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Finite Element Modeling of Heat and Mass Transfer in Food materials during Microwave Heating

Preeda Prakotmak

Department of Mechanical Engineering, Faculty of Engineering at Khamphengsean, Kasetsart University, Khamphengsean Campus, Nakorn Pathom 73140, Thailand

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ABSTRACT

Microwave heating is rapid and convenient. However, microwave heating of food in domestic microwave oven has the issue of non-uniform heating. Food materials such as dough, as used in this study, are generally porous media which refers to a solid having void space that is filled with gas or liquid. During the microwave heating process, the transport of air and water, the vaporization also can happen within the food materials and on food surface, which also will influence the microwave heating performance greatly. A microwave heating model is needed to fully understand the microwave heating process. The objective of this study was to study on microwave heat distribution model in a laboratory scale microwave dryer. A 3-D finite element model was developed to predict temperature of dough during microwave heating. The model includes physics of Maxell's electromagnetic heating and Fourier's heat transfer. The drying experiments were carried out at 100, 180, 300 and 450 W. Predicted temperature profiles were in good agreement with experimental results at low microwave power. The increasing temperature and heat distribution were directly depended on heating time and salt concentration in dough.

Keywords: dough, finite element, heat transfer, microwave heating

INTRODUCTION

In a microwave drying system, the microwave energy has an internal heat generative capacity and can easily penetrate the interior layers to directly absorb the moisture in the sample. The quick energy absorption causes rapid evaporation of water, creating an outward flux of rapidly escaping vapor and therefore the driving force of the dehydration process. When using microwaves as a final drying stage, several advantages exist compared to traditional drying processes e.g. lower environmental impact due to the use of clean energy and low energy consumption and processing time requirements [1].

The temperature of the material depends on the electric field strength and on the material dielectric loss. As the material absorbs energy, its temperature increases with a corresponding relatively large increase in the dielectric loss. The pattern of electric and magnetic fields within the microwave oven is complex, especially with the presence of the load which properties vary during processing such as drying. 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. Two methods have been used to predict electromagnetic energy distribution within the food: solving Maxwell's equations [2,3] or using an approximate description such as Lambert's law, which considers an exponential decay of energy within the food [4-6].

The product composition (moisture and soluble solids content) determines the radiation-food interaction capacity through the variation in dielectric properties [1]. These properties are responsible for microwave heating and dehydration due to the interaction of the electric field with the polar molecules. Several authors have demonstrated the change in dielectric properties of products with different water and sugar contents [7,8]. In addition, Ressing et al.[9] have reported the dependence of the dielectric properties of salt concentration on their composition. The objectives of this study was to develop a microwave heating model to describe the influences of microwave output power and salt concentration on drying temperatures of dough sample.

Materials and Methods

Corresponding Author: Preeda Prakotmak, Department of Mechanical Engineering, Faculty of Engineering at Khamphengsean, Kasetsart University, Khamphengsean Campus, Nakorn Pathom 73140, Thailand
E-mail: fengpdpr@ku.ac.th

Fig.1 shows the diagram of the microwave drying system. A programmable experimental microwave oven (SUMSANG, T.D.S. GE872D) with maximum output of 850 W at 2.45 GHz microwave source via a rectangular waveguide operating in the TE_{10} mode, was used for the drying experiment. The dimension of the inner cavity is 29×30×185 cm. The oven has a fan for air flow in drying chamber and cooling of magnetron. The moisture from drying cavity was removed with the fan by passing it through the opening on the right side of the oven wall to the outer atmosphere. Wet dough was used as a model system of food stuffs that can be dehydrated under drying. Experiment was only done on high gluten flour dough with the range of 0.0–1.5% salt concentration. The dough was assumed to be properly mixed, consisting only of water, flour and salt and an air content of 10% by volume. The microwave turntable motor was removed. A sample with three thermocouples installed inside was used for measuring radial temperature distributions. Transient temperature at three points as shown in Fig. 1 were recorded using a J-type thermocouple (∅ 3mm) in conjunction with a NI acquisition system (Texas). All of the thermocouples were accurate to within ±0.5°C. The experimental samples were place on glass dish which connect to a load cell. The whole system was operated by a program created under LabVIEW 2010 (National Instruments, Texas).

