CST0017

The Effect of Microwave Frequency on Temperature Profiles and Electric Field in a Natural Rubber Glove during Microwave Heating

Pornthip Keangin[1,*], Ukrit Narumitbowonkul[1], Suchai Pongpakpien[2] and Phadungsak Rattanadecho[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, Mahidol University,
25/25 Phutthamonthon 4 Road, Salaya, Nakhon Pathom, 73170, Thailand.
[2]Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus),
99 mu 18, Paholyothin Road, Klong Nueng, Klong Luang, Pathumthani, 12120, Thailand.
*Corresponding Author: E-mail: pornthip.kea@mahidol.ac.th, Tel.: +66 2 8892138 Ext. 6401-3, Fax: +66 2 8892138 Ext. 6429

Abstract

Natural rubber glove (NRG) is a glove made out of natural rubber (concentrate latex). The primary purpose is to protect hands during performing tasks involving chemicals as well as be used in medical. Generally, in the manufacture of NRG often used conventional heating from hot air. It takes a long time in heating and can cause heat distribution uneven, resulting in NRG dry not smooth. To pursue the new ways to eliminate problems in the conventional heating method, the application process heating in the microwave energy is one attractive choice. Several advantages of microwave heating are effective to heat and maintain the quality of the product due to volumetric heating. This research aims to propose the effects of microwave frequency and position on temperature profile and electric field in a NRG due to heating with microwave energy within the microwave oven. The effects of variations at the microwave frequencies of 2.45 GHz, 2.75 GHz and 3 GHz on temperature profile and electric field are systematically investigated. The transient Maxwell's equation coupled with the transient heat transfer equation is solved by using the finite element method (FEM). The numerical simulation results with computer programs are validated with experimental results. Three-dimensional models of NRG and microwave oven are considered. The obtained results can be used as a basis for develop heating process of NRG by microwave energy in the industry.

Keywords: Electric field, Finite element, Heat transfer, Microwave heating, Natural rubber glove

1. Introduction

Natural rubber (NR) is important to everyday life. NR is an elastomer that has greater flexibility compared to synthetic rubbers; therefore, NR is used to produce various products. It can be found in a lot of forms such as tire, rubber soles, rubber band, gloves, hoses and medical equipment, etc. It can also be used as main material in the production of natural rubber gloves (NRG) [1-2]. The NRG manufacturing process starts with dipping liquid latex which mixed with various compounding chemicals. The NRG manufacturing apparatus includes the hand-shaped formers which one controlled to move along system at first station through a last station. The heating process consists of two phases, namely the pre-heating at 70-90 °C and post-heating 110-120 °C [3]. Main problems of productions in NRG industries are the lack of basic knowledge on rubber technology lead to no manufacturing process improvement and the lack of research and development of new products to meet the needs of their target market, especially the problems during the heating of NRG.

The conventional heating method using hot air is mostly used of heating process for NRG heating. Of many previous studies on hot-air vulcanized of NRG [2-6]. Khamdaeng et al. [5] analyzed the rubber deformation to describe the deformation behavior of the combined infrared and hot-air vulcanized of rubber glove. The conventional heating, which is the heat input to the surface of the material, make for problems with thick material, the material were not heat evenly [7]. Therefore, to improve the efficiency of conventional heating methods, the researchers are trying to find new ways of NRG heating.

Microwave energy is one heat source that is an attractive alternative over conventional heating methods because the microwave energy that penetrates into the material will be absorbed and converted into internal energy in the material [8-9]. Microwave technology has several advantages, such as effective to heat and maintain the quality of the product due to volumetric heating, minimizing the heating times, the energy used is clean energy, no emissions, smaller machines and low cost maintenance, etc. Many successful examples of microwave application, including drying of foods, drying of textiles and vulcanizations of rubber. For example, previous studied on vulcanization of the natural rubber with the microwave energy can be found in the research [10-13]. Some research studied of the natural rubber heating process using rectangular wave guide [14-15]. Doo-ngam et al. [14] studied microwave pre-heating of natural rubber using a rectangular wave guide (TE10 Mode). Makul and Rattanadecho [15] presented a new method to pre-cure natural rubber-compounding (NRc) by using microwave energy at a frequency of 2.45 GHz with a rectangular wave guide. Although most of previous investigations considered simulation or experimental of microwave heating in NRG, a little effort has been reported of multi-dimensional heating process of NRG due to microwave heating, especially, full comparison between simulation results with experimental data of three-dimensional NRG and microwave oven models. Narumitbowonkul et al. [16] presented the numerical and experimental analysis of drying process of NRG using microwave energy at a frequency of 2.45 GHz with microwave oven. The influences of physical parameters, i.e., heating time, NRG size and microwave power input were studied.

However, a few works have carried out systematic studies of the effects of microwave frequency and position on the temperature profile and electric field in a NRG during microwave heating. In practical situations, the microwave frequency effects enhance the temperature profile and electric field within the NRG, which can cause changes in temperature within the NRG. In addition, most of previous studies were considered the dielectric properties of NRG to be are constant. However, the changes in the dielectric properties of NRG are expected to lead to changes in the position of microwave energy deposition within the NRG. Therefore, in order to provide adequate information on the appropriate level of microwave heating of NRG, it is essential to consider all of the previously mentioned parameters in the analysis.

In this study, the influences of microwave frequency and position on temperature profile and electric field in a NRG due to heating with microwave energy within the microwave oven have been investigated. The effects of variations at the microwave frequencies of 2.45 GHz, 2.75 GHz and 3 GHz on temperature profile and electric field are studied. The transient Maxwell's equation coupled with the transient heat transfer equation is solved by using the finite element method (FEM) via COMSOL^{TM} Multiphysics. The dielectric properties of NRG as a function of microwave frequency are considered. The numerical simulation results with computer programs are validated with experimental results with same model and same conditions. Three-dimensional models of NRG and microwave oven are proposed. This investigation provides the essential aspects for a fundamental understanding of temperature profiles and electric field within NRG during microwave heating and can be used as a guideline to develop heating process of NRG energy in the industry.

