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Effect of location of a frozen multi-component food on heating patterns in domestic microwave oven

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Abstract

Non-uniform heating is a major issue in microwave heating. This study aims to investigate the effect of food location on heating uniformity in domestic microwave oven. In doing this, a comprehensive model (3-D) is developed to solve coupled electromagnetic and heat transfer equations using finite element method based special software. The model simulated thawing of a frozen multi-component food consisting of fried basil chicken, rice, and fried egg. Dielectric properties, such as dielectric constant and dielectric loss factor, are measured using a portable dielectric measurement (Network Analyzer). Thermo-physical properties of samples are characterized using their composition. Simulated temperature profiles were compared with experimental temperature profiles obtained using a thermal imaging camera and fiber optic sensors. The simulated outlet temperatures had a good agreement with experimental data within the maximum prediction error of 5%. The predicted and experimental temperature profiles were provided as inputs to a microbial in activation kinetic model for *Salmonella* Heidelberg to assess food safety risk in stir fried basil chicken with fried egg and rice. The results from the study can be used to optimize the location of food to achieve more uniform heating and food safety in domestic microwave oven.

Keywords: Microwave heating, modeling, food safety, uniform thawing

1. Introduction

Ready-to-eat frozen food is food that has been prepared and cooked then packaged and rapidly freezing. It is normally kept at -18ºC for preservation. The examples are dumpling, pizza, bread, potato puree, pasta, rice, and vegetable soup. There are available in the market in many countries. The frozen foods need to be thawed before using them. The easy and convenient way to thaw frozen food is put it in microwave. Microwave use a few time after that can cook it or eat it straight away. Therefore, a microwave thawing is one of the most attractive alternative procedures as quick thawing at low temperature. Among its important advantages, microwaves penetrate and produce heat deep within food materials (volumetric heating), as a result of fast accelerating rate, improved bacterial control and low costs. However, the non-uniform distribution of the electromagnetic field in the microwave cavity is a limitation for microwave applications in practice.

Typically, frozen food is thawed in a microwave oven with its package. Concerning microwave food safety, the non-uniform heating of food may cause burning of packaging or container. Thus the improvement on the temperature uniformity during microwave thawing is necessary. The microwave heating of frozen substances depend on material properties and dimensions and the magnitude and frequency of electromagnetic radiation (Pangrle, Ayappa, Davis, Davis, & Gordon, 1991). Material properties such as dielectric properties, which are dielectric constant and dielectric loss factor, are the electric properties which measure the interaction of food with electromagnetic fields. In addition, factors such as thermal properties varying with temperature, irregular shapes and heterogeneity of the food make the thawing process more complicated (Taoukis et al., 1987, Dincˇov et al., 2004). It is important to know materials properties to enhance effective of microwave heating process.

To investigate microwave heating uniformity, the mathematical simulation is very helpful to predict electromagnetic distribution and temperature profile. Several methods are applied to calculate these values, The Finite Difference Method (FDM) (Chen et al, 2008, Zhang et al., 2000), The Charge Simulation Method (CSM), The Finite Element Method (FEM) that is developed by MATLAB program, The Finite Control Volume (FCVM), etc. FEM has been successfully used to model the effect of the structure of mode stirrer on the uniformity of microwave heating (George and Bergman, 2006, Plaza et al., 2005, Curcio et al., 2008), and the power distribution in the material (Liu et al., 2005, 2013 Jia et al., 1992). Moreover, the commercial software, COMSOL Multiphysics, is chosen to calculate too (Pichai et al, 2012, 2014). It is a finite element analyzer and a solver software package for various physics and engineering applications, especially coupled phenomena. From the past literatures, a number of approaches have been developed to model the thawing of frozen substances by commercial software. However, very few models completely report both theoretical and experimental analysis on microwave thawing of frozen food attached with plastic package. Therefore, many of parameters have not yet been investigated.

