Analysis of temperature profile and electric field in natural rubber glove due to microwave heating: effects of waveguide position

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Abstract. Natural rubber (NR) is the key raw material used in the manufacture of other products such as rubber band, tire and shoes. Recently, the NR is used in natural rubber glove (NRG) manufacturing in the industrial and medical fields. This research aims to investigate the electromagnetic wave propagation and heat transfer in NRG due to heating with microwave energy within the microwave oven at a microwave frequency of 2.45 GHz. Three-dimensional model of NRG and microwave oven are considered in this work. The comparative effects of waveguide position on the electric field and temperature profile in NRG when subjected to microwave energy are discussed. The finite element method (FEM) is used to solve the transient Maxwell’s equation coupled with the transient heat transfer equation. The simulation results with computer programs are validated with experimental results. The placement of waveguides in three cases are left hand side of microwave oven, right hand side of microwave oven and left and right hand sides of microwave oven are investigated. The findings revealed that the placing the waveguide on the right side of the microwave oven gives the highest electric field and temperature profile. The values obtained provide an indication toward understanding the study of heat transfer in NRG during microwave heating in the industry.

1. Introduction

Today, rubber is as widely used due to its beneficial proprieties like strength, long lasting, water resistance and heat resistance [1]. Commercially, the most important rubbers are natural rubber (NR); it is an elastomer that has greater flexibility compared to synthetic rubbers. NR is used as the main material in many everyday applications, for example, rubber band, hoses, vehicle tires, automotive industries and medical equipment, especially the main materials of natural rubber gloves (NRG) [2, 3]. The NRG industry becomes bigger and wider. The basic knowledge on rubber technology leads to manufacturing process improvement and development of new products, especially the knowledge on heating of NRG.

In the past, rubber glove heating processes used conventional heating method using hot air. Many previous studies on hot-air vulcanized of rubber glove [4-6]. Due to the lower conductivity of rubber material, frequently, inner temperature of rubber products is less than surface temperature in conventional vulcanization process lead to the nonuniformity in temperature distribution of rubber material [7, 8]. Several NRG heating processes were incorporated into combined infrared and hot-air
vulcanization of rubber glove [9]. Khamdaeng et al. [9] analyzed the rubber deformation to describe the deformation behavior of the combined infrared and hot-air vulcanized of rubber glove. However, the infrared can potentially penetrate into the rubber material with their shorter wavelengths, the heat and mass transfer inside material is subjected to the emission. Infrared combined with hot-air heating will provide the complex phenomena than infrared or hot-air heating only [10-12]. In addition, the infrared heating is complicated setting because of the less space using and expensive equipment but also rapidly responses to temperature controlling [9]. Finding ways to develop the efficiency of rubber material heating processes is an essential for research and particular industry.

A new advancing technique for rubber material heating such as NRG heating is microwave heating. The major advantages of microwave heating are rapidly emerging, precise control, and fast start-up due to the microwave energy that penetrates into the material will be absorbed and converted into internal energy in the material, so-called volumetric heating. In recent years, the utilization of microwave energy on applications of NR has been increasing rapidly in daily life, including drying, vulcanization and pre-heating. Many previous studies on vulcanization of the NR with the microwave energy can be found in the research [13-15]. Martin et al. [13] vulcanized rubber mixtures by using electron beam and microwave irradiation. Sombatsompop and Kumnuantip [14] compared physical and mechanical properties of NR, carbon black and reclaimed rubber blends vulcanized by conventional thermal and microwave irradiation methods. Chen et al. [15] analyzed temperature distribution in rubber material during microwave heating using experimental. There are some experimental studied of the NR heating process using rectangular wave guide [16, 17]. Doo-ngam et al. [16] developed microwave pre-heating process of NR-compounding with various sulphur contents using a rectangular wave guide. Makul and Rattanadecho [17] presented a new method to pre-cure NR-compounding (NRc) with a rectangular wave guide, significant results showed that microwave energy can produce partial cross-linking at temperatures below the actual vulcanizing process.