2. Experimental Study

The experimental apparatus is shown in Fig. 1. A microwave oven cavity has dimensions of 310 × 280 × 190 mm^3 (axial: x, y and z, respectively) . The frequency of microwave inside the microwave oven operates at a frequency of 2.45 GHz. The microwave power input of 100 W is considered. To set up an experiment, start from the dipping ceramic hand-shaped former in natural rubber latex (NRL) with thickness 0.5 mm to make NRG. The NRG placed in center of microwave oven and vertically along the waveguide area. Magnetron generates microwave and transmitted through wave guide, with inside dimensions of 79 x 43 mm^2 toward NRG that is situated at the center of microwave oven. The temperature of NRG measured in experimental using thermocouple K-type at various heating times during microwave heating [17-18] and recorded temperature data by data logger (Wisco DL2200 Data Logger). The equipment setup is shown in Fig. 1. Fig. 2 illustrates the measuring temperature of NRG inside the microwave oven. The recording during microwave operating use the data logger for record 5 positions (A1-A5) of temperature, which data logger is shown in Fig. 3. Fig. 4 displays the positions A1-A5 for measuring the temperature distribution within the NRG with L = 45 mm. The NRG size M is used in the study. The dimension of NRG size M is J = 110 mm and K = 200 mm. An initial temperature of NRG is 24°C for all cases. The heating times of 300 s are considered to represent the period of microwave heating. The temperature distribution from the experimental results various temperature measuring positions (A1-A5) at microwave power input of 100 W and NRG size M at heating times of 60 s, 180 s and 300 s are systematically investigated.

Fig. 1 Equipment setup;
(1) Microwave oven
(2) Data logger (Wisco DL2200)
(3) Thermocouple

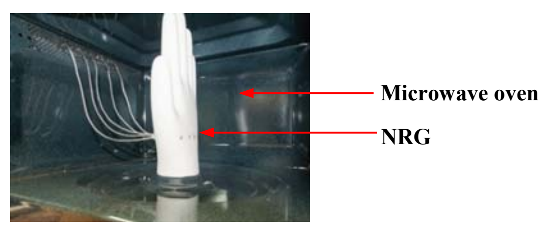


Fig. 2 Measuring temperature of NRG inside the microwave oven

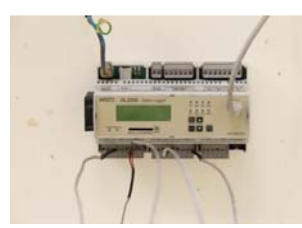


Fig. 3 Data logger (Wisco DL2200 Data Logger)

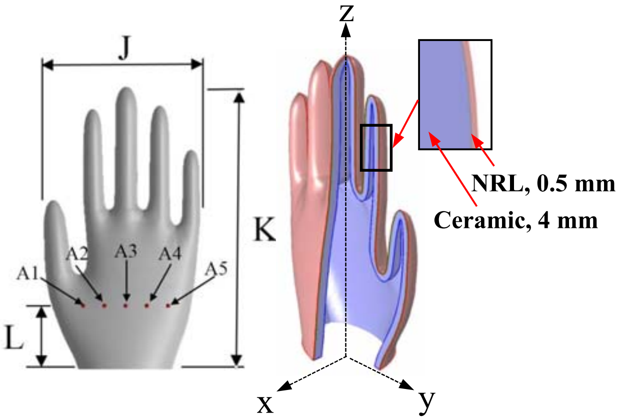


Fig. 4 The positions A1-A5 for measuring the temperature distribution within the NRG

3. Simulation Study

3.1 Physics Model Formulation

In Fig. 5 shows the schematic diagram of the physics models of NRG and microwave oven for numerical analysis. The dimension of microwave oven cavity and rectangular wave guide in numerical study is the same as the dimension in experimental study. Full three-dimensional models of NRG and microwave oven are considered to identify the microwave heating phenomena in a NRG. The thickness of NRL is 0.5 mm and thickness of ceramic is 4 mm in experiment analysis used in numerical simulation analysis with the same conditions. The NRG is subjected to a uniform microwave via a wave guide. Microwave irradiation can penetrate the NRG surface and is converted into thermal energy within the NRG. This results in a very rapid temperature increase throughout the NRG that may lead to dry NRG.

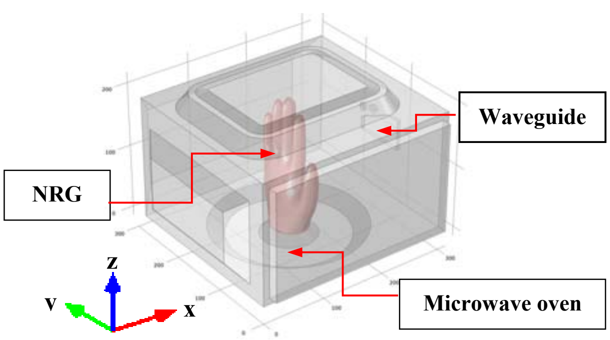


Fig. 5 Physical models for numerical analysis

3.2 Analysis of Electromagnetic Wave Propagation

A mathematical model is formulated to predict the temperature profiles and electric field within the NRG during the microwave heating process. This research is carried on the following assumptions:

1) The mathematical model of heating of NRG by microwave in the multi-mode is purposed.

2) The absorbed energy by air in a microwave oven is negligible.

3) The walls of the microwave oven are impedance and waveguide is perfect conductors.

