International Proceedings of Chemical, Biological and Environmental Engineering, Vol. 86 (2015)
DOI: 10.7763/IPCBEE. 2015. V86. 7

Temperature Profile Prediction on Three Shapes of Banana Slices During Microwave Heating

Wisara Thuto and Kittichai Banjong [+]

Faculty of Agro-Industry, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

Abstract. This study focused on the influence of shape of banana slices on temperature profiles during microwave heating. In this regards COMSOL Multiphysics was used to simulate the three-dimensional computer model based on FEM and it satisfactorily predicted the temperature distributions inside banana slices, models were validated by comparing with temperature data obtained by an infrared thermometer. Three different shape of banana slices (transversal, longitudinal, and diagonal) was investigated, banana samples were heated by microwave at 800 W, 1 min. The most of heating occurs at the center of the samples were obtained in all cases, it can also be observed that temperature distribution is non-uniform within the sample throughout the process. The temperature in the center of the samples during heating were observed to increase faster than other region, that the hot spot was generated and it is evident from the profiles that the edges of sample happens to be slowest heating zone. A fairly good agreement was observed between the experimental and the simulated temperature profiles.

Keywords: temperature profile, Microwave heating, shape, banana, Multiphysics.

Nomenclature

$|\vec{E}|$ the time-harmonic electric field strength (V/m)

μ_r relative permeability

$\in_r$ relative permittivity

k_0 wave number

σ electrical conductivity (S/m)

ω angular frequency (rad/s)

ε_0 free space permittivity (8.854×10^{-12} F/m)

P_v dissipated power per unit volume (W/m^3)

f frequency (Hz)

ε'' relative dielectric loss factor

ρ density (kg/m^3)

C_p specific heat capacity at constant pressure (kJ/kg ^{o}C)

k thermal conductivity (W/m ^{o}C)

T temperature (^{o}C) at simulation time t

1. Introduction

Banana is an important food crop that grown widely in many tropical countries including Thailand. [1] About 82% of total banana production in Thailand is Kluai Namwa (*Musa* (ABB group)). [2] Banana can

[+] Corresponding author. Tel./fax: +66 2329 8526.
E-mail address: kbkittic@kmitl.ac.th

consumed in the fresh form and 80% of ripe banana is processed and is ingredient in many types of food such as baby food, banana streamed pastry, deep fried banana, sun-dried banana, sweet banana crisp and banana stirs. [3] Dried banana is a popular snack food in Thailand. There is a bright future for dried bananas for both internal consumption and export. The international market can also be promoted with dried bananas if the quality of dried banana can be maintained at international standard. However, most of bananas in Thailand are dried with the natural sun drying and dried bananas are usually contaminated by insects. [4]

Microwave heating has vast applications in the field of food processing over a period of several decades. The applications of microwave heating in food processing include drying, pasteurization, sterilization, thawing, tempering, baking of food materials etc. [5]-[7] Even though microwave heating is volumetric and hence is more uniform compared to many traditional heating methods, non-uniform temperature distribution is one of the major problems associated with the microwave heating. Due to non-uniform temperature distribution, few regions of the material get heated very rapidly, whereas the remaining region gets heated to a lesser extent. Because of uneven temperature distribution, microorganisms are not fully eradicated during microwave pasteurization. [7], [8] There are many factors affecting microwave heating uniformity including: dielectric properties (dielectric constant and dielectric loss factor), thermal properties (specific heat capacity and thermal conductivity) and physical properties (size, shape, density, and location in the package) of foods. [9], [10]

Although shape and investigations of shape are not new, they are rarely used to any great extent in food science. [11] The size and shape of the food materials affect the temperature distribution. Three different shapes such as, brick, cylinder and hexagonal prism with three different volumes were studied to determine non-uniform temperature distribution of potato samples. [7], [12]

Over the last two decades, computer simulation is becoming a promising tool to understand complex microwave heating with the availability of powerful computational techniques and the development of efficient numerical methods. A computer-based simulation of microwave heating of foods can assist in optimizing design of food systems and packages to improve food quality and safety. [10] A computer simulation of microwave heating of foods could facilitate proper designing of foods to assure microbial safety. Extensive modeling efforts have been made to simulate microwave heating using simple analytical approaches [13], [14] to computational approaches solved using numerical methods. Knowledge of the three dimensional temperature profile distribution of heated products is essential when optimizing microwave heating processes. [15], [16]

The objective of this work is to predict temperature profiles within the three different shape of banana slices subjected to microwave heating, the software COMSOL-Multiphysics will then be used to predict temperature profiles within the samples. Such discussions aim at improving the understanding of temperature profiles within the banana slices on three different shapes: transversal**,** longitudinal, and diagonal by microwave heating.