Although many previous researches have studied the simulation or experimental of microwave heating in NR, there are few research studies simulation or experimental of NRG microwave heating, especially a detailed study of the parametric effects, i.e. placement of waveguides effects on electric field and temperature profile. This is because complicated of the shape of gloves and complicated of problem that microwave heating is a multiphysics phenomenon involving both electromagnetic waves and heat transfer. A comprehensive understanding of the fundamentals of electromagnetic waves and heat transfer interactions will help to develop the efficiency of NRG microwave heating.

The aim of the proposed study is to investigate the influences of waveguide position on the electric field and temperature profile in a NRG during microwave heating within the microwave oven. The variations in three cases e.g. left hand side of microwave oven, right hand side of microwave oven and left and right hand sides of microwave oven are investigated. The microwave power input of 100 W, microwave frequency of 2.45 GHz, heating times of 300 s and NRG size M are used for this problem. The transient Maxwell’s equation coupled with the transient heat transfer equation is solved by using the finite element method using COMSOL™ Multiphysics. The NRG and microwave oven models are built and simulated via a three-dimensional finite element computational model. The results obtained from the simulation are examine and compared with the experimental results to verify the accuracy of the present numerical model. The obtained results of this work will lead to understanding electric field and temperature profile within NRG during microwave heating and may be of assistance in determining practical guideline to improve heating process of NRG in the process industry.

2. Experimental Study
Figure 1 illustrates the schematic diagram of the experimental apparatus for the measurement of the temperature in the NRG during microwave heating. Microwave cavity with dimensions 310 mm x 280 mm x 190 mm (axial: x, y and z, respectively) is used in experimental. The magnetron with microwave power 100 W radiates to the interior of the microwave oven. The working frequency of microwave is 2.45 GHz, a widely used frequency inside the microwave oven. To set up an experiment, start from the dipping ceramic hand shaped former into natural rubber latex (NRL) with thickness 0.5 mm to mold
NRG. A thin layer of the NRL covering the hand shaped mold is vertically placed in the center of the microwave oven. Microwave energy which is generated by microwave generator propagates through the waveguide (cross sectional area 79 mm x 43 mm) to the NRG that is located at the center of microwave oven. The temperature of NRG measured in experimental using thermocouple K-type at various heating times during microwave heating [18, 19] and recorded temperature data by data logger (Wisco DL2200 Data Logger). Figure 2 shows the NRG temperature measurement inside the microwave oven at different positions (position A1-A5). NRG is formed using the medium (M) size of hand mold, it is standard size commonly used. The dimensions of NRG size M are shown in figure 3. The NRG has a width of 110 mm and a length of 200 mm. Temperature measurement position (position A1-A5) inside NRG from experimental is located at the 45 mm, as displayed in figure 3. The initial NRG temperature is set at 24 °C for all cases. During microwave heating, the heating time of 300 are performed. Experimental results of temperature distribution various temperature measuring positions (A1-A5) at microwave power input of 100 W and NRG size M at heating times of 300 s are systematically investigated.

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

Figure 2. Measuring temperature of NRG inside the microwave oven
3. Simulation Study

3.1 Physics Model

The schematic diagram of the physics models of NRG and microwave oven for numerical analysis are shown in figure 4. The dimension of microwave oven cavity and rectangular wave guide in numerical study is similar to the dimension in experimental study. Full three-dimensional models of NRG and microwave oven are considered to demonstrate the electric field and temperature profile in NRG due to microwave heating. 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 through a wave guide. Microwave irradiation can penetrate the NRG surface and is converted into thermal energy within the NRG.

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 considered.
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 are constant.

