Effects of Waveguide Position on Electric Field and Temperature Profile in Natural Rubber Gloves during Vulcanization Process Using Microwave Energy

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Abstract
Natural rubber gloves (NRG) become a broader industry with fierce competition and demands. The vulcanization process is the most important and takes the longest time in the cycle period of the NRG manufacturing process, so it becomes of paramount importance to improve this process. The purpose of this research is to experimentally and computationally study the characteristics of the electric field as well as temperature profile in NRG during the microwave vulcanization process. The effects of position of waveguide placement are investigated for nine different positions. The experiment of NRG microwave vulcanization is performed for temperature distribution measurement. Three-dimensional models of NRG and microwave oven are considered. Finite element method (FEM) is utilized to solve a mathematic model of the transient Maxwell’s equation coupled with the transient heat transfer equation in order to determine the electric field and temperature profile via computer simulation. The computer simulation results are validated against the experimental results. The validation confirms that the computational model is able to represent the practical transport phenomena in NRG with high accuracy. The outcomes clearly reveal that the position of waveguide effects on the electric field as well as temperature profile in NRG during the microwave vulcanization process. The positioning of waveguides on both the front and backsides on the opposite side of the microwave oven provides higher intensity electric field and higher temperature profile than the positioning of waveguides in the middle of both the front and the backsides of the microwave oven. In addition, the middle backside is the appropriate position for waveguide in which NRG is uniformly dry and not burnt or overheated. However, it is found that there is no direct relationship between the electric field and temperature changes. This research guides to essential aspects of the design of NRG vulcanization to improve the efficiency of microwave and heat delivering along with other heating systems to heat any sorts of material.

Keywords: Natural rubber gloves; Microwave heating; Electric filed; Temperature profile
1. Introduction

Nowadays, rubber is broadly used to be the raw material of various products such as vehicle tires, elastics, helmet, tires or tubes for motorcycle, parts of automotive and rubber bands, especially rubber gloves. Natural rubber gloves (NRG) is one of natural rubber (NR) products that becomes a broader industry. The fierce competition and high demands have forced the organization in this industry to continuously research and develop to improve the manufacturing process and the quality of its products [1-2]. The vulcanization of NRG is the most vital process that improves the strength and elasticity of NR by the chemical-thermal process. The heating process also takes the longest time in the cycle time of the NRG manufacturing process [3].

The conventional NR heating method used hot air as the heat source [4]. In the hot air heating process, the convection and conduction play the essential roles as heat transfer mechanisms [5]. The conductive heating by the hot air causes the very high initial rate of heat transfer on the surface of products because of the high difference of temperature between the hot air and the surface of products. Therefore, the surface temperature is numerously higher than the inner temperature and thus the nonuniformity in temperature distribution occurs and damage on the surfaces in the NR products during hot air heating process. Therefore, the combined heating of convection and radiation heat transfer were developed to improve the weakness of hot air heating about the temperature distribution as well as to optimize the process parameters of the vulcanization. Khamdaeng et al. [6] presented material parameters of NRG using the combined infrared and hot air vulcanization. However, the heat transfer in the infrared heating is subjected to the emission. In addition, the limitation of the combined system is the complex phenomena shown in the above-mentioned study [6]. The exploration of the effective heating method in the NRG manufacturing process becomes of paramount importance for the researches to improve the manufacturing process and the quality of the products.

Microwave energy is a famous alternative of heat source in this day and age. When the material undergoes microwave heating process, microwave impinges on the material and part of the energy is absorbed and converted uniformly into thermal energy by electromagnetic wave effects and delivering the energy to evenly heat the entire volume of the product called volumetric heating. Several advantages of microwave heating are quicker start-up, selective heating, higher uniformity, more precise regulation, better preventing overheating, preferable quality and salability of products, higher energy efficiency as well as environmentally friendly and safety. [7-8]