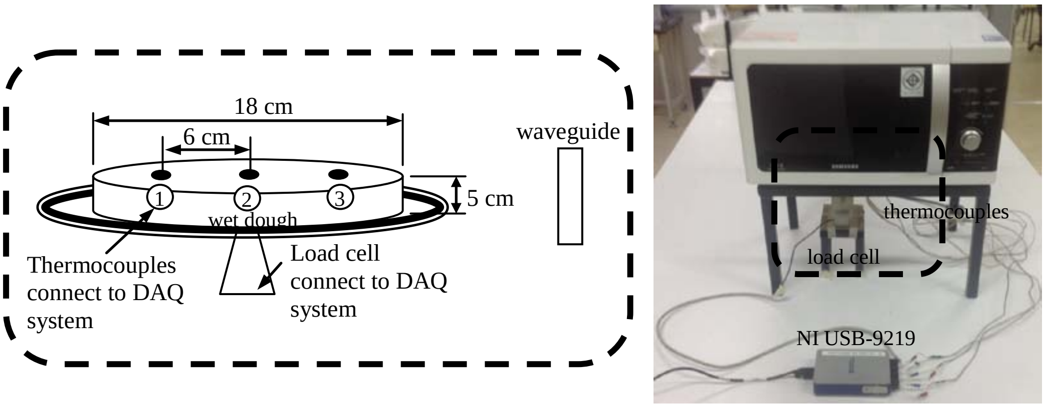

Fig. 1: Experimental setup for the measurement of temperature and weight during drying.

The adjustment of microwave power level and processing time is done with the aid of a digital control facility located on the microwave oven. During drying experiments, each sample was put on the glass plate and placed in the center of the oven. Moisture loss was periodically measured by taking out the glass and weighing on the digital balance with a precision of 0.01 g. Three replications of each experiment were performed according to a preset microwave power level and time schedule, and the data given are an average of these results. The reproducibility of the experiments was within the range of ±5%. The microwave power was applied until the weight of the sample reduced to a level corresponding to moisture content of about 0.15 kg/kg db.

Mathematical Model:

A mathematical model was developed to predict the temperature within sample undergoing microwave drying. In the geometric model, four domains i.e. oven cavity, glass plate, waveguide and sample are included, as shown in Fig. 2. For symmetry reasons, only a haft of the dough was actually modeled. This approach was chosen to keep computational requirements low. The microwave drying model developed here uses the following assumptions:

a) The microwave frequency was assumed to be constant at 2.45 GHz.

b) The adsorption of microwave by air in a waveguide is negligible.

c) The walls of a rectangular waveguide are perfect conductors.

d) There is no bound water in the food domain, which means there is no shrinkage after water vaporization.

e) The initial distribution of moisture content and temperature are uniform.

The wet dough and microwave properties required for the simulation are presented in Table 1 and 2, respectively. With these parameters, the simulation was performed using the commercial software program COMSOL Multiphysics. Tests of mesh independence with finer meshes were made, but no influence was observed on the results. The time step was automatically determined by the solver of the software.

Governing Equations:

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

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

where f is frequency of incident wave (2.45 GHz), c the speed of light (3x10^8 m/s), ε_r relative dielectric constant ε'' dielectric loss factor and μ_r permeability of the medium. Electromagnetic power dissipation density (Q) can be determined by the following equation:

$$Q = 2\pi f \varepsilon_0 \varepsilon'' E^2 \qquad (2)$$

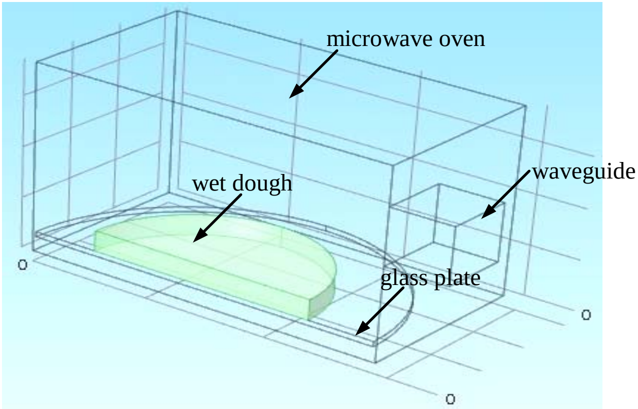

FIG. 2. Geometric model of microwave oven.

Table 1: Material properties used for the model [10-13].