2. Materials and Methods

2.1. Governing Equations

The electromagnetic energy distribution inside an oven cavity is governed by Maxwell's wave form equation. [10], [17]

$$\nabla \times \mu_r^{-1}(\nabla \times \vec{E}) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega_0}\right) \vec{E} = 0 \tag{1}$$

An electromagnetic wave loses its energy while travelling through a losses dielectric medium such as food. Part of the electromagnetic power is converted into thermal energy within the food. Conversion of electromagnetic energy into thermal energy is proportional to the dielectric loss factor (ε'') and square of electric field strength: [10], [18]

$$P_v = \pi f \varepsilon_0 \varepsilon'' \left|\vec{E}\right|^2 \tag{2}$$

The dissipated power term (P_v, W/m^3) is a heat source term in transient heat transfer.

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + P_v \tag{3}$$

2.2. Computational Details

A commercial finite method based software package, COMSOL Multiphisics® 4.3 was used for geometry model building and temperature prediction. All these calculations were done on a workstation with a Intel® Core™ i7 (CPU speed 2.8 GHz) and RAM of 16 GB running a 64-bit Windows 7.

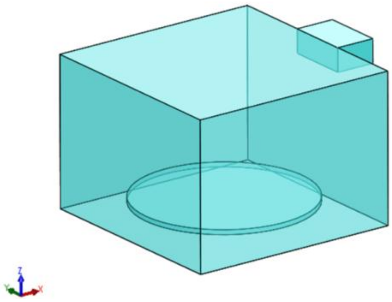

Fig. 1: Geometric model of 800W microwave oven.

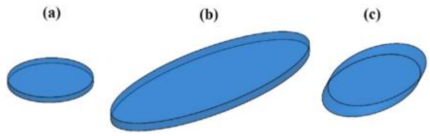

Fig. 2: Geometry of the samples (a) transversal (b) longitudinal (c) diagonal.

Geometric model was developed for a 800W rated power microwave oven (Model: ME711K, Samsung Electronics Co., Ltd.) with dimensions of 33.0×21.1×30.9 cm, representing width, height and depth, respectively. The geometric model included oven cavity, turntable and waveguide as shown in Fig. 1. An electromagnetic wave travels with certain patterns (modes) in the waveguide governed by the frequency and waveguide dimensions (5.0×1.8×7.8 cm.). The rectangular port is excited by a transverse electric (TE) wave, which is a wave that has no electric field component in the direction of propagation. At an excitation frequency of 2.45 GHz, the only propagating mode through the rectangular waveguide.

Fig. 2 presents the loads (banana samples) were trim cut to a uniform estimation size with three different geometries: transversal**,** longitudinal, and diagonal by original banana samples size were used for experiment to validation the model, each load placed on the center of a glass plate (turntable).

The size of the tetrahedral mesh elements was calculated in such a way that there would be at least 2 elements for every wavelength of microwaves in the given medium, so that the convergence could be achieved. [17] With the former criteria the number of tetrahedral elements ranged from 95,462 for the ‘‘extremely coarse’’ size option in COMSOL to 480,560 for the ‘‘extremely fine’’ option. The initial electric field distribution inside the material does not change beyond 98,345 elements, which corresponds to the elements size option ‘‘fine’’. Thus, 98,345 tetrahedral elements were selected for all the simulations. Meshing scheme implemented for oven cavity and the load as shown in Fig. 3.

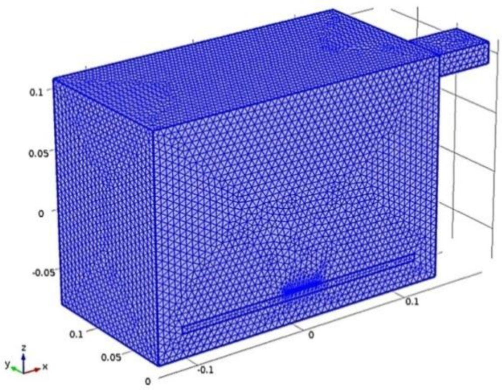

Fig. 3: Meshing scheme implemented for oven cavity and the load.

In order to simulate heat transfer in the banana samples during microwave heating, the following assumptions were considered.

- No chemical reaction takes place during heating.
- Uniform initial temperature and moisture distribution.

- The deformation in structure of sample were not considered.
- The mass and momentum transfer of moisture were not considered.
- External resistance to transport process was negligible.

The parameters used in model were found from literature are mentioned in Table 1.

