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Numerical Simulation of Temperature and Electric Field Distributions in the Microwave Heating of Petroleum Coke

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Numerical simulation of microwave heating of petroleum coke (PC) was successfully predicted by COMSOL Multiphysics software version 5.2. The simulation is used to study how the temperature and electric field are distributed inside the domestic microwave oven. The simulation study was performed at a microwave input power of 500 W and time of 60 s. Numerical modelling has shown that an optimal temperature can be generated while heating a PC sample. The gradient temperatures of the PC sample change with a combination of cavity and the energy dissipated in the sample, an optimal temperature of which is 898 K. Moreover, a decrease in the electric field distribution was observed by conduction inside the PC sample. The results may provide a reference for the study of heating of PC by microwave energy.

Keywords: Petroleum coke, Activated carbon, Microwave oven, Finite element, COMSOL.

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1. INTRODUCTION

In recent years, microwave ovens have been used to prepare activated carbon from biomass waste. The microwave heating method has shown reliability to increase the efficiency of mineral carbonization processes. Petroleum cokes (PCs) are very potential raw materials for activated carbon, carbon fiber, graphite and so on. Activated carbon is generally made from coal or cellulose material by carbonization and activation of physics/chemistry method. Cellulose material has been used as a precursor of the activated carbon but there were very few studies using precursors of PC. The surface of the activated carbon has been modified by oxidation, thermal and chemical treatment with acid/alkaline [1-3]. PC has the form of a black solid, its morphology has many pores with non-homogeneous particle size.

This study purposed to predict the influence of microwave heating method for a PC sample by using a numerical simulation based-finite difference. The transient Maxwell's equations are solved by using the Finite Difference Time Domain (FDTD) method for microwave heating of water layer using a microwave oven. It has been reported both experimentally and numerically [4]. Yi-du et al. [5] predicted the microwave propagation model in a PC sample using COMSOL Multiphysics numerical simulation software. They showed the relation between microwave energy input power with heating temperature. Jindarat et al. [6] reported the analysis of energy consumption in a microwave inside a rectangular waveguide applying the first law of thermodynamics to estimate the ratio of energy utilization in microwave drying. The other report showed that during the heating process the microwave energy was absorbed at the surface of the material [7]. It was found that microwave heating gave an optimal frequency of 2.45 GHz to be effective in coal heating [8]. The approach of two-dimensional finite difference has been applied to simulate the temperature profile of a cylindrical material [9]. Analytical and numerical studies showed the influence of sample size on dielectric materials [10]. The temperature distribution of a sample depends on the dielectric properties of materials as a function of the electromagnetic wave frequency, temperature, and composition of the sample [11]. Through microwave irradiation, Samanli et al. demonstrated a facile treatment on grinding coal samples [12]. Using a mathematical model, Komarov [13] predicted a temperature pattern in dielectric material heated with microwave energy. The temperature profile and electromagnetic field distributions have been simulated using COMSOL Multiphysics software for microwave heating of the oil palm shells (empty fruit bunch) [14], biomass [15], carbon, pyrex, pine wood [16], wood [17], wood-based nanocomposites [18].

However, there are few reports about the simulation of the microwave energy at a frequency of 2.45 GHz applied in the prediction of temperature profile heating of coal [5, 8, 19]. Numerical simulation study on the microwave heating of PC obtained by COMSOL Multiphysics software version 5.2 can be considered as a novelty of this work. To the best of our knowledge, numerical simulation studies of PC via microwave heating have not been reported. The purpose of the present work is to study the temperature and electric field distributions of the microwave heating of PC by COMSOL Multiphysics numerical simulation software inside the domestic microwave oven.