There are previous studies on the process using microwave energy to heat NR [9-14]. Bovtun et al. [9] studied the dielectric properties of rubber compounds during microwave vulcanization to investigate the effects of carbon black. The vulcanizations of carbon black, reclaimed rubber blends and NR were conducted by Sombatsompop and Kumnuantip [10] to monitor and compare the physical and mechanical properties during the microwave irradiation to convention thermal methods. Makul and Rattanadecho [11] computationally and experimentally analyzed the pre-curing process of NR-compounding using microwave energy through a rectangular waveguide. The results showed that partial cross-linking was produced by microwave energy at a temperature below the actual vulcanization. Aiyarak and Sunheem[12] designed and implemented the experiment to measure microwave attenuation for dry rubber content estimation of natural rubber latex during the microwave vulcanization process. Chen et al. [13] experimentally studied the effects of microwave heating and vulcanization process on temperature distribution in sheet rubber.

The waveguide is an important component which delivers microwave energy to the load in a cavity. It governs the characteristics of the electric field as well as temperature profile and effects on the heating pattern of products [14]. However, there are few studies on the design, positioning and operation of the waveguide that will be able to improve the efficiency of NRG vulcanization.

In the present study, the experimental and numerical analysis of NRG undergoing the 2.45 GHz-microwave vulcanization process within a microwave oven is performed. The study aims at examining the influences of the position of the waveguide on the electric field as well as temperature profile when
the position of the waveguide is changed to the variations in nine cases i.e. a couple of middle fronts and backsides, middle front side, middle backside, couple of front right side and back left side, front right side, back left side, couple of front left side and back right side, front left side and back right side. The microwave power input of 100 W is applied to NRG Size M (Medium) for the duration of heating of 300 s. The three-dimensional computational models of NRG and microwave oven are modeled and the finite element method (FEM) is considered to solve this problem. The experiment is performed to validate the numerical results. This work is a basic of the design of NRG vulcanization to improve the efficiency of the heating process of NRG in the industry.

2. Experimental study

The experiment of NRG microwave vulcanization is performed for distribution of temperature measurement and record. The experimental apparatus diagram is illustrated in Figure 1. The dimension of the microwave oven cavity is 310 x 280 x 190 mm³ in x, y and z-axis, respectively. The microwave oven operates at a widely conventional microwave frequency of 2.45 GHz. The microwave power input of 100 W is set for a duration of heating of 300 s as used in the industrial microwave vulcanization process. The experimental setup starts with the preparation of the mold of NRG where a ceramic hand-shaped former is dipped into 0.5-mm thick natural rubber latex (NRL). Then, place it in the microwave cavity at the central position and vertically along the waveguide area. The initial temperature of NRG measured by the thermocouple is 24 °C. The thermocouple K-type is installed inside the NRG to measure the temperature varied in positions and time during microwave vulcanization process [15-16] as shown in Figure 2 and record temperature by a data logger (Wisco DL2200 Data Logger). The dimension of commonly used NRG size M is 110 mm wide by 200 mm long as shown in Figure 3. In addition, Figure 3 illustrates the positions of temperature measurement (position A1-A5) which are located at 45 mm inside the NRG. Microwave energy generated by the microwave generator is transported to NRG located at the center of microwave cavity via waveguide having a cross-sectional area of 79 x 43 mm². The microwave energy delivered at the microwave power input of 100 W for the period of microwave vulcanization of 300 s and the distribution of temperature varied in positions of temperature measurement (consider the position of A1-A5) at various durations of heating (60 s, 180 s and 300 s) is examined.