Properties	Constant values	Unit
Electric conductivity (σ)	0	S/m
Dielectric constant (ε')	4.17-1.55j	-
Dielectric loss factor (ε'') 0.0% salt concentration 0.5% salt concentration 1.0% salt concentration 1.5% salt concentration	 8.5 10.9 11.5 12.9	 - - - -
Relative permeability (μ)	0.48	-
Thermal conductivity (k)	0.59	W/m.K
Density (ρ)	1000	kg/m^3
Heat capacity (C_p)	4180	J/(kg.K)

Table 2: Microwave properties [14].

Properties	Materials		
	Copper	Glass	Air
Electric conductivity (σ, S/m)	5.998×10^7	0	0
Dielectric constant (ε')	1	2.55	1
Relative permeability (μ)	1	1	1

The energy conservation includes convection, diffusion, conduction, phase change of water and microwave heating source can be described by

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

where ρ is the fluid density, C_p the fluid heat capacity, T temperature (K), u the fluid velocity field, Q the heat source of electromagnetic power dissipation density (W/m^3), $(\rho C_p)_{\rm eff}$ and k_{eff} are the effective heat capacity and thermal conductivity, respectively, which are weighted average of solid-fluid system terms [15].

The average temperature at instant t were calculated as follows:

$$\overline{T}_t = \frac{1}{V} . \int T(x,y,z,t) dV \qquad (4)$$

where V is the volume of dough.

Boundary Conditions:

The wall of oven was assumed to be a perfect electrical conductor, where electric field strength E is zero. For the boundaries of food surfaces, the governing heat transfer equation is solved using:

$$-n\cdot\left(-k\nabla T\right)=q_{evp}+h\left(T_{air}-T\right) \quad (5)$$

where n is refractive index, k thermal conductivity (W/m.K) q_{evp} the heat loss due to vaporization and The pressure of food boundaries was set to ambient:

$$P|_S = P_{ambient} \quad (6)$$

Respective to the boundary conditions, the walls of the cavity are considered as perfect conductors, represented by the boundary condition:

$$n\times E=0 \quad (7)$$

As shown in Fig. 2, the symmetry cut has mirror symmetry for the electric field and is represented by the boundary condition:

$$n\times H=0 \quad (8)$$

where E and H are the absorbed electric and magnetic fields.

Results and Discussion

Fig. 3 showed the variation of the temperature in sample exposed to microwave radiation at 3 different points. It can be observed that, the increased absorption of microwave energy by the material, the temperature variation between different points in the sample increases. The observed transient temperature profiles of point 2 and point 3 followed the similar trend. The measured temperature at the point 3 was higher than measured values at 1 and 2. The reason for this is due to the power concentration.

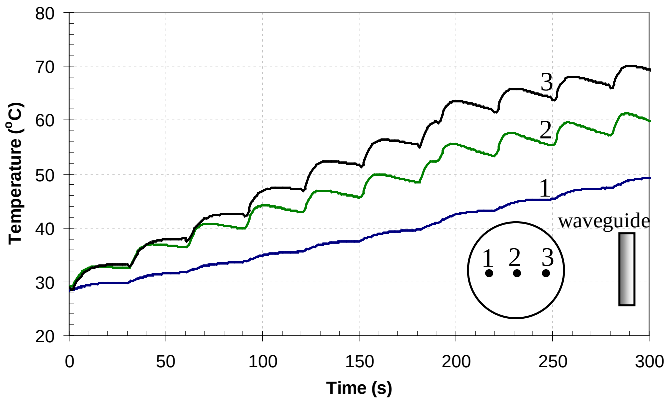

Fig. 3: Observed transient temperature heating profiles at three locations.

The temperature profiles versus drying time for dough at selected average temperature is shown in Fig. 4. From the slope of the heating-up curves, as expected, the temperature rate significant increased with the microwave power (p<0.05), due to the effect of microwave power on the penetration and adsorption of microwave energy into the dough. The temperature of the sample was kept in the range 30-82°C. Except for microwave power of 450 W, the temperature was higher than water's boiling point. Under different microwave power, when the final moisture content of dried material reached 11% (db), the final average temperature of the dough at different microwave powers were measured as follows: 45°C at 100 W, 68°C at 180 W, 82°C at 300 W, 140°C at 450 W. This implied that the increased microwave power intensified the moisture evaporation inside the dough.

The model is validated with an experimental study. The average temperature variation during the drying process, which was predicted by the proposed models, is shown in Fig. 4. This figure shows that for modeling in case 0.0% salt concentration of dough. At low microwave power, the results showed that the model properly predicted the on-off control effect of the microwave oven. In this model did not take into account the overheating stage; therefore, as seen in Fig. 4, the model did not follow the increase in temperature in samples heated by 180-450 W microwave power (R^2<0.93).