Table 1: Summary of material properties and initial conditions used in the model.

Parameter	Value	Source
Density (ρ)	980 kg/m^3	[19]
Specific heat capacity (C_p)	3.35 kJ/kg °C	[20]
Thermal conductivity (k)	0.49 W/m °C	[21]
Dielectric constant (ε')	59.1	[22]
Dielectric loss factor (ε'')	18.9	[22]

2.3. Model Validation

Mature bananas (*Musa* (ABB group)) were obtained from a local supermarket. The bananas were chosen for the study: all yellow, none of brown speckles and also free of scars, cracking or splitting and scabbiness. Prior to heating, samples were peeled manually, cuts three different slice shapes were obtained: transversal**,** longitudinal, and diagonal. The transverse slices were obtained by cuts over the widest part of the sample. These slices had 3.0 cm and 0.6 cm for average diameter and height**,** respectively. The longitudinal slice was obtained by cuts over the longest part of the sample getting slices with average dimensions of 3.0×9.5×0.6 cm, representing length, width and height, respectively. Finally, the diagonal slice was obtained by cuts the sample each half at an angle and the average dimensions of this piece were 3.0 ×6.0×0.6 cm.

The heating was done in 800W microwave oven (Model: ME711K, Samsung Electronics Co., Ltd.) for 1 minute. One sample for each treatment was used and it was placed on the center of a glass plate. Every 20 seconds, the temperature of sample after heating was quickly measured using an infrared thermal thermometer, five selected points at different radial distances from the center of the samples at which temperature were measured. Each experiment was performed in triplicate and data were collected as average temperature.

3. Results and Discussion

The simulated results in terms of the temperature profiles were presented, average temperature profiles from simulation were compared with experimental data. A comparison between average experimental and simulated temperature data at the center of the samples for three different shapes during microwave heating for 1 minute as shown in Fig. 4. A fairly good agreement was observed between the average experimental and simulated values, the R-squared values are 0.9832, 0.9686 and 0.9679 for transversal, longitudinal, and diagonal, respectively.

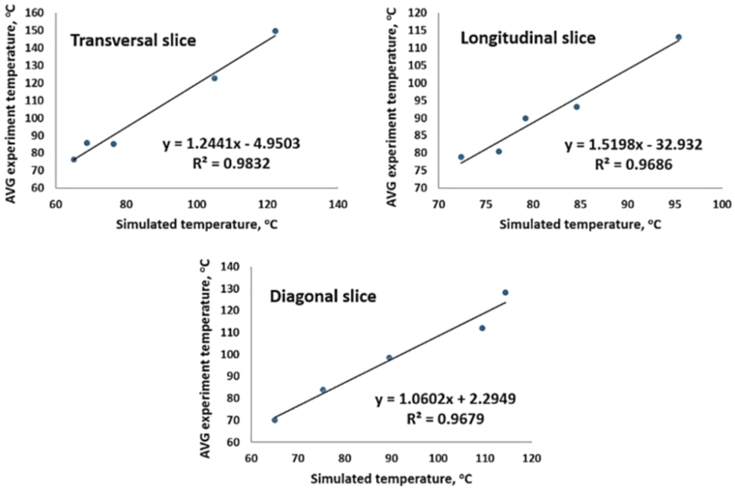

Fig. 4: Comparison of average experiment and simulated temperature of three different shapes of banana slice.

Fig. 5 presents change of temperature with time. They show how microwave heating is non-uniform when applying microwaves to the samples located in the center of a microwave oven. Faster heating of one part of the samples are evident and even hot spots can be identified. This is related with the distribution of the electric field inside applicator and consequently inside the plant. This kind of results is not surprising and has been previously reported in experimental works. [23]-[25] The time variation of temperature profile along the transversal sample is shown in Fig. 5a. The temperature distribution increases all the time from the center to outer regions of the sample. Similar to the diagonal sample, the simulated temperature profile shows banana slice did not reach higher temperature except on the center. The result shows the greatest temperature displays in the center of the samples with the temperature increasing towards the other regions of sample as shown in Fig. 5c. Fig. 5b depict temperature distribution inside the longitudinal sample, temperatures observed at the central axis regions along the length of the samples were slightly higher than at the other locations.