![Figure 1. Experimental apparatus; ① Microwave generator ② Datalogger (Wisco DL2200) and ③ Thermocouple](image-url)
3. Computer Simulation Study

3.1 Physics Model Formulation

Figure 4 shows the model of a microwave oven, rectangular waveguide and NRG used in the numerical study where their dimensions and those used in the experimental study are totally identical. The three-dimensional model of the microwave oven and NRG are presented to obtain the electric field as well as temperature profile results during microwave vulcanization process in a computer simulation. The NRL which is 0.5 mm thick and ceramic which is 4 mm thick are used in the computational analysis with the same condition to the experimental analysis. In a computer simulation, a uniform microwave propagates via a waveguide to the NRG, then penetrate the surface of NRG and resistive heating transforms the microwave into internal heat energy within the NRG.
3.2 Electromagnetic Wave Propagation Analysis

A mathematical model is formulated to determine the electric field as well as temperature profiles within the NRG during the microwave vulcanization process. The assumptions used in numerical analysis are as follows:

1) The multi-mode microwave used for vulcanizing NRG is purposed in a mathematical model.
2) The energy absorbed by air occupied the microwave oven can be ignored.
3) The model of NRG is considered stationary in simulation.
4) The waveguide is considered to be perfect conductors while the microwave oven’s walls are considered to be impedance.
5) The NRG and ceramic have dielectric properties which are assumed to be constant in this model.

Maxwell’s equations are mathematical models which describe the interdependence among the electric and magnetic field. In this numerical study, for analysing electromagnetic wave propagation in NRG and to predict the electric fields penetrated in NRG, the general form of Maxwell’s equations is simplified as the following equation [17]:

\[
\nabla \times \left( \frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \left( \epsilon'_r - j \frac{\sigma}{\omega \epsilon_0} \right) \vec{E} = 0
\]

where \( \mu_r \) is the relative magnetic permeability (H/m), \( \vec{E} \) is the electric field intensity (V/m), \( \epsilon'_r \) is the relative dielectric constant, \( \sigma \) is the electric conductivity (S/m) and \( \epsilon_0 \) is the permittivity of free space (8.8542x10-12 F/m), \( \epsilon_r = n^2 \) and \( n \) is the refractive index.

Figure 5 illustrates the boundary conditions for analyzing the electric field considered as follows:

In the numerical analysis, a microwave power transports into the microwave cavity through the waveguide. After that, it is absorbed by the NRG and so the NRG is heated as a result of increasing of thermal energy. To be consistent with the position of the waveguide of the microwave oven used in the experiment, it is assumed that the uniform microwave power irradiates to the left side of the NRG. That’s why at this port of microwave oven, the port power level and port phase of wave excitation are specified. There is stored energy within electric and magnetic fields and thus it can be carried by the electromagnetic wave. The Poynting vector represents the energy flux transported by a propagating electromagnetic wave. Thus, the port boundary condition is using an electromagnetic wave propagation simulator specified to the boundary of the considered domain at the left as follows [18]:

\[
S = \int \frac{(\vec{E} - \vec{E}_1) \cdot \vec{E}_1}{\int \vec{E}_1 \cdot \vec{E}_1}
\]

In addition, the propagation constant is defined as:

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

Where \( \beta \) is the propagation constant, \( c \) is the speed of light in a vacuum (3x10^8 m/s), \( f \) is the operating microwave frequency (2.45 GHz) and \( a \) is the depth dimension of waveguide (3.4 inches).

The waveguide is considered to be perfect conductors. The perfect conductor boundaries thus are applied to the walls of the waveguide:

\[
\hat{n} \times \vec{E} = 0
\]
The wall surfaces of the microwave oven are considered to be impedance. The impedance boundary so applied to wall surfaces of the microwave oven:

$$\frac{\mu_0 \mu_r}{e_0 e_r - j \sigma / \omega} \hat{n} \times \vec{H} + \vec{E} - (\hat{n} \cdot \vec{E}) \hat{n} = (\hat{n} \cdot \vec{E}) \hat{n} - \vec{E}$$  \hspace{1cm} (5)

Furthermore, at the internal boundary along with the interfaces between NRL and the ceramic, the continuity boundary conditions are applied as follows:

$$\hat{n} \times (E_{NRL} - E_{air}) = 0$$  \hspace{1cm} (6)

$$\hat{n} \times (H_{NRL} - H_{air}) = 0$$  \hspace{1cm} (7)

### 3.3 Heat Transfer Analysis

Coupling mathematical model of the propagation of electromagnetic wave with unsteady-state heat transfer along with the boundary conditions is solved for analyzing the thermal problem. Nevertheless, only within the NRG is considered in heat transfer analysis.