4) The model assumes that dielectric properties of NRG and ceramic properties depend on microwave frequency.

The electromagnetic wave propagation in NRG is calculated using Maxwell's equations which mathematically described the interdependence of the electromagnetic waves. The general form of Maxwell's equations is simplified to demonstrate the electromagnetic fields penetrated in NRG as the following equation [19]:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \left(\varepsilon_r' - \frac{j\sigma}{\omega \varepsilon_0} \right) \vec{E} = 0 \qquad (1)$$

where $\vec{E}$ is the electric field intensity (V/m), μ_r is the relative magnetic permeability (H/m), ε_r' is the relative dielectric constant, ε_0 = 8.8542x10^{-12} (F/m) is the permittivity of free space, and σ is the electric conductivity (S/m), $\varepsilon_r = n^2$ and n is the refractive index.

The boundary condition for analyzing electromagnetic field, as shown in Fig. 6, is considered as follows:

In numerical simulation analysis, the NRG subjected to a uniform microwave power input on the left side corresponded to the position of waveguide of microwave oven in the experimental. The port power level and port phase of wave excitation at this port of microwave oven. The power flux associated with a propagating electromagnetic wave is represented by the poynting vector. Therefore, at the left boundary of the considered domain, an electromagnetic wave propagation simulator employs are the port boundary condition as follows [20]:

$$S = \frac{\int \left(\vec{E} - \vec{E}_1 \right) \cdot \vec{E}_1}{\int \vec{E}_1 \cdot \vec{E}_1} \qquad (2)$$

In addition, the propagation constant is defined as:

$$\beta = \frac{2\pi}{c} \times \sqrt{f^2 - \frac{c^2}{4 \times a^2}} \qquad (3)$$

where β is the propagation constant, a = 3.4 inch is the depth dimension of waveguide, c = 3x10^8 (m/s) is the speed of light and f = 2.45 GHz is the operating frequency of the microwave generator.

The walls surfaces of the microwave oven are impedance boundaries are applied:

$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r - j\frac{\sigma}{\omega}}}\hat{n}\times\vec{H} + \vec{E} - (\hat{n}\cdot\vec{E})\hat{n} = (\hat{n}\cdot\vec{E}_s)\hat{n} - \vec{E}_s \tag{4}$$

The waveguide of the microwave oven are good conductors. Therefore, the wall of waveguide as perfect conductor boundaries:

$$\hat{n}\times\vec{E} = 0 \tag{5}$$

The internal boundary along the interfaces between NRL and the ceramic is considered as continuity boundary conditions (no contact resistant occurs) as shown in Fig. 6 and as follows:

$$\hat{n}\times(E_{NRL} - E_{air}) = 0 \tag{6}$$

$$\hat{n}\times(H_{NRL} - H_{air}) = 0 \tag{7}$$

3.3 Analysis of Heat Transfer

Heat transfer analysis of microwave heating in NRG is solved to illustrate the temperature profiles and it is considered only in a NRG. To reduce complexity of the problem, several assumptions have been offered into the heat transfer equations:

1) Corresponding to electric field distribution, considering temperature distribution can be assumed to be three-dimensional.
2) There is no phase change of substance in the NRG.
3) There is no chemical reaction in the NRG.
4) The contact surface of NRG is assumed to be smooth.
5) The effect of shrinkage of NRG is negligible.
6) The model assumes that thermal properties of NRG and ceramic are constant.

The heat transfer equation describing the heat transport in a NRG is identical as given by [16]:

$$\rho C_p \frac{\partial T}{\partial t} - k\nabla^2 T = Q \tag{8}$$

where ρ is the density (kg/m^3), C_p is the heat capacity (J/kg·K), T is the temperature (°C), k is the thermal conductivity (W/m·K) and Q is the external heat source term (W).

In Eq. (8), the first and second on the left-hand side of equation denoted the transient term and heat conduction term. While, the term Q appeared on the right-hand side of equation denote the external heat source term, respectively. The external heat source term is equal to the resistive heat generated by the electric field (microwave power absorbed), which is a function of the electric field, relative dielectric loss factor, loss tangent coefficient and frequency are defined as Eq. (9):

$$Q = 2\pi f\varepsilon_0\varepsilon_r'(\tan\delta)\vec{E}^2 \tag{9}$$

where $\tan\delta$ is the loss tangent coefficient. The electric field in our external heat source term is calculated through the electromagnetic wave propagation analysis.

Consistent with the assumption, the boundary condition for analyzing heat transfer, as shown in Fig. 6, is considered as follows:

The surface of NRL and ceramic are assumed to be a thermal insulation boundary condition:

$$-\hat{n}\cdot(-k\nabla T) = 0 \tag{10}$$

Boundary conditions along the interfaces between NRL and ceramic glove mold former are considered as continuity boundary condition:

$$T_{NRL}(x_0,t) = T_{Ceramic}(x_0,t) \tag{11}$$

$$-k_{NRL}\frac{\partial T(x_0,t)}{\partial x} = -k_{Ceramic}\frac{\partial T(x_0,t)}{\partial x} \tag{12}$$

where k_{NRL} and $k_{Ceramic}$ are the thermal conductivities of the NRL layer and ceramic layer, respectively.

The dielectric properties can be written in the general form of complex permittivity (ε). The complex permittivity is a function of dielectric constant and dielectric loss factor as defined by [10]:

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0(\varepsilon_r' - j\varepsilon_r'') \tag{13}$$

where ε'' is the dielectric constant, ε' is the dielectric loss factor, ε_r' is the relative dielectric constant and ε_r'' is the relative dielectric loss factor.