It was noticeable that most of heating occurs at the center of the test sample, it can also be observed that temperature distribution is non-uniform within the sample throughout the process. The temperature in the center of the samples during heating were observed to increase faster than other region, that the hot spot was generated and it is evident from the profiles that the edges of sample happens to be slowest heating zone. This provides a better insight of the slowest heating zone which is important to assess the effectiveness of any process involving heat transfer. [26], [27]

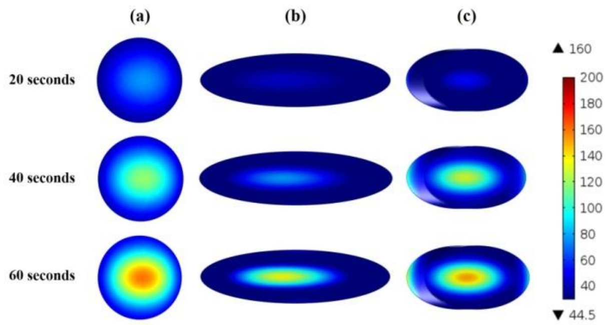

Fig. 5: Predicted results on temperature profiles of three different banana slices geometries (a) transversal (b) longitudinal (c) diagonal during 800W microwave heating, at 3 different time steps (20, 40, and 60 seconds).

The prediction of temperature from the simulations were also compared with digital photograph of actual banana samples used in experiments after 1 minute of microwave heating as shown in Fig. 6. It can be seen that the agreement between two final of heating patterns was qualitatively consistent, particularly in the hot spot region and it was also indicate that simulated results quite accurately.

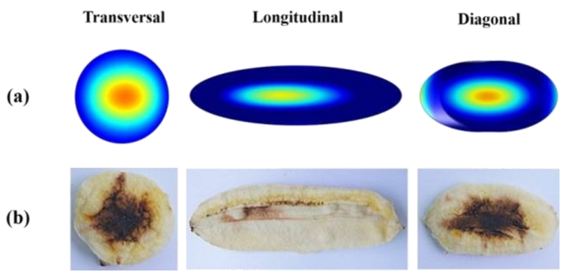

Fig. 6: Comparison of (a) predicted results (b) digital photograph of actual banana samples used in experiments after 1 minute of microwave heating.

In another study, hot spots were found to be at the center for spherical shaped products whereas for cylindrical products, high temperature was observed at the center as well as at the surface [7], [28] and the hot spots generally occur at the center than at other regions for slab shaped. [7]

4. Conclusions

To predict the temperature distributions of food sample during microwave heating, a computer model with a new simulation approach based on the finite element method was developed. The simulated results for the temperature profiles in three different shapes of banana samples are in agreement with experimental results. The quality of the predicted results illustrates that the 3D model of the heat distribution in the banana samples are satisfactory. In addition, this model provides a better understanding of the heat generation phenomenon inside the banana samples on three different shapes and can be used in the future for optimizing the microwave heating process.

The most of heating occurs at the center of the samples were obtained in all cases, it can also be observed that temperature distribution is non-uniform within the sample throughout the process. The temperature in the center of the samples during heating were observed to increase faster than other region, that the hot spot was generated and it is evident from the profiles that the edges of sample happens to be slowest heating zone. Thus, microbial safety of food products undergoing microwave treatment cannot be assured by measuring the temperature in few locations. The temperature profiles from model simulations can help identify the location of cold or hot spots and estimate temperature at several locations within the food product during microwave heating. Used properly, it has the potential to assist in microwave food product development for the identification of parameters to achieve better heating uniformity resulting in enhanced food safety.

Although good agreement was found between the predictions and measurements in this study, further development of this model is required. Many physical or chemical changes during microwave heating such as mass transfer and deformation are considered to be taken into account in future studies.

5. References

[1] DAE. *Grown areas of Thailand. Grown areas statistics*. Thailand: Department of Agricultural Extension. 2003, http://www.ssnet.doae.go.th/ssnet2/mis/kpp/rpt3_1.htm. 11/05/2008.

[2] J. Boonyanuphap, D.Wattanachaiyingcharoen and K. Sakurai. GIS-based land suitability assessment for *Musa* (ABB group) plantation. *Journal of Applied Horticulture*. 2004, 6(1): 3-10.

[3] N. Pisutpaisal, S. Boonyawanich and H. Saowaluck. Feasibility of Biomethane Production from Banana Peel. *Energy Procedia*. 2014, 50: 782 – 788.

[4] R. Smitabhindu, S. Janjai and V. Chankong. Optimization of a solar-assisted drying system for drying bananas. Renewable Energy. 2008, 33: 1523–1531.

[5] M. Gupta and W. L. E. Wong. *Microwaves and metals. Singapore*. John Wiley & Sons (Asia) Pte. Ltd., 2007.

[6] A. C. Metaxas and R. J. *Meredith. Industrial microwave heating*. London: Peter Peregrinus Ltd., 1983.

