Excerpt from the Proceedings of the 2011 COMSOL Conference in Boston

Modeling of Microwave Heating of a Rotating Object in Domestic Oven

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Abstract: Modeling of the microwave heating is vital to understand heating characteristics of food in domestic microwave ovens. A model was developed to study the feasibility of coupling rotation of the load along with heating in a microwave oven. The model was validated using a 1 % gellan gel cylindrical for 30 s heating in a 1100 W microwave oven. The temperature profiles (patterns of hot and cold spots) of the simulations showed good agreement with the experimental profiles. Simulation of microwave heating of a non-axisymmetric rotating load revealed that the COSMOL software's moving mesh module does not solve electric field at each different location but only at the initial position and moves the values to new locations. Further improvements are needed in the software to simulate realistic scenarios.

Keywords: microwave heating, heating uniformity, dielectric properties, heat transfer

1. Introduction

Microwave ovens are known for their uneven heating, which can result in both thermal runaways and cold spots. The uneven microwave heating can lead to serious health hazards as a meal can contain raw or partially cooked ingredients which may have pathogens. An understanding of the heating patterns can help to design food which heat more evenly in microwave ovens. Therefore modeling of microwave heating is highly desirable.

Modeling of microwave heating of foods in domestic microwave ovens has been the target of a lot of research work in the last few decades. Accurate modeling of microwave heating requires taking into account of rotation of turntable and object, which has not been the focus of much research.

Finite Difference Time Domain method was used in the simulation of rotation of a square object in a microwave oven by Kopyt and Celuch (2003). A transient geometry condition was used to simulate rotation of the object. This involved changing the geometry to place the heated object in new positions to simulate rotation. At each time step, the object was moved by a user defined angle and a new simulation was run. This meant that a new mesh had to be created at each of the transient positions, which can be very memory intensive. Further, the object was assumed to move instantly at the end of a time step to a new position and remain stationary at the new location for the duration of the entire time step. Moreover, the method involved some post processing to bring the values saved by the different simulations together.

The role of a carousel in improving heating uniformity of a food (potato) in a microwave oven was studied by Geedipalli et al (2007). A finite element software, ANSYS was used for solving the electromagnetic field and FIDAP, another finite element software, was used for the simulation of heat transfer. One-way coupling was used, assuming that the material's dielectric properties are independent of temperature. This assumption does not hold when a material undergoes phase change.

The effects of turntable rotation and natural convection, power sources, and aspect ratio of container on the temperature profiles were studied by Chatterjee et al. (2007) for a liquid load using Finite volume method based FLUENT software. The study considered a rotating load placed in a radially symmetrical electromagnetic field. However a domestic microwave oven has a varying, highly uneven electromagnetic field dependent on a number of factors such as oven geometry, load size, waveguide etc.

COMSOL has been shown to be able to model coupled electromagnetic and heat transfer equations (COMSOL, 2011). A library model was seen to be able to simulate coupled electromagnetic field and rotation in an electric motor using the moving mesh module. This prompted an attempt to solve simultaneous electromagnetic and heat transfer equations for a rotating object in a microwave oven.

The main objective of this study was to explore the feasibility of simulating a rotating object in a microwave oven using three-way coupling of electromagnetic, heat transfer and moving mesh. The simulated results were compared with experimental heating profiles of a model food.

2. Model Development

2.1. Governing Equations

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

$$\nabla \quad {}_{r}^{-} (\nabla \quad) - \frac{f}{c} \left({}_{r} - i \quad \right) \qquad (1)$$

where f is frequency (2.45 GHz), c is the speed of light, and ${}_r$ and ${}_r$ are dielectric constant, permeability, and permittivity respectively.

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

$$f \ {}_{o} \qquad (2)$$

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

$$C_p \frac{d}{dt} \quad \nabla \quad \nabla T) + Q \qquad (3)$$

where k is thermal conductivity, C_p is specific heat capacity and is the density of material.