This research is the illustration of transport phenomena, including the electric filed and heat transfer in sample during subjected to electromagnetic fields at different conditions. Concerning major parameters as food locations are analyzed by simulation with the commercial software COMSOL^{TM}-Multiphysics. This study leads a framework for selecting the required model parameters which are critical for better temperature distribution. In addition, the model can be used to identify the hot and cold spots in frozen food with plastic container to achieve better heating uniformity and electromagnetic distribution inside the cavity and to avoid burning of plastic containers.

2. Experimental analysis

2.1 Sample preparation

Basil fried chicken is made from the composition of 40% chicken sliced, 55.8% of seasoning (soup stock powder, cooking oil, soy sauce, fish sauce, sugar), and 4.2% of vegetable (red chili, Holy basil, kaffir lime leaves) by weight basis.

All samples are packed into microwaveable plastic container and stored at -18°C in a freezer until used for experimental.

Fig. 1 Frozen Basil fried chicken samples

2.2 Dielectric properties measurement

The instrument is warmed up for at least 30 min before the calibration and measurements are made. Calibration of the probe is done using air and water at 25°C. The sample is placed in a wide glass tube and the open coaxial probe is set into the tube. The sample holder is dipped into a temperature controlled water bath. The surface and internal temperature of the samples is monitor by using an infrared thermometer (Testo 845, German) and the thermocouple temperature sensor (Fluke 51 II, USA), respectively. The sample is heated from -18 to 80°C and the dielectric properties are measured. The experiments are repeated three times. The results are reported at frozen and unfrozen stages as a function of temperature and at 2.45 GHz. The typical error of the dielectric properties measurements is about 5% following standard calibration procedures.

2.3 Thermal properties analysis

In this study, the thermal properties (thermal conductivity and specific heat capacity) are calculated using mathematical models. The steps are following: (1) to send all samples to SGS (Thailand) Limited Laboratory Services for measuring their nutritional values, (2) to calculate the thermal properties of food components (including protein, fat, carbohydrate, fiber, and ash) by using the Choi and Okos equations (Choi and Okos, 1986)., and (3) to determine thermal properties of foods by using the parallel model given by Murakami and Okos (1989).

In this study, the ratio of ice and water is 50:50 at a temperature of 0°C. The resulting thermal properties of ice or water mix are then combined successively with the thermal properties of each remaining food constituent to determine the thermal properties of the food product.

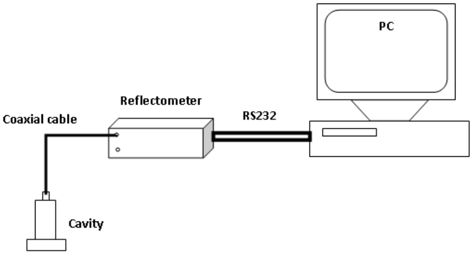
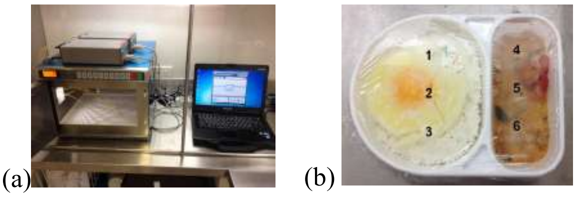


Fig. 2 Portable dielectric measurement (network Analyzer)

2.4 Temperature measurements

The microwave oven used in all of the heating experiments is a 7-Eleven microwave oven Panasonics model No. NE1356 (Fig.3(a)). The oven has a medium sized cavity with a plastic plate. The cavity is top and bottom fed and the rated input power is 1.3 kW. The ready frozen foods are put on a plastic plate. The plastic plate is used in order to reduce the bottom heating, and to provide more temperature distribution. The measurement order is collected every each 10s and the meals are heated according to the recommended for a commercial product at full power. The resting period of the oven between the measurements is about 20 minutes. In an experimental, the infrared imaging (IR-thermography) is used to measure temperature distribution on the top side of the meals. Temperature inside the meals are measured using a fiber optic system during microwave heating. In the basil fried with chicken is registered six points for (3 points in rice and 3 points in meal) during heating (Fig.3(b)). The fiber optic system is connected to computers with a temperature logging system.