[7] S. Chandrasekaran, S. Ramanathan and T. Basak. Microwave food processing—A review. *Food Research International.* 2013, 52: 243–261.

[8] R. Vadivambal and D. S. Jayas. Non-uniform temperature distribution during microwave heating of food materials — A review. *Food and Bioprocess Technology*. 2010, 3: 161–171.

[9] H. Zhang and A. K. Datta. Coupled electromagnetic and thermal modeling of microwave oven heating of foods. *J. Microw. Power Electromagn. Energy*. 2000, 35 (2): 71–85.

[10] K. Pitchai, J. Chen, S. Birla, R. Gonzalez, D. Jones, and J. Subbiah. A microwave heat transfer model for a rotating multi-component meal in a domestic oven: Development and validation. *Journal of Food Engineering*. 2014, 128: 60–71.

[11] A. G. Flook. *Fourier analysis of particle shape. In N. G. Stanley-Wood, & T. Allan (Eds.), Particle size analysis*. Wiley Heyden Ltd., 1982.

[12] R. S. Vilayannur, V.M. Puri and R. C. Anantheswaran. Size and shape effect on nonuniformity of temperature and moisture distributions in microwave heated food materials: Part I simulation. *Journal of Food Process Engineering*. 1998, 21: 209–233.

[13] M. Watanabe, M. Suzuki, S. Ohkawa. Analysis of power density distribution in microwave ovens. *Journal of Microwave Power and Electromagnetic Energy*. 1978, 13 (2): 173–182.

[14] K. Pitchai, S.L. Birla, J. Subbiah, D. Jones and H. Thippareddi. Coupled electromagnetic and heat transfer model for microwave heating in domestic ovens. *Journal of Food Engineering*. 2012, 112: 100–111.

[15] K. Knoerzer, M. Regier and H. Schubert. Microwave heating: a new approach of simulation and validation. *Chemical Engineering & Technology*. 2006, 29: 796–801.

[16] D. Salvi, D. Boldor, G.M. Aita and C.M. Sabliov. COMSOL Multiphysics model for continuous flow microwave heating of liquids. *Journal of Food Engineering*. 2011, 104: 422–429.

[17] COMSOL, *COMSOL Multiphsics v4.3a manual*, 2013.

[18] A.K. Datta and R.C. Anantheswaran. *Handbook of Microwave Technology for Food Applications*. Marcell Dekker, Inc., 2001.

[19] S. O. Nelson. Dielectric Spectroscopy of Fresh Fruits and Vegetables. IMTC 2005 – Instrumentation and Measurement Technology Conference Ottawa, Canada, 17-19 May 2005.

[20] J. E. Lozano. Fruit Manufacturing: Scientific Basis, Engineering Properties, and Deteriorative Reactions of Technological Importance (Food Engineering Series). Springer, 2006.

[21] O. J. Ikegwu and F. C. Ekwu. Thermal and Physical Properties of Some Tropical Fruits and Their Juices in Nigeria. *Journal of Food Technology*. 2009, 7 (2): 38-42.

[22] Y. Huang. *Impact of Banana (Musa acuminata) ripening on resistant and non-resistant starch using hot-air and microwave drying*. Master of Science Thesis, Department of Bioresource Engineering, McGill University, Montreal, Canada, 2013.

[23] D. Dibben. Electromagnetics: fundamental aspects and numerical modeling. in: Datta, A.K., Anantheswaran, R.C. (Eds.), *Handbook of Microwave Technology for Food Applications*, CRC Press, 2001.

[24] H. Zhang and A.K. Datta. Electromagnetics of microwave heating: magnitude and uniformity of energy absorption in an oven. in: Datta, A.K.,Anantheswaran, R.C.(Eds.), Hand book of Microwave Technology for Food Applications, CRC Press, 2001.

[25] A. Navarrete, R.B. Mato and M.J. Cocero. A predictive approach in modeling and simulation of heat and mass transfer during microwave heating. Application to SFME of essential oil of Lavandin Super. *Chemical Engineering Science*. 2012, 68: 192–201.

[26] R. Padmavati and C. Anadharamakrishnan. Computational fluid dynamics modeling of the thermal processing of canned pineapple slices and titbits. *Food Bioprocess Technol*. 2013, 6 (4): 882–895.

[27] J. Aprajeeta, R. Gopirajah and C. Anandharamakrishnan. Shrinkage and porosity effects on heat and mass transfer during potato drying. *Journal of Food Engineering*. 2015, 144: 119–128.

[28] L.A. Campanone and N. E. Zaritzky. Mathematical analysis of microwave heating process. *Journal of Food Engineering*. 2005, 69: 359–368.