4. Calculation Procedure

The numerical modeling is utilized to perform the FEM to analyze the transient problems. In this study, the transient Maxwell's equation coupled with the transient heat transfer equation and related boundary conditions are numerically simulated using FEM with COMSOL™ Multiphysics software to demonstrate the phenomenon that occurs within the NRG during microwave heating. The computational scheme starts with computing an external heat source term by running an electromagnetic wave propagation calculation using dielectric properties and subsequently solves the time dependent temperature using thermal properties. All the steps are repeated until the required heating time is reached. Due to the fact that phase transition is included in the problem, the time-steps must be small enough.

The three-dimensional FEM model is discretized using triangular elements with the Lagrange quadratic shape functions. In order to obtain a good approximation, a fine mesh is specified in the sensitive areas. This study demonstrates the numbers of elements for solving the problem. The convergence test is carried out to identify the suitable numbers of element required and to assure that the transient solution is accurate. The number of elements where solution is independent of mesh density is found to be around 431,110 elements. Fig. 7 shows the three-dimensional finite element mesh of physical model The NRG is assumed to be homogeneous and electrically as well as thermally isotropic.

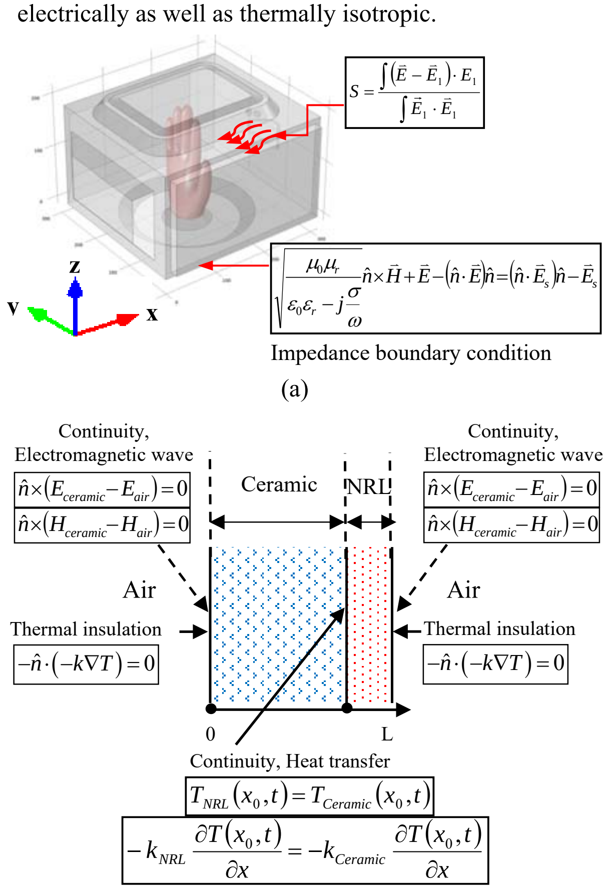


Fig. 6 The boundary condition for numerical analysis (a) inside of microwave oven and (b) inside of NRG

The model assumes that dielectric properties of NRG and ceramic properties is a function of microwave frequency. However, the thermal properties of NRG and ceramic are assumed to be constant, that are not frequency dependent because of it has a little bit change with this frequency range during microwave heating. The physical properties of the materials involved in the model are selected from several literatures [21-25]. The dielectric properties and thermal properties of NRL and ceramic are given in Tables 1 and 2, respectively. The effects of microwave frequency on temperature profile and electric field of NRG heating by microwave energy obtained from numerical simulation are studied in this research.

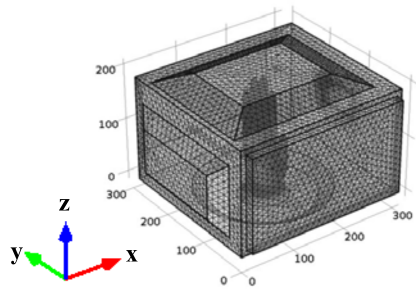


Fig. 7 Three-dimensional finite element mesh of physical model

5. Results and Discussion

To verify the accuracy of the present numerical model, the simulation results are validated against the experiment results with the same geometry and same conditions. The comparison of NRG temperature distribution of simulation results with the experiment results various heating times based on microwave power input (P) of 100 W and NRG size M are displayed in Fig. 8. Consider the temperature distribution at the position A1, A2, A3, A4 and A5 as shown in Fig. 8, it can be seen that the temperature distributions in NRG of simulation results are in excellent agreement with the temperature distributions in NRG of experiment data. Certain amounts of mismatch between the simulation results and the experiment results are caused by the numerical scheme. The temperature distribution from the simulation and experiment results gradually increase at position point A1 and A2 to a maximum at position point A3 after that the temperature distribution decreases at position point A4 and A5. Fig. 8 also shows that at position point A3 or approximate the center of NRG has the maximum temperature. In addition, Fig. 8 also indicates that an increase in the heating times results in an increase temperature distributions. This favorable comparison lends confidence in the accuracy of the present numerical model.

The next section, the effects of microwave frequency on temperature profile and electric field in a NRG exposed to microwave heating is illustrated. The basic principle of microwave heating is to apply microwave power to the NRG through the waveguide. The microwave energy is absorbed within the NRG and heated it. Fig. 9 shows the simulation results of electric field and temperature profile in the NRG during microwave heating various microwave frequencies based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M.