(a) (b)

Fig. 3 Experiment setup (a) equipment (b) thermal position

3. Mathematical modeling

This part is shown the model of heating process of ready frozen foods in microwave oven. The distributed heat source is computed in a stationary, frequency-domain electromagnetic analysis followed by a transient heat transfer simulation showing how the heat redistributed in the food.

3.1 Model geometry

The model is developed in finite element based software COMSOL Multiphysics 4.3a (COMSOL Inc., Boston, MA). A geometric model is developed for a domestic microwave oven (Panasonics model No. NE1356) rated at 1300 W and frequency of 2.45 GHz. Detail of oven cavity, magnetron, waveguide, sample are included in the model.

3.2 Model assumptions

In order to reduce the complexity of simulation heat transfer in the ready frozen food during microwave thawing, the following assumptions are considered.

1) The heat transfer is not considered in the air and PP (Polypropylene) tray due to negligible dielectric loss factor.
2) The initial temperature of food compartments is considered as homogeneous and isotropic.
3) The convective natural heat flux boundary at the food-air interface and air temperature is assumed to be constant at 25°C.
4) The simulation is performed by considered a single 2.45 GHz magnetron frequency.
5) The mass and momentum transfer of moisture are not considered.

3.3 Governing equations and boundary conditions

The electromagnetic distribution inside an oven cavity is governed by a set of Maxwell's equations. The equation of the solution for the electric field vector $\vec{E}$ inside the waveguide and oven:

$$\nabla \times \left(\mu_r^{-1} \nabla \times \vec{E}\right) - \left(\frac{2\pi f}{c}\right)^2 \left(\varepsilon' - i\varepsilon''\right)\vec{E} = 0 \qquad (1)$$

Where f is the microwave frequency of magnetron, c is the speed of light, $\varepsilon', \varepsilon'', \mu_r$ are the dielectric constant, dielectric loss factor and relative permeability, respectively.

Conversion of electromagnetic energy into thermal energy is proportional to the dielectric loss factor (ε''), square of electric field strength $(\vec{E})$ and the frequency of the wave (f). The electromagnetic power loss density (Q) is calculate as

$$Q = \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' \cdot \left|\vec{E}\right|^2 \qquad (2)$$

The dissipated electromagnetic power loss density (Q) is a heat source term in transient heat transfer equations.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla\left(k \cdot \nabla T\right) + Q \qquad (3)$$

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

The summarized information of initial condition and material properties of computational domain is given in table 1.

4. Results and discussions

4.1 Experimental validation of frozen models

4.1.1 Spatial temperature profiles

Fig.4 shows the comparison between the simulated temperature profile of frozen basil fried chicken and three replicates of experimental temperature profile obtained using a thermal imaging camera. From the fig., it is shown the location of hot and cold pattern in the frozen foods. In addition, simulated spatial temperature profile thermal patterns are in agreement with the experimental thermal images. The basil fried chicken; it is multi-component meal and multi-layer because it has fried egg on top of steamed rice. It is shown that the hot spots or higher temperature are happen on the edge about 160°C. The average temperature is remained around 65°C.

4.1.2 Point temperature profiles

The comparison of the transient point temperature between experiment and simulation during the 140 s of microwave heating of frozen basil fried chicken is displayed in fig.5. From the fig, it is shown the trend sigmoid curve at location of L5. This is because of latent heat of thawing and evaporative of basil fried chicken. The simulated transient temperature shown a phase-change effect in their trend (in thawing region) similar to experimental profile. Thus, it indicates that the microwave physics and obtained solution in the model were correct. The root mean square error (RMSE) between simulated model and average value of experiment profiles using eq.(4), ranged from 10.46 to 20.25°C. The transient point temperature profiles of model are generally higher than the experiment for all three locations. The temperature prediction is shown very close to experiment profile (RMSE = 10.46°C) at location L4, with is the hot spot in the frozen basil fried chicken. The hot spot is the critical point to concern in microwave heating in term of food safety because it may be cause of packaging melting. Therefore, the accurate prediction of the hot spot in the model showed the promise of the simplified model.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_{\text{sim}} - T_{\text{exp}}\right)^2} \qquad (4)$$