2.1.1. Moving Mesh

The effect of rotation of the turntable and gel was modeled using the Moving mesh (Arbitrary Langrangian-Eulerian, ALE) module available in the COMSOL 4.2. Moving mesh module had all the boundaries set to zero displacement. The air domain was set to 'free displacement' whereas turntable and gel domains were prescribed the following 'mesh deformation' in x and y directions.

$$dx \quad \cos(\quad N\,t) \ - \sin(\quad N\,t) \ - \qquad (3)$$

$$dy \quad \sin(\quad N\,t) \quad \cos(\quad N\,t) \ - \qquad (4)$$

where N is in rps (0.01), X and Y are the coordinates of the original position of the rotating object, dx and dy refer to the change in position of the rotating object in the x and y direction.

The load domain (gel) and the turntable were rotating at 6 rpm.

2.2. Geometric Model

A geometric model was created for a 1100 W Panasonic oven (Fig.1) (Model No. NN-SD767W). Microwaves are fed into the cavity through a waveguide located on the right side of the cavity wall. The magnetron was included as a coaxial microwave power source as shown in Fig 1. Output power for the magnetron was set as 900 W, which was determined using the IEC Method (IEC, 2006).

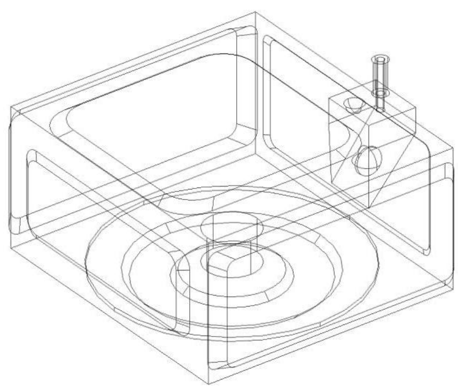

Fig 1. Geometric model of the microwave oven

2.3. Meshing Scheme

It is very important to carry out mesh independent study to find out optimum mesh size for the given model. Meshing of the domain was done using the rule that 10 linear elements were needed per wavelength (COMSOL, 2011). Six-mm maximum element in the gel domain was found to be the optimal mesh size. The completed mesh for the entire domain consisted of 111,325 tetrahedral elements.

2.4. Solver

Frequency-Transient solver was used for the solving coupled Eqs 1-3. The frequency of the oven was assigned as 2.45 GHz and the simulation was run for 30 s in steps of 2 seconds. Segregated solver steps were used for calculation of electromagnetic field wave (emw), temperature (T) and movement of the gel moving mesh (ale). The model used an iterative GMRES solver for 'emw' whereas direct solver was used for 'T' and 'ale'.

2.5. Assumptions

The following assumptions were made in the simulation.

1. The walls of the oven are perfect electrical conductors and reflect all of the incident energy.
2. The heat transfer coefficient at the air – material interface was assumed to be constant at 10 W/m^2K.
3. The mass transfer is negligible and can be ignored.
4. The initial temperature of the gel, air and turntable domain was assumed to be uniform at 20 °C.

2.6. Material Properties

Temperature dependent dielectric properties of 1% gellan gel were measured using an open ended coaxial probe method. Table 1 shows the material properties used in the simulation.

Table 1. Material properties used in model

Properties	Gellan gel	Glass
Specific heat, J/kg/K	4160	0.55
Density, kg/m^3	1010	2050
Thermal conductivity, W/mK	0.53	0.1
Dielectric constant	-0.23T+81.103	4
Loss factor		0

2.7. Experimental Validation

The validation of the model was carried out by heating a food analogue, 1 % gellan gel (Kelco, Atlanta, GA) cylindrical load (80 mm x 50 mm). The gel was prepared by heating 10 g of the gellan gel powder in 1 liter of water. On the temperature reaching 80 °C, 1.6 g of Calcium chloride di hydrate ($CaCl_2$ $2H_2O$) was added. The liquid was poured into a container of diameter 80 mm and height 50 mm and allowed to solidify. The gel was cooled to 20 °C and removed from the container for use.

The gel was placed at the center of the oven turntable. The gel was heated on the rotating turntable for 30s. Fiber optic sensors (FISO Technologies, Quebec, Canada) were used to record the transient temperature of the gel at different locations (Fig 3). Immediately upon completion of microwave heating, thermal images of the top, middle and bottom layer of the heated gel was recorded using a thermal imaging camera (ThermaCam SC-640, FLIR Systems, Boston, MA). The three profiles were compared with the simulated results.