The effects of microwave frequency on electric field and temperature profile of 2.45 GHz in x-y plane, 2.75 GHz in x-y plane, 3 GHz in x-y plane, 2.45 GHz in z-x plane, 2.75 GHz in z-x plane and 3 GHz in z-x plane are displayed in Fig. 9(a), 9(b), 9(c), 9(d), 9(e) and 9(f), respectively. The results show that the microwave frequencies have significant effect on the electric field and temperature profile in the NRG. When the electromagnetic field released from the waveguide of microwave oven, the electromagnetic field will induce an electric field. From the figure, the electric field move from the right-hand side to the left-hand side and move into the NRG. Electric fields cause the heat on the NRG. This is because when an electric field propagates in the NRG, it is absorbed by the medium and converted into internal heat generation, which causes its temperature to rise. It is found that the electric field intensity in the palm of the NRG and intensity toward the area on the index finger and middle finger, it resulted in very high temperatures in this zone. Considering the influences of the microwave frequency on the electric field in each plane, it can be seen that in x-y plane at low frequency of 2.45 GHz has the electric field intensity than the higher frequency of 2.75 GHz and 3 GHz, respectively. However, in z-x plane the simulation results that are the opposite of the results in x-y plane. Higher frequency of 3 GHz and 2.75 GHz has higher electric field intensity than the frequency of 2.45 GHz, respectively. Regard to the result, it cannot conclude with certainty. This is probably due to the characteristic of electromagnetic waves in a cavity, are multi-mode and uncertain direction. In addition, it may also depend on the absorption of the material under electric field.

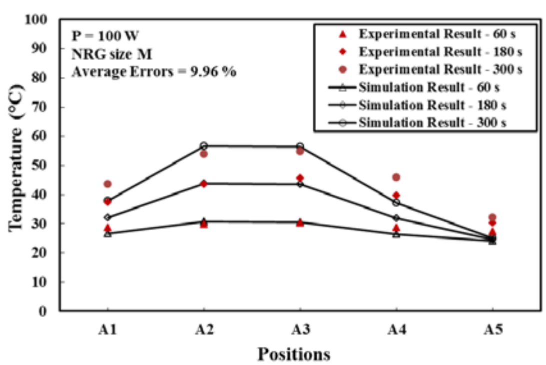


Fig. 8 The comparison of NRG size M temperature distribution (°C) of simulation results with the experiment results various heating times at microwave power input of 100 W.

The simulation results of profiles of temperature in the NRG during microwave heating various microwave frequencies based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M are shown in Fig. 10. The effects of microwave frequency on temperature profile of 2.45 GHz, 2.75 GHz and 3 GHz in the front side of the NRG are illustrate in Fig 10(a), 10(b) and 10(c), respectively, while the temperature profile of 2.45 GHz, 2.75 GHz and 3 GHz in the back side of the NRG are show in Fig 10(d), 10(e) and 10(f), respectively. From the figures, the results show that at microwave frequency of 3 GHz has more hot spot zone than at frequency 2.75 GHz and 2.45 GHz. Moreover, at frequency of 3 GHz has the higher temperature of the maximum temperature than at microwave frequency of 2.75 GHz and 2.45 GHz too. It found that the maximum temperatures at microwave frequency of 3 GHz is 193.11 °C, microwave frequency of 2.75 GHz is 161.95 °C and microwave frequency of 2.45 GHz is 68.21 °C, respectively. This result is according to the results of the electric field in plane z-x from Fig. 9(d), 9(e), and 9(f). This is because the NRG are influenced under strong electric field, the increasing electric field intensity level provides more energy absorption, and then energy is converted to thermal energy as well as increased temperature, as shown in Eq. (9).

Fig. 11 shows the relationship between temperature distributions and positions in a NRG from simulation analysis various microwave frequencies. The condition tests based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M. It is found that the results of Fig. 11 corresponding to the previous results of Fig. 10. At microwave frequency of 3 GHz, the NRG has temperature higher than at microwave frequency of 2.75 GHz and 2.45 GHz, respectively. However, at position A3, A4 and A5 at microwave frequency of 2.45 GHz has higher temperature then at microwave frequency of 2.75 GHz, as a result of the influence of non-uniform electric field. In addition, it can be seen that the at microwave frequency of 2.45 GHz, the temperature distribution results gradually increase at position point A1 and A2 to a maximum at position point A3 after that the temperature distribution decreases at position point A4 and A5. Nevertheless, at microwave frequency of 2.75 GHz and 3 GHz, the temperature distribution results gradually increase at position point A1 and A2 after that the temperature distribution is gradually decreases because of its dielectric properties.

6. Conclusions

This study presents the numerical simulation of temperature profiles and electric field in NRG during microwave heating in various microwave frequencies. Parametric studies on thermal enhanced effects of microwave frequencies for achieving the optimum condition for NRG due to microwave energy. The transient electromagnetic wave propagation coupled with the transient heat transfer equation is solved by using the FEM. The three-dimensional model of NRG and microwave oven are considered in this work. The numerical model is validated with an experimental study. The results show that the numerical results are in agreement with the experimental results. It is found that the temperature profiles and electric field increases with increasing microwave frequency. The hot spot zone and maximum temperature appears on palm of the NRG and area of middle finger. The obtained values provide an indication of guidance for the study of microwave heating of NRG in industry. However, this studies just a preliminary study which is using microwave oven. Consequently, the research of the future might be to study the microwave heating of NRG with the larger microwave oven size. Moreover, the study of increasing number of waveguides will be proposed in future work.

7. References

[1] Ismail, H., Tan, B.K., Suharty, N.S. and Husseinsyah, S. (2015). Comparison of the effects of palm oil Ash, carbon black and halloysite nanotubes on the properties of polypropylene/recycled natural rubber glove composites, *Journal of Physical Science*, vol. 26(2), pp. 89 – 99.

[2] Hayeemasae, N., Ismail, H., Khoon, T.B., Husseinsyah, S. and Harahap, H. (2016). Effect of carbon black on the properties of polypropylene/ recycled natural rubber glove blends, *Progress in Rubber, Plastics and Recycling Technology*, vol. 32(4), September 2015, pp. 241 – 252.