2. NUMERICAL AND GEOMETRY

2.1 Numerical Model

The modeling is done using GUI Heat Transfer electromagnetic heating in particular microwave heating on COMSOL Multiphysics version 5.2 which is a partial differential equation that can be used to model heat distribution. Therefore, nine algorithms are made to the model as follows. (1) Define the components involved in heating such as microwave oven size (length,

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width and height), wave size, waveguide depth, glass plate radius, height and width of glass plate and radius of the sample. (2) Define the initial temperature T_0. (3) Design the component geometry using COMSOL Multiphysics version 5.2. (4) Meshing geometry is formed with the 3D design. (5) Insert the material and the values of the parameters involved in heating. (6) Determine the coefficient equal to 6. Define the microwave model coefficients β and ε. (7) Use the heat transfer equation with initial condition setting and temperature boundary conditions. (8) By solving the Maxwell equation, the heat transfer equation is found. Then change the time variation and time value found. (9) Improvement and variation of heat distribution modeling are done on the heat distribution design of microwave oven by changing the coefficient of microwave oven.

2.2 Geometry and Meshing

A 3D geometric design of the microwave oven with the input power of 500 W at $t = 60$ s in COMSOL simulation is shown in Fig. 1.

This model consists of an oven cavity, made from copper, with dimensions of 457 × 254 × 356 mm, a magnetron rectangular waveguide (2.45 GHz in TE_{10} mode) with dimensions of 50 × 78 × 18 mm, a glass plate crucible (113.5 × 6 mm) and PC which takes the shape of a cylinder (radius 100 mm and height 20 mm). The parameters used in these simulations are shown in Table 1.

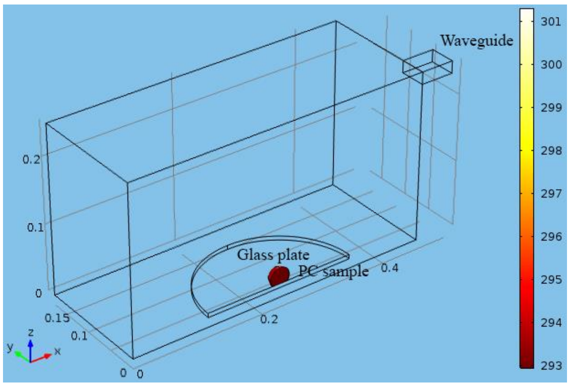

Fig. 1 – Geometric model of microwave oven

Table 1 – Simulation model parameters (mm)

Name	Width	Depth	Height	Radius
MW	457	254	356	–
WG	50	78	18	–
GP	–	–	6	113.5
PC	–	–	20	100

MW – microwave; WG – waveguide; GP – glass plate

The cavity of the microwave oven and the waveguide, on the other hand, were both assigned to simulate a predefined normal mesh element size of 33 mm as shown in Fig. 2.

The mesh quality evaluation of the PC sample has very good quality at an applied electromagnetic power input of 500 W during 60 s and is accurate enough to obtain reliable results as shown in Fig. 3.

The electrical and thermal properties of the PC sample are shown in Table 2.

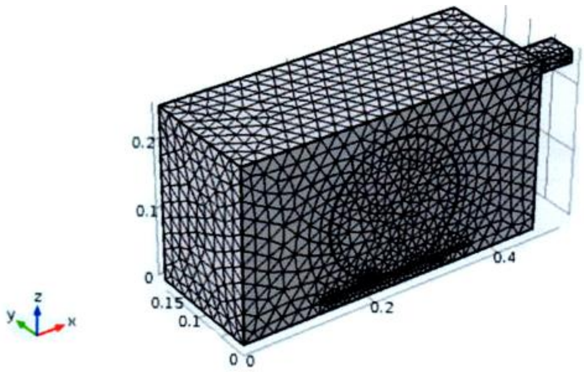

Fig. 2 – Meshing element

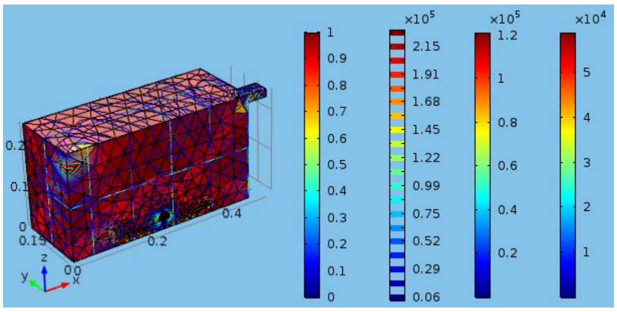

Fig. 3 – Meshing quality evaluation

Table 2 – Material properties used in this study

Properties	Pet. Coke	Glass Plat	Cooper
ε_r	2	1	1
μ_r	1	2.55	1
σ	0.159	0	$5.998 \cdot 10^7$
C_p	2.54	–	385
ρ	750	–	8700