In microwave heating process, microwave propagates via a waveguide to the NRG and electric field is generated. Then, it is absorbed by NRG and converted into thermal energy. Increasing of thermal energy causes temperature within NRG to increase. In this research, the heat transfer analysis of microwave heating process is based upon the following assumptions:

1) The phase change of substance in the NRG does not occur.
2) The chemical reaction in the NRG does not occur.
3) The effect of shrinkage of NRG can be ignored.
4) The smooth contact surface of NRG is considered.
5) The NRG and ceramic have thermal properties which are assumed to be constant in this model.
6) The NRG is considered to be stationary in simulation, while the mold of NRG is rotated in a number of replications in the practical microwave vulcanization.

The unsteady-state heat transfer equation describes the transfer of heat in the internal energy within the NRG and is formulated to approximate the temperature profile within NRG as given by [19]:

$$\rho C_p \frac{\partial T}{\partial t} - k \nabla^2 T = Q$$  \hspace{1cm} (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).

Considering Eq. (8), the first term on the left-hand side of the equation indicates the transient term and the second one indicates the heat conduction term. While, considering the term $Q$ on the opposite one, when microwave energy generates electric field and it is absorbed by NRG. The NRG heats up due to resistive heating that is an external heat source in the analysis of microwave heating process called microwave power absorbed as given in Eq. (9):

$$Q = 2\pi \varepsilon_r \varepsilon_r' (\tan \delta) \tilde{E}^2$$  \hspace{1cm} (9)

Where $\tan \delta$ is the dissipation factor. As the external heat source in this research is obtained from resistive heating generated by an electric field which is the result of the electromagnetic wave, the electric field in Eq. (9) is calculated via the electromagnetic wave propagation analysis mentioned before.
Figure 5 illustrates the boundary conditions for analyzing the electric field considered as follows:

As only within the NRG is considered in heat transfer analysis, the thermal insulation boundary condition is applied to the surface of NRL and ceramic:

\[-\hat{n} \cdot (-k \nabla T) = 0\]  \hspace{1cm} (10)

The continuity boundary conditions applied at the interfaces between NRL and ceramic glove mold former in perfect contact that has the same temperature at the region of contact and does not store any energy are expressed as:

\[T_{NRL}(x_0, t) = T_{Ceramic}(x_0, t)\]  \hspace{1cm} (11)

\[-k_{NRL} \frac{\partial T(x_0, t)}{\partial x} = -k_{Ceramic} \frac{\partial T(x_0, t)}{\partial x}\]  \hspace{1cm} (12)

Where \(k_{NRL}\) and \(k_{Ceramic}\) are the thermal conductivities of the NRL layer and ceramic layer, respectively.

Complex permittivity (\(\varepsilon\)), being a function of dielectric loss factor and dielectric constant, is a general form of the dielectric properties and can be expressed as [20]:

\[\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0 \left(\varepsilon'_r - j\varepsilon''_r\right)\]  \hspace{1cm} (13)

where \(\varepsilon'\) is the dielectric loss factor, \(\varepsilon''\) is the dielectric constant, \(\varepsilon'_r\) is the relative dielectric constant and \(\varepsilon''_r\) is the relative dielectric loss factor.

The NRG is considered to be homogeneous and isotropic in electrical and thermal processes. The NRG and ceramic have dielectric and thermal properties in this computer simulation are assumed to be constant and presented in Table 1.
Figure 5. The boundary condition for numerically analyzing the electromagnetic wave propagation as well as heat transfer within (a) microwave oven and (b) NRG during the microwave vulcanization process.