Table 1 Summary of initial conditions and material properties applied in the model

Parameter	Domains	Value
Initial temperature (°C)	Air Ready frozen foods	25 -18
Dielectric properties -dielectric constant $\left(\varepsilon'\right)$ -dielectric loss factor $\left(\varepsilon''\right)$	Air Ready frozen foods	1 Ref.[6]
Thermal properties -Specific heat capacity $\left(c_p, \mathrm{kJkg^{-1}\,{}^{\circ}C^{-1}}\right)$ -Density $\left(\rho, \mathrm{kgm^{-3}}\right)$ -Thermal conductivity $\left(k, \mathrm{Wm^{-1}\,{}^{\circ}C^{-1}}\right)$	Air Ready frozen foods	Ref.[6]
Heat transfer coefficient $\left(h, \mathrm{Wm^{-2}\,{}^{\circ}C^{-1}}\right)$	Food-Air	10

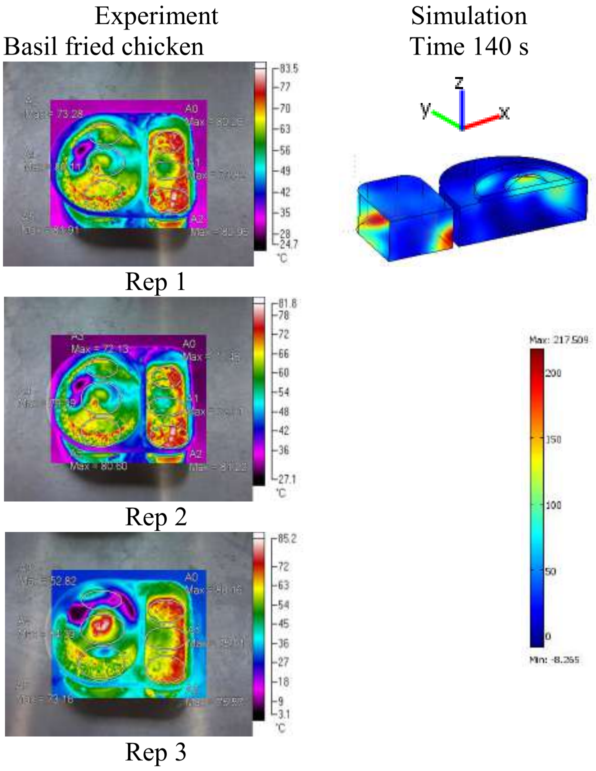
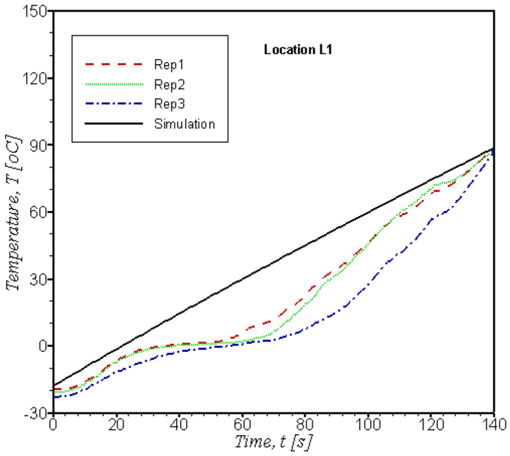
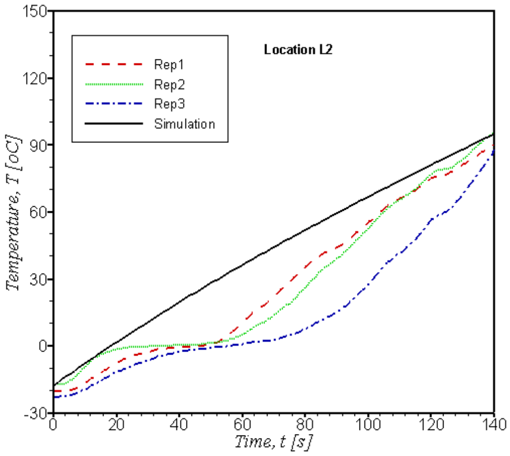
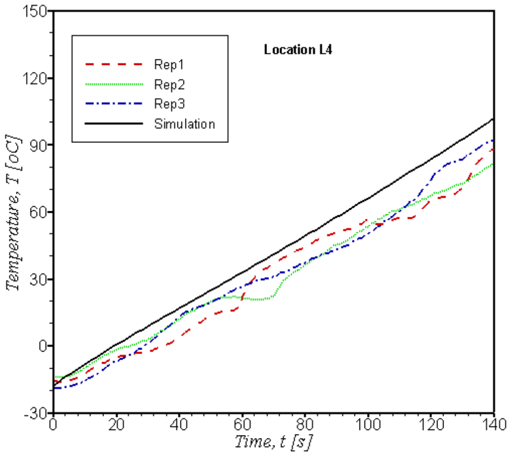