3. GOVERNING EQUATIONS

The governing equations of the electric field wave when heating PC in the microwave oven are expressed as follows [15]:

$$\nabla \times \mu_r^{-1} (\nabla \times E) - k_o^2 \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_o} \right) E = 0 , \qquad (1)$$

where E is the electric field intensity (V/m), ω is the angular frequency (rad/s), ε_0 is the permittivity of vacuum ($8.85 \cdot 10^{-12}$ F/m), μ_r is the relative permeability, ε_r is the relative permittivity, $j = \sqrt{-1}$, σ is the electrical conductivity (S/m), k_0 is the wave number in free space (rad/m) given by the expression:

$$k_o = \omega \sqrt{\varepsilon_o \mu_o} = \frac{\omega}{c_o} , \qquad (2)$$

where c_0 is the speed of light in vacuum ($3 \cdot 10^8$ m/s). When the electrical conductivity is perfect, no electric field occurs before the heating process as shown in equation [20]:

$$n \times E = 0 . \qquad (3)$$

Initial values of the tangential component of the electric field at the position (x, y, z) are 0 V/m or E_x, E_y, E_z are equal to 0.

The heating rate of PC by microwave depends on the input power and can affect the quantity of electric field input at the position (*x, y, z*). The boundary conditions of an electric field, that occur when electric field source E_s heating at the position (*x, y, z*) is 0 V/m, are shown in the heat transfer which can be referred to as follows by COMSOL [20]. An impedance boundary condition was defined for the microwave cavity walls and waveguide, where it refers to a wave that does penetrate outside the boundary condition by only a short distance.

$$\sqrt{\frac{\mu_{\circ}\mu_r}{\varepsilon_{\circ}\varepsilon_r - j\dfrac{\sigma}{\omega}}}n \times H - (nE)n = (nE_s)n - E_s , \tag{4}$$

where μ_0, μ_r, ε_0, ε_r and σ are the material parameters, n is the refractive index, $j = \sqrt{-1}$, ω is the angular frequency (rad/s), H is the magnetic field intensity (A/m), E is the electric field intensity (V/m) and E_s is the source field intensity (V/m).

We must consider that there is no heat flux across to the boundary, in other words, the boundaries are thermally well insulated. The perfect magnetic conductor boundary condition occurred in the area of PC, glass plates, metallic box and the waveguide port. The magnetic field H is given by the equation [14]

$$n \times H = 0 . \tag{5}$$

Microwave oven is excited at 2.45 GHz, the rectangular waveguide port operates in TE_{10} mode and requires a propagation constant β which is given by the equations expressions [20]

$$\beta = \frac{2\pi}{c_{\circ}}\sqrt{\nu^2 - \nu_c^2} , \tag{6}$$

where β is the propagation constant (rad/m), ν is the microwave frequency (Hz), ν_c is the cut-off frequency. The heat transfer equation that couples with microwave field can be written as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q . \tag{7}$$

Eq. (8) shows that the heat transfer equation couples the microwave field by Fourier's energy.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla q = \nabla(k\nabla T) + Q . \tag{8}$$

Eq. (7) and Eq. (8) show that electromagnetic heating occurs due to radiation and heat transfer equations during PC heating to distribute the electric field (E). Radiation of electromagnetic waves that are dominant in the area of PC is given by

$$-n(-k\nabla T) = Q , \tag{9}$$

where Q is the energy content of PC (J/kg).