Table 1. The dielectric and thermal properties of NRL and ceramic used for numerically analyzing the electromagnetic wave propagation as well as heat transfer during microwave vulcanization process [21-25]

| Parameters                              | 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/m$^3$)                      | $\rho$ | 975                  | 2,200   |
| Heat capacity (J/kg·K)                  | $C_p$  | 1894                 | 480     |

4. Problem Statement

This study aims to examine the effects of various positions of the waveguide on the electric field as well as temperature profile in NRG during the microwave vulcanization process. The models of microwave oven with various positions of the waveguide and the condition studied are exhibited in Figure 6 and Table 2. Computer simulation analysis of the characteristics of the electric field as well as temperature profile within NRG and microwave oven undergoing microwave vulcanization process which operates at a microwave frequency of 2.45 GHz varies in the following parameters:
- NRG size $M$
- Microwave power input of 100 W
- Duration of heating of 300 s
- Positions of the waveguide of 9 conditions as shown in Figure 6 and Table 2

Figure 6. 2-D Physical models of microwave oven with various positions of the waveguide

Table 2. The conditions of positions of a waveguide for simulation analysis

| Type | Models equipped with various waveguide | Waveguide 1 | Waveguide 2 |
|------|----------------------------------------|-------------|-------------|
| I    | Case 1                                 | open        | open        |
|      | Case 2                                 | open        | close       |
|      | Case 3                                 | close       | open        |
|      | Case 4                                 | open        | open        |
| II   | Case 5                                 | open        | close       |
|      | Case 6                                 | close       | open        |
In this study, the mathematic model coupling of electromagnetic wave propagation and heat transfer equations solved by FEM is carried over the entire domain. The coupled equations of transient Maxwell’s with the transient heat transfer along with related boundary conditions via COMSOL™ Multiphysics software are solved. The heat is generated by electric filed as an external heat source of the heat transfer equation. The three-dimensional model of the microwave oven and NRG is assigned with triangular elements. The electric field and temperature variations across each element are then calculated approximately using the Lagrange quadratic elements. The approximately 431,110 elements of mesh are identified using a grid independence test as it is the appropriate number of elements required in the computer simulation study.

5. Results and Discussion
The present study is aimed at investigating the influences of the position of the waveguide on the electric field as well as temperature profile during NRG microwave vulcanization.

5.1 Validation of Computational Results Against Experimental Results
For verifying the accuracy of the computational model, the validation of the computational results is performed, in the identical conditions, against the experimental results. Figure 7 shows the comparison between distributions of temperature in NRG at various positions of temperature measurement (A1-A5), exhibited in Figure 3, using computer simulation and experiment based on microwave frequency of 2.45 GHz, microwave power input 100 W lasting for the duration of heating of 300 s and NRG size M. It depicts that the perfect agreement exists in the comparison between distributions of temperature in NRG from computer simulation and experiment with approximately 9.96 % difference in error values. The results also display that the distributions of temperature from computational and experimental study increase little by little at position A1 to the maximum at position A2, thereafter the distributions of temperature decrease gradually at position A3, A4 and A5. Therefore, this validation confirms that it is valid to represent the practical propagation of electromagnetic wave along with heat transfer within NRG undergoing microwave vulcanization process by the present computational model with high accuracy.

![Figure 7. The comparison of distributions of temperature in NRG obtained by computer simulation results against the experimental results.](image-url)
5.2 Computer simulation results from the effects of the position of the waveguide

Figure 8 exhibits the top view of the computer simulation results that is electric field as well as temperature profile, influenced by the variation of the position of the waveguide. For Cases 1-9, the electric field, as well as the temperature profile of NRG, is shown in Figure 8 (a)-(i), respectively. It does maintain that positioning of waveguides on both sides of the microwave oven results in good electric field distribution with high intensity. However, the overlap of their combined microwave in Case 1 (middle of both the front and the back sides of the microwave oven) results in the less absorbed microwave along with less hot spot zone. The highest intensity electric field occurs in cases which place the waveguide couple of front right side and back left side of the microwave oven in Case 7. However, it reveals that the change in the electric field is not consistent with the change in temperature. When the position of a waveguide in the microwave oven is the front left side in Case 8, it is found that electric field is better at distributing around and then is absorbed by NRG, converted to heat, consequently results in more a hot spot zone. An asymmetric model with a concave surface on the front side and the backside of microwave oven cause low-intensity electric field as well as low hot spot zone in cases which place the waveguide on the front right side in Case 5.