3. Results and Discussion

Fig. 2 shows the comparison of simulated and experimental thermal profiles at the top, middle and the bottom layer after 30 s of microwave heating. The simulated temperature profiles showed good agreement with the experimental profiles. Fig 4 shows the comparison of simulated and experimental temperature at two different points. The simulated values over predicted the temperatures at all the points monitored. This can be corrected by finding the correct power output of the magnetron which is a strong function of load size and shape. We used magnetron power output based on energy absorbed in 1000 ml water load (IEC 2006) whereas the gel volume was 250 ml. Further the transient temperature data showed a period of constant temperature at the beginning of the heating cycle, due to the come up period of the magnetron, which is about 2.5 s. This can be corrected by using a ramp function in the magnetron power input. Interestingly the simulated transient temperature at all the monitored points except the center of the load, in the simulation shows a cyclic pattern of increasing temperature, followed by a flatter temperature profile. This is attributed to the movement of the points through various hot and cold spots in the oven. Absence of such cyclic temperature profile in the experimental values could be attributed to the thermal lag of the fiber-optic sensors which even out the time variations. A similar trend was observed by Geedipalli et al (2007) at points away from the center of the load. Center point transient temperature is not affected by rotation as it does not move and experience a varying EM field.

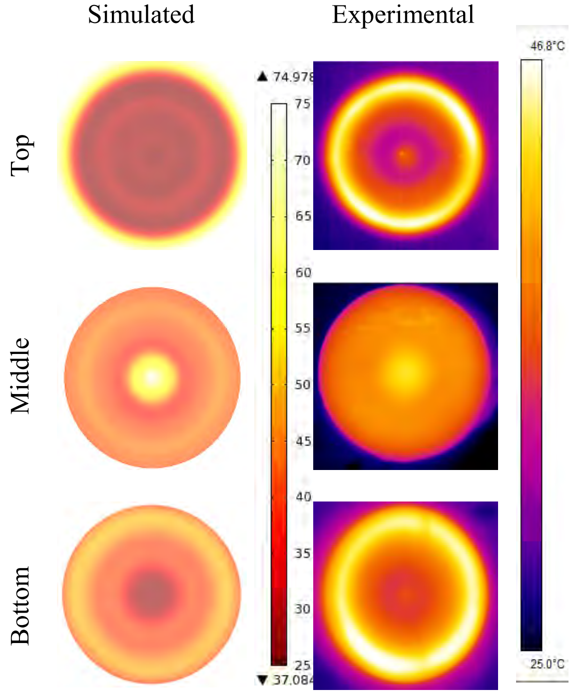

Fig 2. Simulated and experimental temperature profiles at three planes

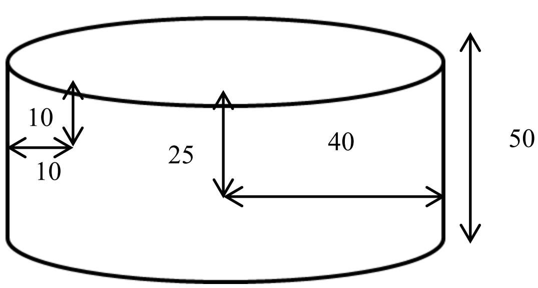

Fig 3. Position of the sensors

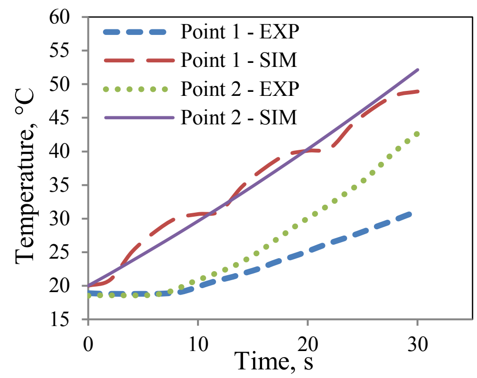

Fig 4. Simulated and experimental temperature profiles at point 1 is in the left top corner and point 2 is at center