4. RESULTS AND DISCUSSION

All the parameters and initial conditions are defined in Table 1 and Table 2. Fig. 4 indicates the results of electric field distribution heating of a PC sample applied with 500 W electromagnetic power at 60 s. The reflection of the microwave on the copper wall at the microwave oven indicates the presence of low- and high-energy zone for coal samples [9]. Fig. 5 shows the multi-slice of normal electric field distribution in the microwave cavity with the PC sample at applied input power P of 500 W and time 60 s.

When the electric field enters the cavity from the middle-side, the dominant distribution around the vertical plane can be seen in the microwave oven, whereas from the bottom-fed waveguide oven the dominant distribution of electric field can be seen around the horizontal plane in a range of 100-1000 V/m.

This can be attributed due to the electromagnetic waves propagation moving from the bottom ($2.18 \cdot 10^3$ V/m) as compared to electromagnetic waves that enter from the side of the microwave oven ($8.85 \cdot 10^3$ V/m). The reduction of the electric field distribution by conduction in the inside of the PC sample.

Fig. 5 shows that the PC sample changes the electric field intensity distribution inside the cavity and the normal electric field drops from an earlier maximum of about $1.54 \cdot 10^4$ V/m to $6.01 \cdot 10^4$ V/m suggesting microwave absorption by the PC sample. The electric field intensity from the side can be observed as the difference of standing wave patterns distributed dominantly around the vertical plane of the microwave oven. This result indicates the intensity of standing waves contributing to any changes with respect to microwave energy input power within the cavity as suggested by ref [5].

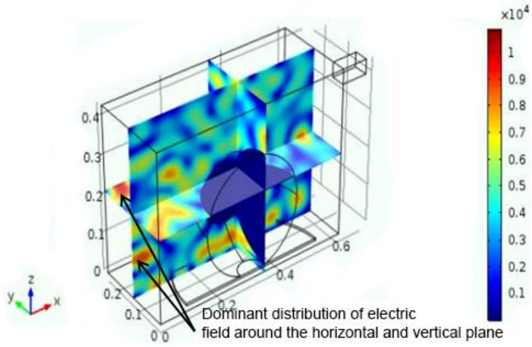

Fig. 4 – Electric field distribution (V/m) of microwave oven with the PC sample at applied input power P = 500 W and time 60 s

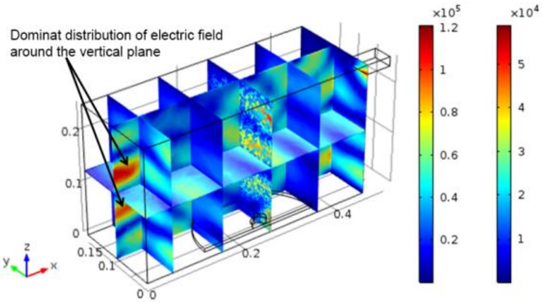

Fig. 5 – Multi-slice of normal electric field distribution in the microwave cavity with the PC sample at applied input power P = 500 W and time 60 s

Absorption of microwave energy by the PC sample and reflections from the walls of the microwave cavity redistribute the electromagnetic field. Based on Fig. 6, the simulation results in the center of the PC sample heated under electromagnetic power of 500 W at 60 s produce the best heating in a temperature range of 600-1000 K. This result is similar to the previous study reported in [5].

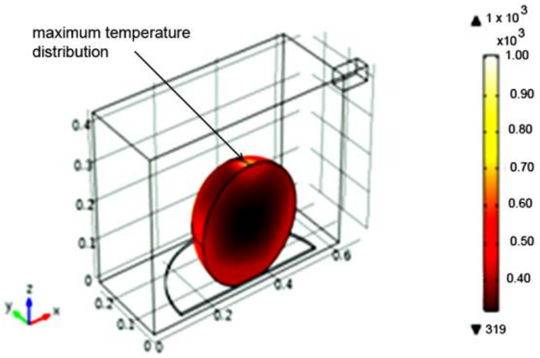

Fig. 6 – Electric field distribution (V/m) of microwave oven with the PC sample at applied input power P = 500 W and time 60 s

