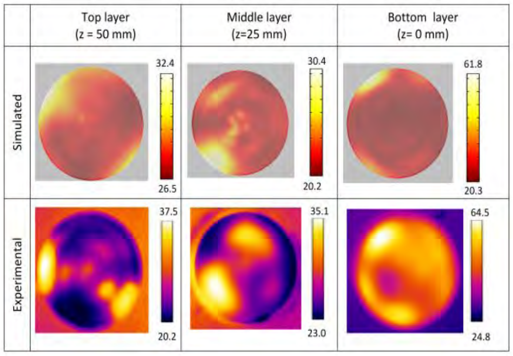

Fig 7. Comparison of simulated and experimental spatial temperature profiles at three layers of gel cylinder shielded on top.

For experimental validation of the model, food grade aluminum foil was placed on top of the gel cylinder to act as shielding material. Fig 7 shows the comparison of the simulated and experimental spatial temperature profile at three layers. It is evident that simulated heating patterns are similar to the experimental patterns at all three layers; however simulated temperature were lower than the experimental temperature. Fig 8 compares observed and simulated temperature profile at a point close to the top surface of the gel (z = 40 mm). The simulated temperature profile follows the same trend of experimental profile until the 15 s and then a deviation was seen. The RMSE error of the profile is 1.78 °C. The slope of simulated temperature profile was different from the experimental profile. In experimental profile we can see a lag in the temperature raise. This lag is mainly attributed by the fact that magnetron takes 2-3 s for delivering full power. In simulation, it can be included using ramp function in port input power.

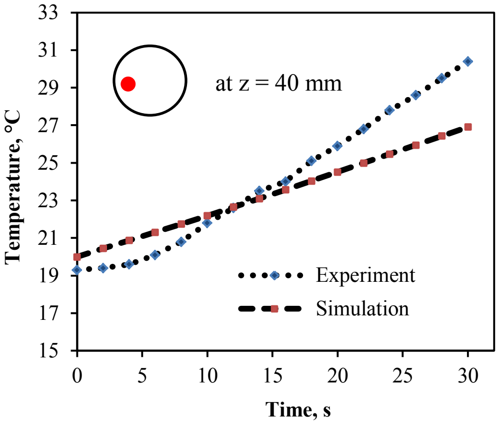

Fig 8. Simulated and experimental temperature profile at z = 40 mm point in the gel cylinder covered by aluminum film at top.

4. Conclusions

In this study, a simulation model was developed and validated for microwave interaction of model food with active package in a domestic oven. Two methods were used to model the susceptor interaction with food and microwave field. Both transient boundary condition and domain discretization method predicted the same temperature pattern as experimental conditions. Transient boundary condition takes only 20% of the time required for domain discretization method and therefore it is preferable to use in simulation. The developed model was also used for predicting temperature in shielding type package. The validated model can be further explored to design various food packages to alleviate one or more problems encountered in microwaveable product development.

5. References

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6. Acknowledgements

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