Figure 9 displays the temperature profile of NRG influenced by the variation of the position of waveguide during microwave vulcanization where the 2.45-GHz microwave is applied to heat NRG size M using microwave power input of 100 W for the duration of heating of 300 s. The results from Type I (Case 1-3) of positions of the waveguide are shown in Figure 9 (a) - (c). Figure 9 (a) exhibits that at the adjacent region of the middle of the palm of NRG, the influences of the position of waveguide during microwave vulcanization causes the hot spot zone with a maximum temperature of 77.13 °C in Case 1. Meanwhile, in Case 2, Figure 9 (b) illustrates that there is not much variation in temperature profile at the adjacent region of the middle finger with a maximum temperature of 57.84 °C. In Case 3, at the adjacent region of the middle finger, the little finger as well as the middle of the palm, microwave heating creates the hot spot zone with the maximum temperature of 135.58 °C as shown in Figure 9 (c). The results from Type II (Case 4-6) of positions of the waveguide are shown in Figure 9 (d) - (f). The temperature profile in Case 4 varies a bit at the region near the middle finger with the maximum temperature of 50.41 °C, likewise, it varies a bit at the palm in Case 5 with the maximum temperature of 25.13 °C as shown in Figure 9 (d) and 9 (e), respectively. In Case 6, the region in which the hot spot zone occurs with the maximum temperature of 211.38 °C includes the palm and the tip of the middle finger as shown in Figure 10 (f). The results from Type III (Case 7-9) of positions of the waveguide are shown in Figure 9 (g) - (i). Figure 9 (g) exhibits that the effects of position of the waveguide in Case 7 caused not much variation in temperature profile at the adjacent region of the middle of palm with the maximum temperature of 50.03 °C. However, the hot spot zone with a maximum temperature of 382.47 °C is reached in Case at the adjacent region of the tip of the middle finger and especially the middle of the palm as shown in Figure 9 (h). In Case 9, there is a bit of variation in temperature profile with the maximum temperature of 25.16 °C in the region of the middle fingertip as shown in Figure 9 (i). Because of the very high temperature shown in the simulation results, it has to be emphasized that the phase changes of substance in the NRG are ignored. It is discovered that the position in Case 3, Case 6 and Case 8 are good positions for the waveguide. Although the position in Case 8 results in the hottest spot zone with the highest temperature distribution in NRG, temperatures above 300 °C may cause a burning in NRG. Therefore, the positioning of the waveguide in the middle backside in Case 3 is the appropriate position for waveguide in which NRG is uniformly dry and not burnt or overheated.
Figure 8. The top view of the electric field as well as temperature profile in NRG influenced by the variation of the position of the waveguide in each case.
Figure 9. The effects of the position of the waveguide on the temperature profile in NRG in...
6. Conclusions
In the present study, the computational and experimental study on the electric field as well as temperature profile in NRG during microwave vulcanization process is performed in order to investigate the effects of different position of the waveguide. The distribution of temperature from simulation results during microwave vulcanization is validated against experimental results. The obtained results showed that the middle backside (Case 3), the back left side (Case 6) and the front left side (Case 8) are good positions for the waveguide. However, positioning the waveguide at the front left side (Case 8) results in the hottest spot zone with the highest temperature distribution in NRG may cause burning in some areas. The positioning of the waveguide in the middle backside in Case 3 is the suitable position for waveguide in which NRG is homogeneously dry and not burnt or overheated. This investigation provides fundamental information and knowledge on heat transfer within NRG during microwave vulcanization process and can be applied to use in NRG industry as a guideline to improve the heating process of NRG and lead to improve the manufacturing process of NRG to gaining the competitive advantage.

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