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 electric fields penetrated in NRG which can be written as follows [20]:

![Diagram of NRG and temperature measurement position](image)

**Figure 3.** Dimensions of NRG and temperature measurement position (position A1-A5) inside NRG

![Physical models of NRG and microwave oven](image)

**Figure 4.** Physical models of NRG and microwave oven for numerical analysis
\[ \nabla \times \left( \frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \left( \varepsilon_r' - \frac{j\sigma}{\omega\varepsilon_0} \right) \vec{E} = 0 \]  

(1)

where \( \vec{E} \) is the electric field intensity (V/m), \( \mu_r \) is the relative magnetic permeability (H/m), \( \varepsilon_r' \) is the relative dielectric constant, \( \varepsilon_0 = 8.8542x10^{-12} \) (F/m) is the permittivity of free space, and \( \sigma \) is the electric conductivity (S/m), \( \varepsilon_r = n^2 \) and \( n \) is the refractive index.

The boundary condition for analyzing the electric field, as presented in figure 5, is considered as follows:

In numerical simulation analysis, the NRG subjected to a uniform microwave power input via waveguide, so as to NRG is heated by microwave. The combination of microwave power input and heating time can be set, which is the advantage of this microwave heating device. The geometric models and condition in numerical simulation analysis corresponded to 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 the port boundary condition as follows [21]:

\[ S = \frac{\int (\vec{E} - \vec{E}_i) \cdot \vec{E}_i}{\int \vec{E}_i \cdot \vec{E}_i} \]  

(2)

Furthermore, the propagation constant is defined as:

\[ \beta = \frac{2\pi}{c} \times \sqrt{f^2 - \frac{c^2}{4 \times a^2}} \]  

(3)

where \( \beta \) is the propagation constant, \( a = 3.4 \) inch is the depth dimension of waveguide, \( c = 3 \times 10^8 \) (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:

\[ \left[ \begin{array}{l} \frac{\mu_0 H_r}{\varepsilon_0 \varepsilon_r - j \frac{\sigma}{\omega}} \hat{n} \times \vec{H} + \vec{E} - (\hat{n} \cdot \vec{E}) \hat{n} = (\hat{n} \cdot \vec{E}_x) \hat{n} - \vec{E}_x \\ \end{array} \right] \]  

(4)

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

\[ \hat{n} \times \vec{E} = 0 \]  

(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 figure 6 and as follows:

\[ \hat{n} \times (E_{NRL} - E_{air}) = 0 \]  

(6)

\[ \hat{n} \times (H_{NRL} - H_{air}) = 0 \]  

(7)
### 3.3 Analysis of Heat Transfer

To solve the thermal problem, the coupled model of the electromagnetic wave propagation and unsteady heat transfer as well as the boundary conditions is investigated. However, the heat transfer analysis of microwave heating is considered only in a NRG.

The temperature profile is corresponded to the electric field. This is because when the electric field propagates in the NRG, it was absorbed by the medium and converted into internal heat generation, which causes its temperature to rise. This research is based upon the following assumptions:

1. The NRG is assumed to be homogeneous and thermally isotropic.
2. There is no phase change of substance and no chemical reaction in the NRG.
3. The contact surface of NRG is assumed to be smooth.
4. The effect of shrinkage of NRG is negligible.
5. 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 the following equation [22]:

\[
\rho C_p \frac{\partial T}{\partial t} - k \nabla^2 T = Q
\]  

(8)

where \( \rho \) 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 equation (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 equation (9):

\[
Q = 2\pi f \varepsilon_r \varepsilon_0 (\tan \delta) E^2
\]

(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 figure 5, is considered as follows:

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

\[
-\hat{n} \cdot (-k \nabla T) = 0
\]

(10)

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

\[
T_{NRL}(x_0, t) = T_{Ceramic}(x_0, t)
\]

(11)

\[
-k_{NRL} \frac{\partial T(x_0, t)}{\partial x} = -k_{Ceramic} \frac{\partial T(x_0, t)}{\partial x}
\]

(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 (\( \varepsilon \)). The complex permittivity is a function of dielectric constant and dielectric loss factor as defined by [23]:

\[
\varepsilon = \varepsilon_r \varepsilon_0 (\tan \delta)^{-2}
\]
where $\varepsilon''$ is the dielectric constant, $\varepsilon'$ is the dielectric loss factor, $\varepsilon'_r$ is the relative dielectric constant and $\varepsilon''_r$ is the relative dielectric loss factor.