The temperature of the material depends on the electric field strength and on the material dielectric loss. As the dough absorbs energy, its temperature increases with a corresponding relatively large increase in the dielectric loss. The higher loss allows the dough to absorb more energy resulting in a higher temperature. Increases in temperature as function of time for various salt concentrations are shown in Fig. 5. The model predicted the increase in temperature reasonably well for low salt contents (R^2>0.95). The salt content of dough sample was varied between 0-1.5% with low salt content exhibiting lower loss factors than higher salt contents as shown in Table 1. At higher salt contents an unrealistic rise in temperature due to the higher dielectric loss factor was observed. Hence, there appears to be mechanism for losing energy which has not been accounted for in the model. For greater salt concentrations the temperature rise was unrealistically high and greatly exceeded experimental results. Additionally, the reasons for these differences may be explained as follows (1) non-uniform power distribution; (2) insufficient accuracy in the measured material temperature; (3) insufficient accuracy of material properties which were obtained from the literature [16].

As shown in Fig. 6, the power absorbed in the dough is evaluated and amounts to about 50% of the input microwave power. This indicated that the penetration depth of microwaves into materials depends on the electrical properties of them, and gives rise to a heat source. The electromagnetic wave absorption is responsible for the macro and micro structural changes in the materials morphology, and consequently for their electrical properties.

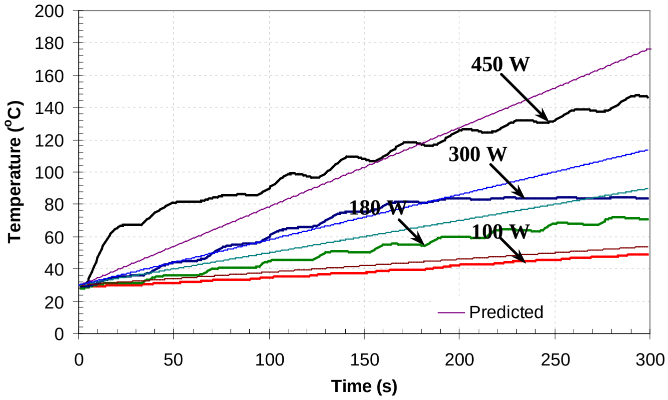

Fig. 4: Average temperature curves of dough at different microwave power (0.0% salt concentration).

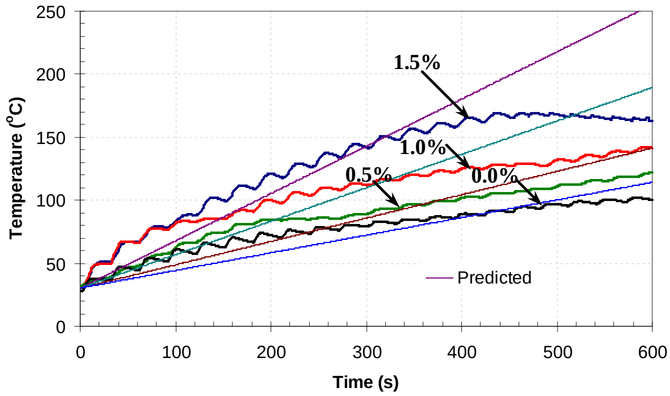

Fig. 5: Temperature increase for various salt concentration at microwave power of 300 W (point 3).

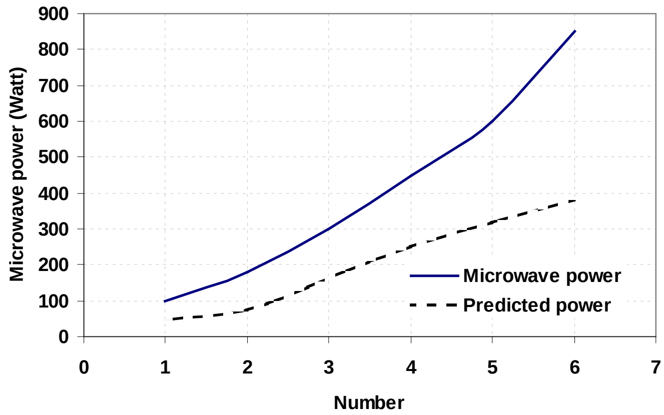

Fig. 6: Comparison of power between input microwave power and predicted values of the model (A dough with 0.0% salt concentration).