[3] Jirasukprasert, P., Garza-Reyes, J.A., Soriano-Meier, H. and Rocha-Lona, L. (2012). A case study of defects reduction in a rubber gloves manufacturing process by applying six sigma principles and DMAIC problem solving methodology, paper presented in *the Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management Istanbul 2012*, Turkey.

[4] Roberts, A.D. and Brackley, C.A. (1990). Surface treatments to reduce friction: rubber glove Applications, *Rubber Chemistry and Technology*, vol. 63(5), November 1990, pp. 722 – 733.

[5] Khamdaeng, T., Panyoyai, N. and Wongsiriamnuay, T. (2014). Material parameter of rubber glove vulcanized using combined infrared and hot-air heating, *American Journal of Applied Sciences*, vol. 11(4), August 2014, pp. 648 – 655.

[6] Ramli, R., Jaapar, J., Jaswan Singh, M.S., Maqsood Ul Haque, S.N.S. and Yatim, A.H.M. (2016). Characterizing mechanical properties of peroxide-vulcanized natural rubber latex films, *Advanced Materials Research*, vol. 1134, December 2015, pp. 236 – 242.

[7] Metaxas, A.C. (1991). Industrial microwave heating. Peter Peregrinus Ltd., London. 1991.

[8] Chen, H.L., Li, T., Liang, Y., Sun, B. and Li, Q.L. (2016). Experimental study of temperature distribution in rubber material during microwave heating and vulcanization process, *Heat and Mass Transfer*, July 2016, pp. 1–10.

[9] Cha-um, W., Rattanadecho, P. and Pakdee, W. (2009). Experimental analysis of microwave heating of dielectric materials using a rectangular wave guide (MODE: TE10) (Case study: water layer and saturated porous medium), *Experimental Thermal and Fluid Science*, vol. 33(3), November 2008, pp.472 – 481.

[10] Rattanadecho, P. and Makul, N. (2016). Microwave-assisted Drying: A review of the state-of-the-art, *Drying Technology An International Journal*, vol. 34(1), May 2015, pp. 1 – 38.

[11] Martin, D., Ighigeanu, D., Mateescu, E., Craciun, G., Ighigeanu, A. (2002). Vulcanization of rubber mixtures by simultaneous electron beam and microwave irradiation, *Radiation Physics and Chemistry*, vol. 65(1), August 2002, pp. 63 – 65.

[12] Sombatsompop, N. and Kumnuantip, C. (2006). Comparison of physical and mechanical properties of NR/carbon black/reclaimed rubber blends vulcanized by conventional thermal and microwave irradiation methods, *Journal of Applied Polymer Science*, vol. 100(6), June 2006, pp. 5039 – 5048.

[13] Zou, H., Shuhuan, L., Zhang, L., Yan, S., Wu, H., Zhang, S. and Tian, M. (2011). Determining factors for high performance silicone rubber microwave absorbing materials, *Journal of Magnetism and Magnetic Materials*, vol. 323(12), June 2011, pp. 1643 – 1651.

[14] Doo-ngam, N., Rattanadecho, P., and Klinklai, W. (2007). Microwave pre-heating of natural rubber using a rectangular wave guide (MODE: TE10), *Songklanakarin Journal Science and Technology*, vol. 29(6), November 2007, pp. 1599 – 1608.

[15] Makul, N. and Rattanadecho, P. (2010). Microwave pre-curing of natural rubber-compounding using a rectangular wave guide, *International Communication in Heat and Mass Transfer*, vol. 37(7), April 2010, pp. 914 – 923.

[16] Narumitbowonkul U., Keangin P. and Rattanadecho P. (2014). Experimental and numerical analysis of drying natural rubber glove by microwave energy, paper presented in *the 5th TSME International Conference on Mechanical Engineering 2014*, Chiang Mai, Thailand.

[17] Olmstead, W.E. and Brodwin, M.E. (1997). A model for thermocouple sensitivity during microwave heating, *International Journal of Heat and Mass Transfer*, vol. 40(7), May 1997, pp. 1559 – 1565.

[18] Potter, D. (1996). Measuring temperature with thermocouples – a tutorial, *National Instruments Corporation*, November 1996, pp. 1 – 15.

[19] Wessapan, T., Srisawatdhisukul, S. and Rattanadecho, P. (2011). The effects of dielectric shield on specific absorption rate and heat transfer in the human body exposed to leakage microwave energy, *International Communications in Heat and Mass Transfer*, vol.38, December 2010, pp. 255 – 262.

[20] COMSOL Multiphysics Reference Guide 1998–2012 COMSOL Protected by U.S. Patents 7,519,518; 7,596,474; and 7,623,991. Patents pending.

[21] Rands, R.D., Ferguson W.J. and Prather, J.L. (1944). Specific heat and increases of entropy and enthalpy of the synthetic rubber GR-S from 0° to 330°

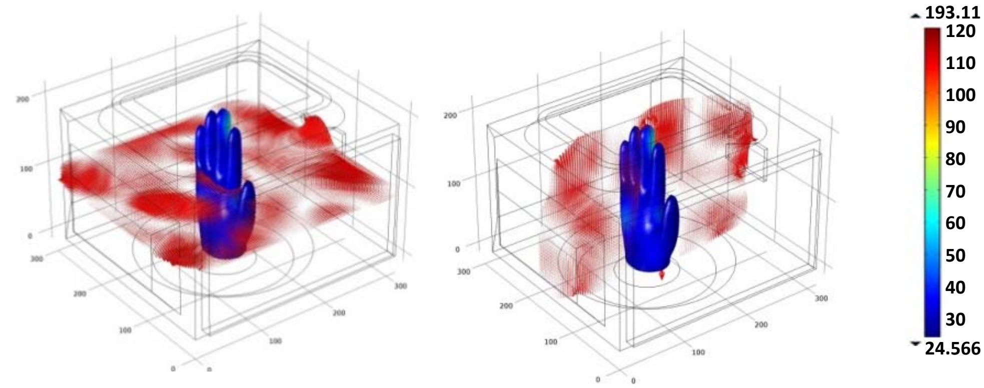
K, *Journal of Research of the National Bureau of Standards*, vol. 33, July 1944, pp. 63 – 70.