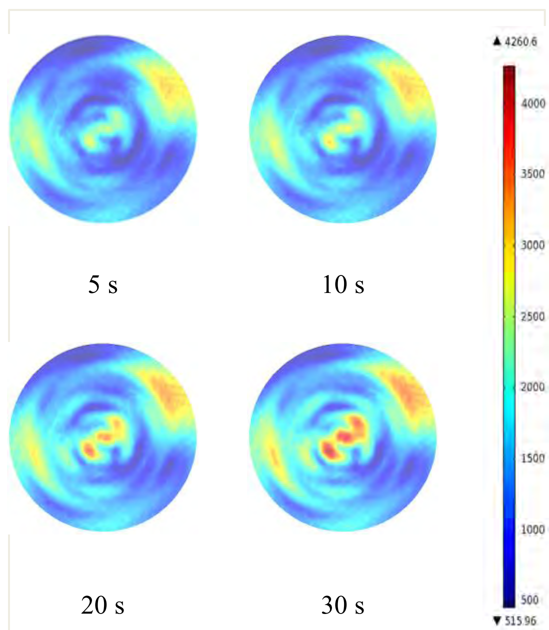

Fig 5. Normalized electric field, V/m in the gel center cross section at different heating times

Fig 5 shows the normalized electric field visualized at different time steps. As the electric field was not changing at various time steps the moving mesh module was probably not solving for each different position but determined the electromagnetic field assuming the load was stationary at one position. This was further corroborated by simulating the gel cylinder kept offset from the center of the turntable.

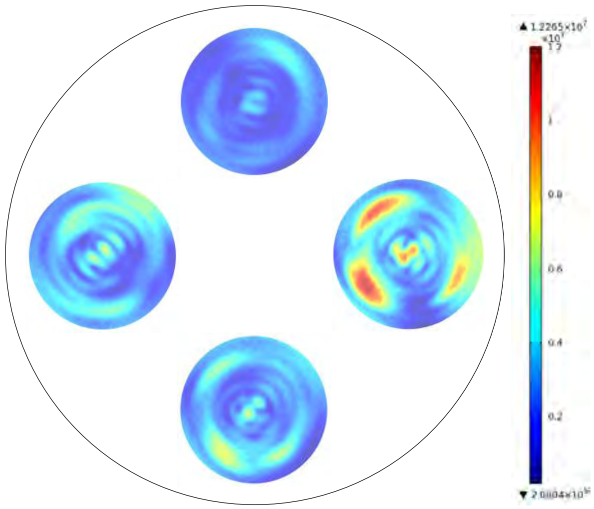

Fig 6. Normalized electric field (V/m) in the center cross section of gel load kept at different places on turntable

When the cylinder was kept in center, rotation on its own axis did not influence the electric field. The field patterns remained same even after rotation of the gel on the turntable. A slight variation in the intensity of the pattern was seen because of the changing temperature and the temperature dependent properties of the load as shown in Fig 5. However simulated electric field using moving mesh did not show any change in the pattern. Hence it was found that moving mesh module does not really work for electric field.

When the cylinder was kept offset from the center of the turntable, moving mesh was expected to simulate different electric field patterns as the cylinder went through different locations in the cavity; however that was not the case. We simulated a series of EM simulation with the gel at different positions and studied the electric patterns. Fig 6 shows that at each position the electric field patterns will be different and their values change dramatically. This study revealed that the software calculated only the electric field for the initial location and moved the values to new locations for calculating temperature. This software glitch has been communicated to the COMSOL R&D personnel for fixing the issue. We have started exploring MATLAB-COMSOL interface to resolve this issue.

4. Conclusions

A simulation model was developed to study the feasibility of coupling rotation of the load along with microwave heating in a microwave oven. The simulated results agreed well with the experimental pattern with respect to hot and cold spots. However the model over predicted the temperature at all the points monitored. Indication of the hot spots and cold spots could help in food product development. The electromagnetic field did not change with the movement of the load to a new position. The rotation effect applies only to the heat transfer. Modeling of rotating object was limited to axi-symmetrical objects kept in the center of the turntable. The moving mesh model does not work for simulating microwave heating of items kept offset from the center as wells as non-axial symmetrical objects. There is further improvement needed in the software to simulate realistic microwave heating scenarios.

5. References

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6. Acknowledgements

We acknowledge the financial support provided by the USDA CSREES – NIFSI grant (Project number: 2008-51110-04340).