Fig. 4 Comparison of spatial temperature profile of experiment with simulation subjected to a 1300 W microwave oven







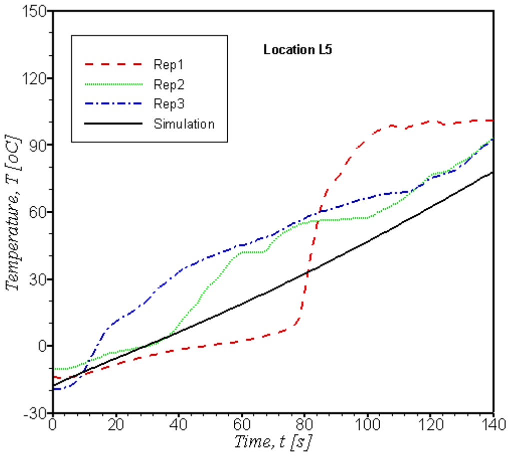


Fig. 5 temperature profile at three locations of congee subjected to 140 s heating in a 1300 W microwave oven.(Refer location in Fig.3(b))

Table 2 Root mean square error and end temperature difference of simulation and averaged experiment temperature profile after 140 s of microwave heating

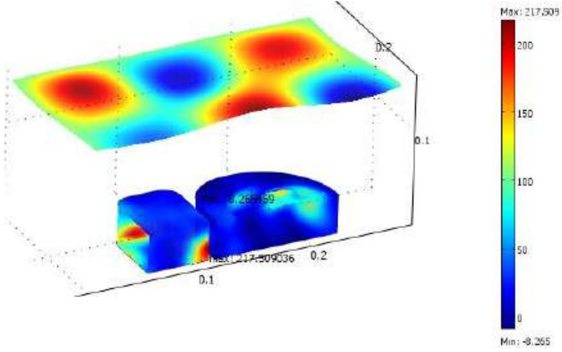
Location	L1	L2	L4	L5
component	Rice	Fried egg	Basil fried chicken	
RMSE	18.08	20.25	10.46	15.78
Tsim	88.54	94.83	101.73	78
Texp	88.07	91.70	87.83	96
ΔT	0.47	3.13	13.9	18

4.2 Effect of food location on temperature prediction

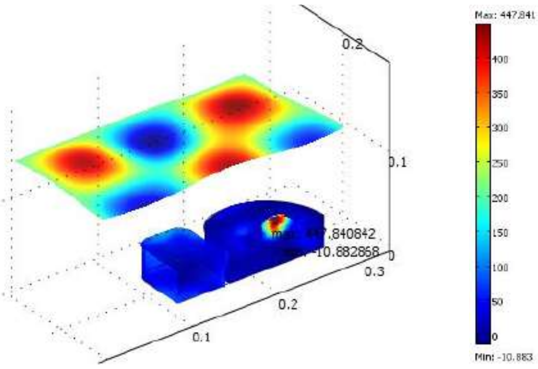
Fig. 6 is shown how important to find the optimal feed location in microwave oven to predict better temperature profile. As shown in Fig, location of sample at center is quite uniform. However, the edge of sample has temperature greater than the center of sample. This is because of distribution of electric field is relatively uniform.