[22] Khalid, K.B. (1992). Microwave dielectric properties of hevea rubber latex. , paper presented in *the Microwave Conference, APMC 92. Asia-Pacific*, vol. 2, pp. 611 – 616.

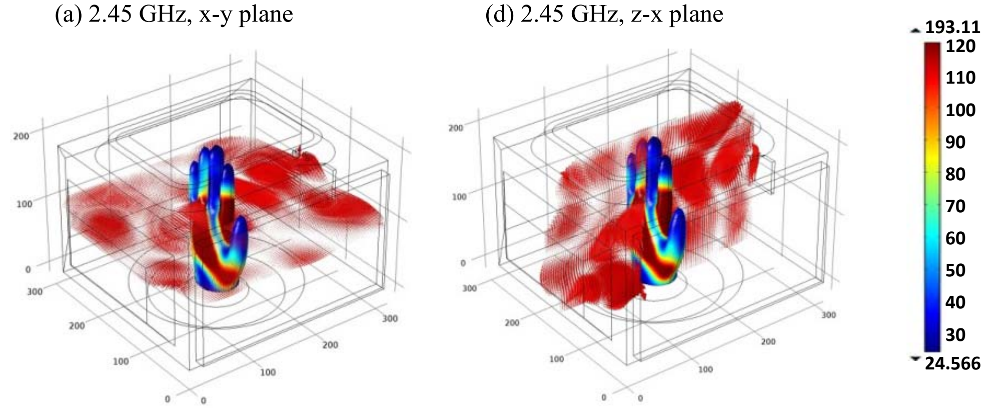
[23] Hassan, J., Khalid, K., Mohammad, W. and Yusoff, D.W. (1997). Microwave dielectric properties of hevea rubber latex in the temperature range of -30 °C to 50 °C, *Pertanika Journal of Science & Technology*, vol. 5(2), pp. 179 – 190.

[24] Sridee, J. (2006). Rheological properties of natural rubber latex, *A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Polymer Engineering Suranaree University of Technology Academic Year 2006*, ISBN 974 – 533 – 588 – 6.

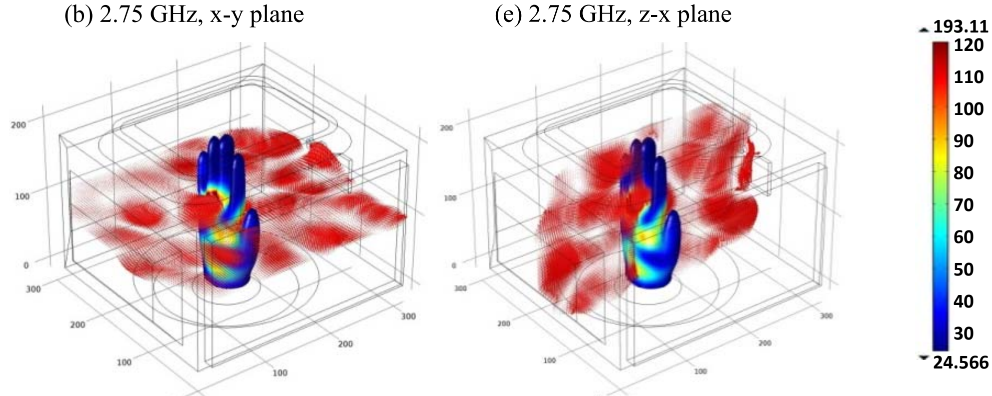
[25] Ortiz-Serna, P., Díaz-Calleja, R., Sanchis, M.J., et al. (2010). Dynamics of natural rubber as a function of frequency, temperature, and pressure. A dielectric spectroscopy investigation, *Macromolecules*, vol. 43(11), May 2010, pp. 5094 – 5102.



(a) 2.45 GHz, x-y plane (d) 2.45 GHz, z-x plane



(b) 2.75 GHz, x-y plane (e) 2.75 GHz, z-x plane



(c) 3 GHz, x-y plane (f) 3 GHz, z-x plane

Fig. 9 The simulation results of electric field and temperature profile in the NRG during microwave heating various microwave frequencies based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M; (a) 2.45 GHz, x-y plane, (b) 2.75 GHz, x-y plane , (c) 3GHz, x-y plane, (d) 2.45 GHz, z-x plane, (e) 2.75 GHz, z-x plane and (f) 3GHz, z-x plane