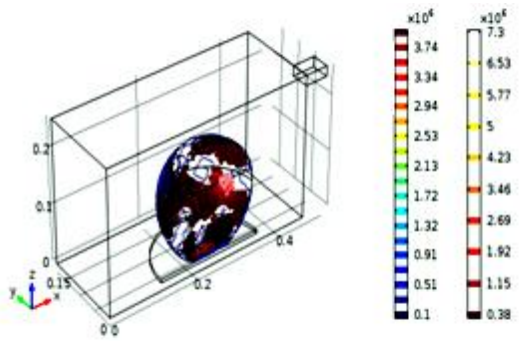

Fig. 7 – Dissipated microwave power distribution at applied input power P = 500 W and time 60 s

The maximum temperature of the PC sample is 898 K with a 500 W microwave power during the 60 s. As can be seen clearly from Fig. 6, due to the low thermal conductivity of the PC sample, the heat is distributed rather slowly, and the temperature distribution after 60 s has a maximum temperature in the top sample surface.

The waveguide and the cavity show a non-uniformity along the width of the PC sample, between the center and the outer surface. This is indicated by a temperature gradient where the temperature at the center of the PC sample is higher than the surface temperature. This temperature gradient can be explained as one consequence of two causes: in a waveguide or a cavity, the energy dissipated in the sample decreases is getting closer to the walls where electromagnetic wave tends to be absorbed, which leads to the low thermal diffusivity of the PC material.

The energy conversion can be visualized by means of the dissipated microwave distribution shown in Fig. 7. As can be seen, the electromagnetic power loss density is high in the entire microwave cavity before the PC sample heating. The rate and intensity of the electromagnetic power loss density are largely dependent on the electric field distribution and complex relative permittivity of the sample.

5. CONCLUSIONS

In this work, we have developed a model to solve the problem of irradiation by microwave oven and have proposed a 3D simulation of microwave heating on the finite element method describing temperature and electric field distributions for spherical PC sample. By using the COMSOL simulation, it was found that the result was reasonably accurate to reflect the microwave heating process especially the temperature distribution. It was found the best heating temperature in a temperature range of 600-1000 K, the electric field distribution decreases significantly under microwave radiation, which decreased from $6.01 \cdot 10^4$ V/m to $1.54 \cdot 10^4$ V/m under 2.45 GHz and 500 W microwave radiation during 60 s. It can be concluded that the temperature distribution in the PC material showed non-uniformity or a gradient of temperature to a combination of a waveguide or a cavity and the energy dissipated in the sample that influences the heat transfer conversion. However, this finding proves that the numerical simulation of microwave heating of PC can be optimized for the preparation of activated carbon, carbon fiber and graphite. Moreover, these studies are still required due to various parameters such as sample size and microwave input power, motivating further work on the combination between modelling and experiment.

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Числове моделювання розподілу температури та електричного поля при мікрохвильовому нагріванні нафтового коксу

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Чисельне моделювання мікрохвильового нагріву нафтового коксу (НК) було успішно передбачено програмним забезпеченням COMSOL Multiphysics версії 5.2. Моделювання використовується для вивчення розподілу температури та електричного поля всередині побутової мікрохвильової печі. Модельне дослідження проводилося при вхідній потужності мікрохвильової печі 500 Вт і часі 60 с. Числове моделювання показало, що оптимальна температура може бути створена при нагріванні зразка НК. Градієнті температури зразка НК змінюються за допомогою комбінації порожнини та енергії, що розсіюється у зразку, оптимальна температура якого становить 898 К. Крім того, зменшення розподілу електричного поля спостерігалося за допомогою провідності всередині зразка НК. Результати можуть служити еталоном для вивчення нагріву НК за допомогою мікрохвильової енергії.

Ключові слова: Нафтовий кокс, Активоване вугілля, Мікрохвильова піч, Кінцевий елемент, COMSOL.