The NRG is assumed to be homogeneous and electrically as well as thermally isotropic. The dielectric and thermal properties of NRG and ceramic are constant. Table 1 tabulates the dielectric and thermal properties of NRG and ceramic used in the computations.

**Figure 5.** The boundary condition for numerical analysis;
(a) inside of microwave oven and (b) inside of NRG

4. Formulation of the Problem

In this study, the effects of waveguide position on the electric field and temperature profile in NRG are studied. The placement of waveguides in three case are left hand side of microwave oven, right hand side of microwave oven and left and right hand sides of microwave oven are examined. The conditions of waveguide positions are shown in figure 6. The simulation results of electric field vector and temperature profile in NRG during microwave heating based on microwave power input of 100 W and heating time of 300 s are presented. The frequency of microwave of 2.45 GHz and NRG size M are used in this study.

**Figure 6.** Physical models equipped with various waveguide positions
5. Calculation Procedure
In this study, the finite element formulations of the coupled electromagnetic wave propagation-heat transfer model in the NRG are carried out over the entire domain. The transient Maxwell’s equation coupled with the transient heat transfer equation and related boundary conditions are implemented using finite element method with COMSOL™ Multiphysics software. To obtain a good approximation, a fine mesh is specified in the sensitive areas. The three-dimensional model is discretized using triangular elements and the Lagrange quadratic elements are then used to approximate the temperature and electric field variations across each element. A grid independence test is carried out to identify the appropriate number of elements required. This grid independence test leads to a mesh with approximately 431,110 elements. It is reasonable to assume that, at this element number, the accuracy of the simulation results is independent of the number of elements.

Table 1. The dielectric and thermal properties of NRG and ceramic used in the numerical simulation at microwave frequency of 2.45 GHz [24-28]

| Property                          | Emblem | Natural Rubber Latex | Ceramic |
|-----------------------------------|--------|----------------------|---------|
| Electric conductivity (S/m)       | $\sigma$ | 0                    | 0       |
| Relative dielectric constant (-)  | $\varepsilon'$ | 20                  | 3.4     |
| Relative dielectric loss factor (-)| $\varepsilon''$ | 0.3                | 0       |
| Thermal conductivity (W/m·K)     | $k$    | 0.13                 | 1.1     |
| Density (kg/m³)                  | $\rho$  | 975                  | 2,200   |
| Heat capacity (J/kg·K)           | $C_p$  | 1894                 | 480     |

6. Results and Discussion
The accuracy of the present numerical model is verified by the validation against the experiment results with the same geometry and same conditions. The comparison of NRG temperature distribution of simulation results with the experiment results based on microwave power input of 100 W, microwave frequency of 2.45 GHz, heating times of 300 s and NRG size M at the position A1, A2, A3, A4 and A5 are shown in figure 7. It is found 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. Figure 7 also displays that at position point A3 or approximate the center of NRG has the maximum temperature. In addition, it is also found that an increase in the heating times results in an increase temperature distribution. This comparison guarantees that the present numerical model can accurately represent the transport phenomena in NRG.
Figure 7. The comparison of NRG temperature distribution of simulation results with the experiment results at heating times of 300 s.