CST0017

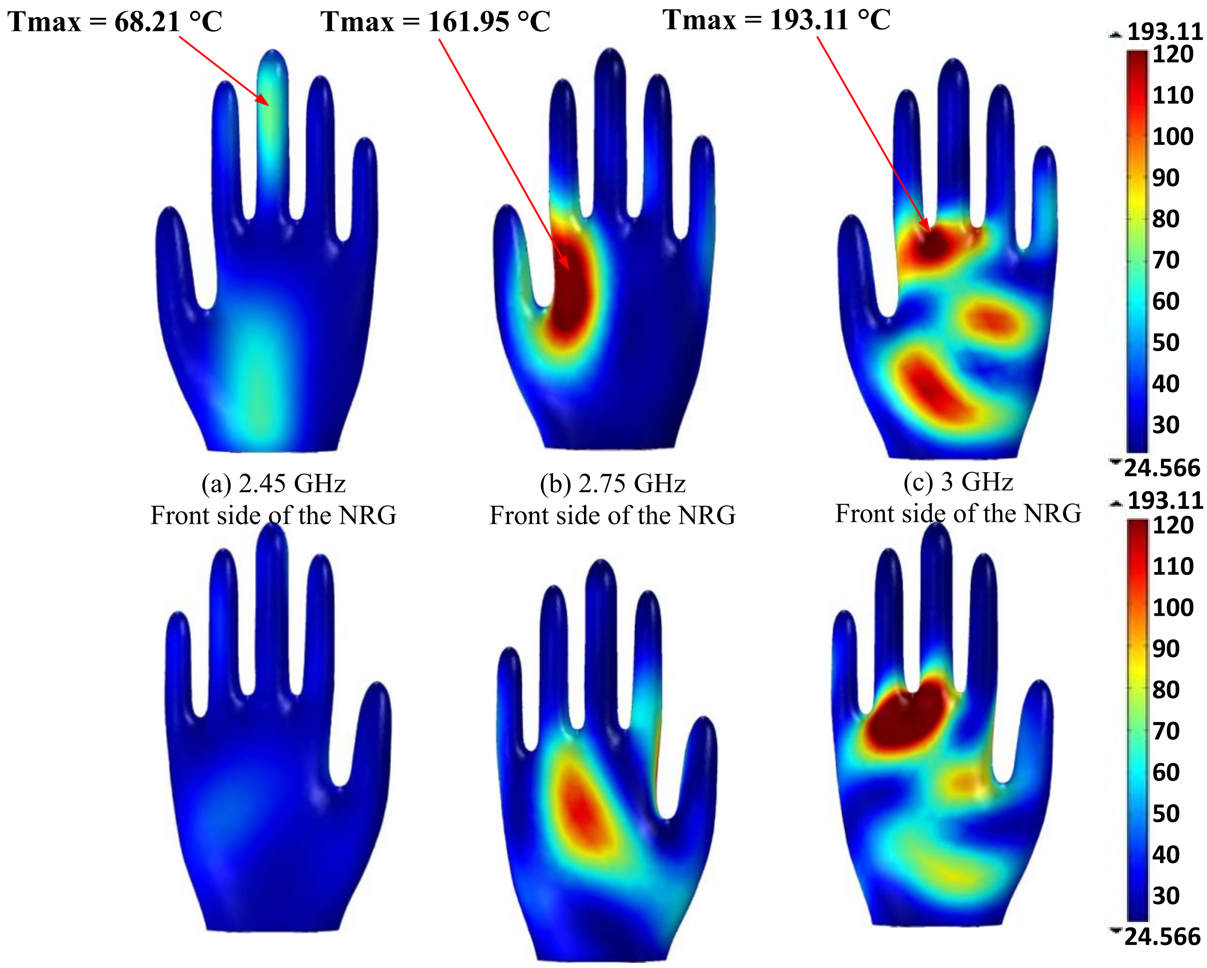
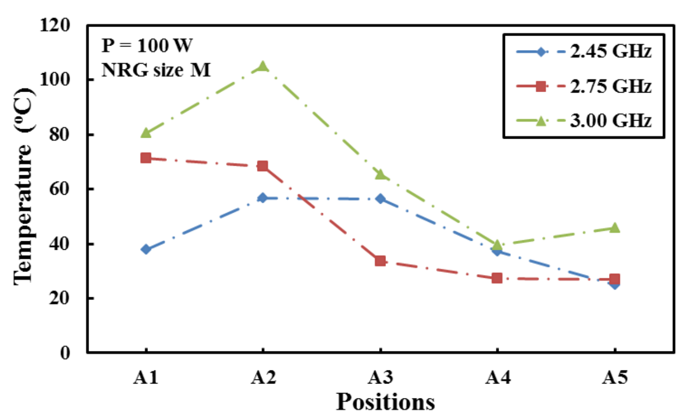


Fig. 10 The simulation results of profiles of temperature in the NRG during microwave heating various microwave frequencies based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M; (a) 2.45 GHz in the front side of the NRG, (b) 2.75 GHz in the front side of the NRG, (c) 3 GHz in the front side of the NRG, (d) 2.45 GHz in the back side of the NRG, (e) 2.75 GHz in the back side of the NRG and (f) 3 GHz in the back side of the NRG



CST0017

Fig. 11 The relationship between temperature distributions and positions in a NRG from simulation analysis various microwave frequencies based on microwave power input (P) of 100 W, heating time (t) of 300 s and NRG size M
Table. 1 Dielectric properties of NRL and ceramic [21-25].

Dielectric Properties	**Emblem**	**Microwave frequency**					
		2.45 GHz		**2.75 GHz**		**3 GHz**	
		NRL	**Ceramic**	**NRL**	**Ceramic**	**NRL**	**Ceramic**
Electric conductivity (S/m)	σ	0	0	0	0	0	0
Relative dielectric constant (-)	ε_r'	20	3.4	19.6	3.4	19.1	3.4
Relative dielectric loss factor (-)	ε_r''	0.3	0	0.28	0	0.26	0

Table. 2 Thermal properties of NRL and ceramic [21-25].

Thermal Properties	**Emblem**	**Microwave frequency**					
		2.45 GHz		**2.75 GHz**		**3 GHz**	
		NRL	**Ceramic**	**NRL**	**Ceramic**	**NRL**	**Ceramic**
Thermal conductivity (W/m·K)	k	0.13	1.1	0.13	1.1	0.13	1.1
Density (kg/m^3)	ρ	975	2,200	975	2,200	975	2,200
Heat capacity (J/kg·K)	C_p	1894	480	1894	480	1894	480