Fig. 7 presented the temperature and moisture profiles during microwave drying at 180 W and 1.0% salt concentration of dough. As shown in Fig. 7, this salt concentration value and microwave power density resulted in greater moisture removal and shorter drying duration. The visualization of finite element predictions for temperature distribution within dough is illustrated in Fig. 8 at 0, 18, 40 and 65 s after drying. The red regions show lower and the yellow region show higher temperature. As shown in Fig. 8a, the initial temperature distribution remains uniform in sample. Figs. 8b-d indicates that during drying process the moisture content throughout the dough is not quite uniform. As shown in Fig. 8d, the region with lowest temperature was observed to be away from the waveguide. For simulation results at 65 s, the highest temperature (110^{o}C) is observed at the region near waveguide. But the lowest temperature (45^{o}C) is observed at the region far from heat source.

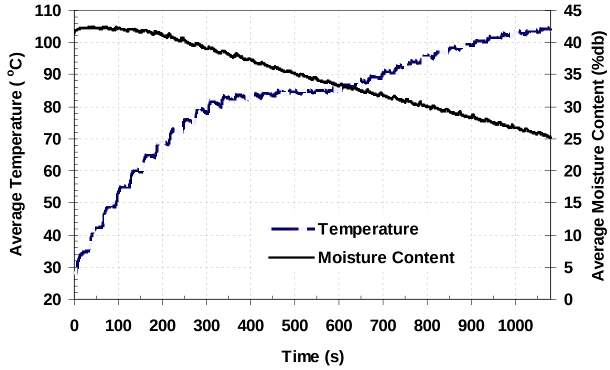

Fig. 7: Changes in t moisture content and temperature of dough during drying at microwave power of 180 W (A dough with 1.0% salt concentration).

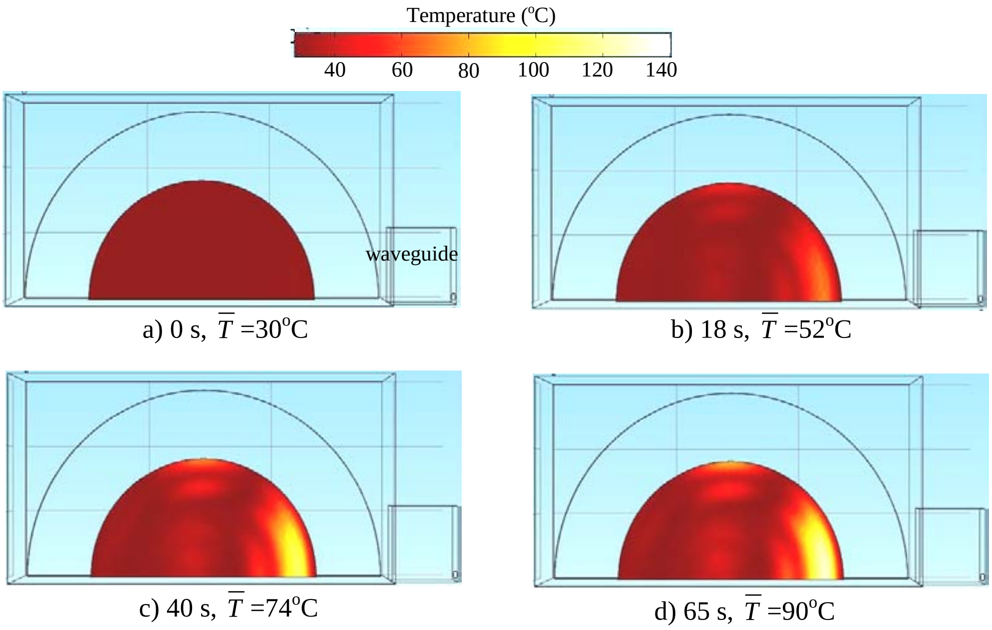

Fig. 8: Temperature distribution in the dough during drying at 300 Watt as a function of drying time. (A dough with 1.0% salt concentration).

Conclusion:

The finite element model predicted temperature in dough samples agreed with experimental results for low salt concentrations. The increasing temperature and heat distribution were directly depended on heating time and salt concentration in dough. Higher salt concentrations showed unrealistically high increases due to their greater dielectric loss factor. Thus, there appears to be a drying mechanism for loss of energy which the model is not accounting for. This simulation model can facilitate the design and operation of microwave drying of dough and can further apply to other foods.

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