The effects of waveguide position on the electric field vector and temperature profile of NRG based on microwave power input of 100 W, microwave frequency of 2.45 GHz, heating times of 300 s and NRG size M are shown in figure 8. Figures 8(a)–(c) show the electric field vector and temperature profile of NRG in Case 1, Case 2 and Case 3 as described in section 4, respectively. These figures illustrate the volumetric heating effect expected from microwave heating. From figures 8(a), it is found that the electric field intensity in the palm of the NRG and intensity toward the area on the middle finger, it resulted in very high temperatures in this zone. However, the hot spot zone occurs at the position near the middle finger at low temperature in Case 1. The hot spot zone occurs at the position near the middle of palm, little finger and middle finger in Case 2, as shown in figure 8(b). While, the hot spot zone occurs at the position near the middle of palm and middle finger in Case 3, as shown in figure 8(c) due to in case of the waveguide is in place on both sides of the microwave oven, the overlap between their combined waves. Considering the influences of the waveguide position on the hot spot zone in each case, it can be seen that in Case 2 has more hot spot zone than Case 3 and Case 1, respectively.

Figure 9 show the effects of waveguide position on the electric field vector and temperature profile of NRG in top view under same condition of figures 8. Figures 9(a)–(c) show the electric field vector and temperature profile of NRG in Case 1, Case 2 and Case 3, respectively. From the figures, electric field is propagated through the waveguide toward NRG, which causes its temperature to rise. It is found that the electric field vector and temperature profile for all cases have the same pattern with figure 8.

Figure 8. The effects of waveguide position on the electric field vector and temperature profile of NRG; (a) Case 1 (b) Case 2 and (c) Case 3
Figure 9. The effects of waveguide position on the electric field vector and temperature profile of NRG in top view; (a) Case 1 (b) Case 2 and (c) Case 3

Figure 10. The effects of waveguide position on the temperature profile of NRG; (a) Case 1 : Font , (b) Case 1 : Back, (c) Case 2 : Font , (d) Case 2 : Back, (e) Case 3 : Font and (f) Case 3 : Back

Figure 10 displays the effects of waveguide position on the temperature profile of NRG based on microwave power input of 100 W, microwave frequency of 2.45 GHz, heating times of 300 s and NRG size M. It is found that the temperature profile follows the electric field profile. The hot spot zone occurs at the position near the middle of palm, little finger and middle finger in Case 2, while, the hot spot zone
occurs at the position near the middle of palm and middle finger in Case 3. However, the temperature profile varies little at the position near the middle of palm in font of NRG and at the position on the middle finger in back of NRG in Case 1. It is seen that the maximum temperatures in Case 1 is 57.84 °C, in Case 2 is 135.58 °C and in Case 3 is 77.13 °C, respectively. The temperature distribution of NRG at various positions of waveguide at heating times of 300 s is shown in figure 11. It can be observed that the Case 2 has highest temperature distribution more than the temperature distribution in Case 3 and Case 1, respectively corresponds to the results in figure 10 because the waveguide is placed on the left side of the microwave oven with a concave surface in the case 1 and it is found that the wave overlap occurred in the case 3.

![Temperature distribution of NRG at various positions of waveguide at heating times of 300 s](image)

**Figure 11.** The temperature distribution of NRG at various positions of waveguide at heating times of 300 s

### 7. Conclusions

This research is carried out to observe the effects of waveguide position on the electric field and temperature profile in NRG. The results obtained represent the phenomena occurring in NRG during microwave heating. The governing equations in the study are analyzed by the finite element method. The simulation results with computer programs are validated with experimental results. The placement of waveguides in three cases, namely left hand side of microwave oven, right hand side of microwave oven and left and right hand sides of microwave oven are investigated. The results show that the hot spot zone occurs at the position of the middle finger in Case 1, however, hot spot zone occurs at the position near the middle of palm, little finger and middle finger in Case 2. In addition, the hot spot zone occurs at the position of the middle of palm and middle finger in Case 3. It is found that the placing the waveguide on the right side of the microwave oven (Case 2) gives the highest electric field and temperature profile. The advanced results in this research can be used in applications such as it provides guidance for the study of microwave heating of NRG manufacturing process.

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