From the results, it is shown the significant effect of non-uniform heating in a domestic microwave oven. However, a simulated model can help in optimizing the product layout, location, and modifying the properties of food system.

(a) Center



(b) Plus 5 mm



(c) Minus 5 mm

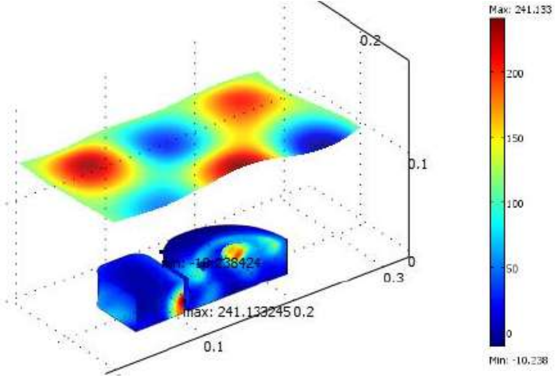


Fig. 6 The electric field distribution and temperature profile of frozen Basil fried chicken, t=140 s (P=1300 W, f=2.45 GHz)

4.3 Integrated microbial inactivation model

The thermal inactivation of microorganisms during microwave heating of non-isothermal conditions can be expressed using thermal death time (Bigelow, 1921)

$$F = \int_0^t 10^{\frac{T_t - T_{ref}}{z}} dt \qquad (5)$$

Where T_t is temperature at various times, T_{ref} is reference temperature. To determine microbial inactivation level, we used a published D-value of 0.15 at 62°C min and z value of 4.73°C of *Salmonella* Heidelberg calculated for chicken nuggets (Bucher et al., 2008).

Fig. 7 compares time needed to achieve ≥ 7 log reduction of *Salmonella* Heidelberg in basil fried chicken. On the average, simulation results showed that the time required was 137 s, while the experiment indicate 140 s. Thus, the simulation prediction terms of microbial reduction level was well in agree with the experiment conditions. Due to the non-uniform heating persisted in the multi-component meal after microwave heating, it is very important to consider temperature in microbial point of view as a function of space coordinate. Fig. 5 clearly shows that at time was less than120 s, temperature was not reaching baseline of 62°C to reduce the population of *Salmonella* Heidelberg by 7-log. Therefore microorganisms are present if time heating was less than 120 s and cause foodborne illness.

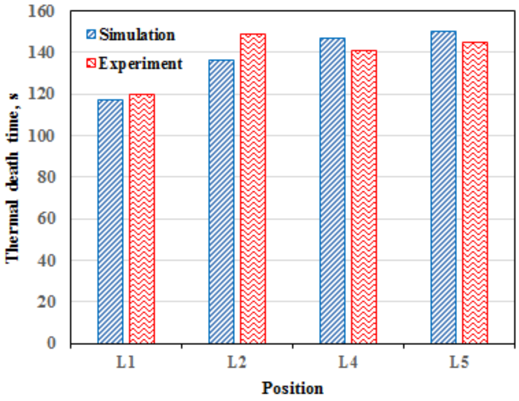


Fig. 7 Comparison of time needed to achieve ≥ 7 log reduction of *Salmonella* Heidelberg calculated from simulated and experimental time-temperature profile of basil fried chicken subjected to 140 s heating in 1300 W microwave oven.

5. Conclusions

This study shows excellent validation between develop comprehensive mathematical model and experiment for microwave heating the frozen basil fried chicken. Whether, there is little difference in overall heating rate and uniformity. The heating uniformity and thawing time significantly depends on location of sample inside oven. The effect of food location on temperature predictions was studied and at canter of microwave oven was found to be optimal. The predicted and experimental temperature profiles were provided as inputs to a microbial inactivation kinetics model for *Salmonella* Heidelberg to asses food safety of basil fried chicken cooked by microwave heating. Overall, the model is powerful tool and effective way of predicting microwave heating rate and the uniformity.

6. Acknowledgement

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