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Modelling Coupled Rotation and Microwave Heating of an Object in a Domestic Microwave Oven

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ABSTRACT
Modelling of the microwave heating is vital to understand the heating characteristics of food in domestic microwave ovens. A model was developed to study the feasibility of coupling rotation of the load along with microwave heating in a microwave oven. The model was validated using a 1 % cylindrical gellan gel for 30 s heating in an 1100 W microwave oven. The temperature profiles (patterns of hot and cold spots) of the simulations showed good agreement with the experimental profiles. However the transient temperature was over-predicted in the model at all the four points monitored by an average of 14.87 °C.
Keywords **-** Dielectric properties, Finite element Method, Heat transfer, Heating uniformity, Microwave heating

I. 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 containing raw or partially cooked ingredients may contain pathogens. An understanding of the heating patterns can help to design food which heat more evenly in microwave ovens. Therefore modelling of microwave heating is highly desirable. Modelling of microwave heating of foods in domestic microwave ovens has been the target of plenty of research work (Chen et al, 2008) (Pitchai et al, 2012) [1] [2], in the last few decades. The accurate modelling of microwave heating requires taking into account the rotation of turn table and object, which has not been the focus of much research though .

Finite Difference Time Domain (FDTD) method was used in the simulation of rotation of a square object in a microwave oven by Kopyt and Celuch (2003) [3]. 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) [4].A finite element software, ANSYS was used for solving the electromagnetic field and FIDAP, 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 goes under 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) [5] 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 . A model was developed using the moving mesh module to simulate the moving electromagnetic field in an electric motor (COMSOL, 2011) [6]. This prompted an attempt to solve simultaneous electromagnetic and heat transfer equations for a rotating object in a microwave oven.

This study was undertaken to explore the simulation of microwave heating of a rotating object in domestic 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.

II. 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

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

:Where f is frequency (2.45 GHz), c is the speed of light, and ϵ_r and μ_r are dielectric constant, permeability, and permittivity respectively. (COMSOL, 2011) [6]

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

$$Q=2\pi f\epsilon_0\epsilon'' E^2 \quad (2)$$

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

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

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

2.1.1. Moving Mesh

The effect of rotation of the turntable and gel was modelled 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 with following 'mesh deformation in x and y directions.

$$dx=\cos(2\pi\ N\,t)\,X-\sin(2\ \pi\,N\,t)\,Y-X \quad (4)$$

$$dy=\sin(2\pi\ N\,t)X+\cos(2\ \pi\,N\,t)\,Y-Y \quad (5)$$

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 a1100 W Panasonic oven (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) [7].

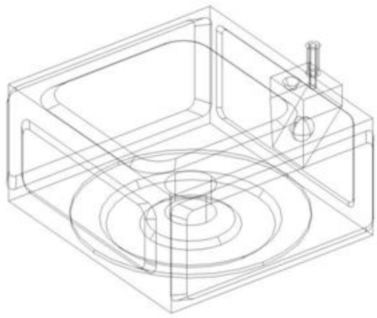

Fig 1. Geometric model of the microwave oven

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 given 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 was 20 °C, and the rest of the domain was also assumed to be at 20°C.

2.6. Material Properties

The material properties used in the model are shown in Table 1.

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	$0.0019T^2$-0.264T+18.033	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 (80mm 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 30 s. Two fiber optic sensors (FISO Technologies, Quebec, Canada) were used to record 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 as shown in Fig 2.

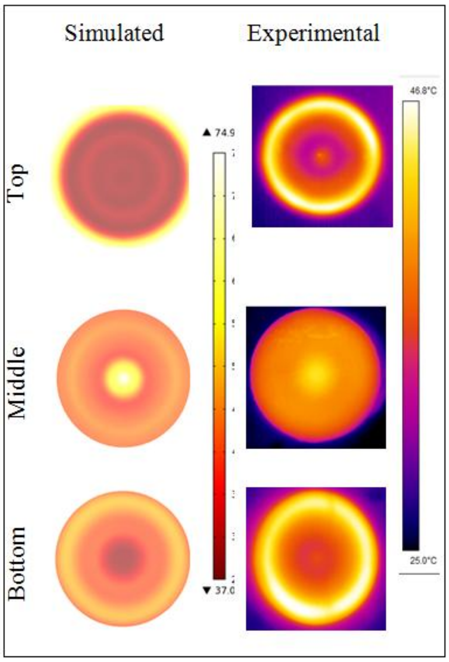

Fig 2.Temperature (°C) profiles of simulated and experimental gel planes

III. Results and Discussion

The simulated temperature profile seemed to be in good agreement with the experimental profile. 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 could be partly attributed to the properties used for the simulation. Further the transient temperature data showed a period of constant temperature at the beginning of the heating cycle, due to the come up time of the magnetron which is about 2.5 s. The transient temperature at all the monitored points except the centre 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. Similar trends in heating were reported by Pitchai et al (2012) [2].

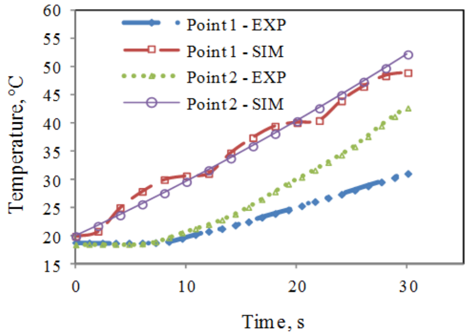

Fig 3. Simulated and experimental temperature profiles at point 1 is in the left top corner and point 2 is at centre

IV. CONCLUSION

A simulation model was developed to study the feasibility of coupling rotation of the load along with microwave heating in a microwave oven.The model's 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. It was attempted to simulate operating the microwave oven with the load placed off centre but the model seemed to have convergence issues.

V. ACKNOWLEDGEMENTS

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