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STUDY ON THE EFFECT OF INSERTING MULTI-ELECTRODES IN A MATERIAL EXPOSED TO ELECTROMAGNETIC WAVE

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ABSTRACT

The increase in the waste accumulation requires an innovation for use a green technology to burn the waste accumulation rapidly in order to protect the environment while saving the consumption of combustion energy. Hence, this paper shows that a new clean technology can be used for the heating and burning of a material rapidly, saving the consumed electromagnetic energy by presenting a computational modelling for the effect of inserting multiple metallic electrodes on the electric field, generated heat, and temperature distribution inside a material exposed to electromagnetic wave. The modelling was implemented computationally by using the three-dimensional finite element method to simulate electric field, generated heat and temperature distribution in a dielectric material containing three metallic electrodes located in a microwave cavity having surfaces of perfect electric conductors and incident microwave port of mode TE_{10}, supplied with 1500 W electromagnetic power and 2.45 GHz operating frequency. The methodology was based on that the electromagnetic wave creates an elevated electric field inside the material between the ends of metallic electrodes. This electric field assists in generating a thermal energy increasing the material temperature to attain the oxidation temperature rapidly. The results showed that the time required to raise the temperature of a dielectric material by 602 K is minimized locally from 12 seconds to less than 1 second due to the presence of metallic electrodes in the material that exposed to electromagnetic wave. The maximum temperature is increased by 100 K when reducing the gap length between the metallic electrodes from 0.0015 m to 0.0005 m.

Keywords: electromagnetic, electrodes, electric field, thermal energy, modelling, environment.

INTRODUCTION

The electromagnetic wave when interacts with a dielectric material generates heat, due to the rapid reversals of the electric field of the electromagnetic wave, which works continuously to change the direction of dipole molecules in a dielectric material, producing a current density. The power resulted from the current density and electric field is absorbed and dissipated as a rate of thermal energy inside the dielectric material. The process of producing heat from the radiation of electromagnetic wave called microwave heating [1]. The microwave heating is used in many processes in addition to food cooking such as thawing, dehydrating, freeze-drying, sterilization, and vulcanization of rubber [2]. As well, the microwave heating is employed for environmental protection such as in the contaminated soil therapy, waste burn, minerals treatment, volatile organic compounds remediation, waste sludge abatement [3], and soot filter regeneration [4], [5]. The microwave heating has advantages on conventional heating, which include higher heating rates, no direct contact between the surfaces of heating source and the material, selective heating, heat controlling, and less pollution and cost [6]. Microwave for metal processing is a minor application, because the bulk metals may not heated well, contrary to the other materials, such as food, organics, and ceramic materials [7]. However, Cheng *et al*. [8] tested the microwave heating for compact powder of pure copper inside a mono-mode cavity of 2.5 GHz and 150 W. The test results showed that the powder temperature attained to 700 ºC during 1-2 minutes of microwave heating. The similar test was conducted on a pure solid copper bar of same shape and size, and the results showed that the temperature was not increasing even after 10 minutes. While, Shayeganrad and Mashhadi [9] investigated the behavior of metallic objects exposed to microwave. It was found that thick metallic objects reflected the microwave. The thin metallic objects generated an electric current on the surface and this current with microwave irradiation formed a high voltage at the metallic ends, which generated a heat in the metallic object that raised the temperature of the metallic surface and led to a melting in the metal. Mishra *et al*. [10] described a computational model for microwave heating of tin, copper, and tungsten particulate compacts compressed in silicon carbide susceptor to simulate the variation in temperature with time during the microwave process. The results revealed that the metallic compacts were heated rapidly when placed inside the dielectric susceptor. Meir and Jerby [11] simulated local rapid heating for glass by low microwave power and electrode. The microwave of 80 W power and 2.1 GHz frequency was supplied by a solid-state source and a metallic electrode of 1 mm diameter. The simulation results explained that the glass temperature at 300 K attained to the softening temperature of 930 K close to the electrode end in 17 seconds. Hence, several studies were conducted by the current authors to present the simulation of microwave heating for soot as a dielectric material [12], soot oxidation using microwave heating with metal [13], [14], and localized rapid soot oxidation using metal aided microwave radiation [15].

In this paper, a computational simulation for the insertion of multiple metallic electrodes inside a dielectric material exposed to electromagnetic wave is presented to study the effect of multiple electrodes on the electric field,

generated heat and temperature distribution induced inside a dielectric material in order to reduce the time of microwave heating and reduce the consumption of energy.

METHODOLOGY

The methodology of microwave heating for a dielectric material combines three parameters, which are the electric field of electromagnetic wave, absorbed electromagnetic energy, and heat transfer.

Electric field of electromagnetic wave

The Maxwell's equations include electric field, ***E*** and magnetic field, ***H***. The two fields are aligned each one with other at a right angle in a same phase of time and space traveling as a wave. For the purpose of this study, Maxwell's equations were represented as a wave equation of transverse electric field (TE) called Helmholtz equation [16] as presented in Equation. (1).

$$\nabla\times\nabla\times E=\omega^2\mu_0\,\mu_r\,\varepsilon_0\,\varepsilon_r\,E-j\omega\mu_0\,\mu_r\,\sigma E \tag{1}$$

Absorbed electromagnetic energy

The absorbed electromagnetic energy, P_{abs} is dissipated as a generated heat, *JHEAT* in the dielectric material as shown in Equation. (2) [16].

$$P_{abs}=JHEAT=\left(\frac{1}{2}\right)\omega\,\varepsilon_0\left(\varepsilon_r''+\frac{\sigma}{\omega\varepsilon_0}\right)|E|^2 \tag{2}$$

Unsteady heat transfer equation

Generated heat can be used as a heat source in the unsteady heat transfer equation as in Equation. (3) [17].

$$-\left[\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)\right]dV +\left[JHEAT-\rho\,c_p\frac{\partial T}{\partial t}\right]dV-h(T-T_a)ds=0 \tag{3}$$

Electromagnetic wave with electrodes

The electromagnetic wave with the existence of metallic electrodes obtains an elevated electric field, generating heat increasing the temperature locally in a very short time. The reason of inducing high electric field in the material accumulating on metallic electrodes exposed to electromagnetic wave is attributed to the active influence of the electric conductivity, σ. Where, the high σ inside the electrode leads to low resistivity, R. The ***E*** around the rod forms a potential difference, V between the electrodes ends, and a current, I is generated along the electrode length, ***l***, as presented in the following equations.

$$R=1/\sigma \tag{4}$$

$$V=E.l \tag{5}$$

$$I=V/R=E.l.\sigma \tag{6}$$

Then the current or its charges, Q jumps from the electrode's ends to the surrounding because the length of the electrode is short. Q creates high electric flux, ***D*** leading to inducing of a high electric field intensity ***E*** within the material based on the following equations.

$$D=Q/S \tag{7}$$

$$E=D/E \tag{8}$$

SIMULATION

The simulation was conducted by employing the three-dimensional finite element method of ANSYS software. The simulation methodology was based on the coupling of Helmholtz equation of electromagnetic wave with heat transfer equation to determine the electric field, generated heat, temperature distribution, and weight removal in a dielectric material.

The simulation assumptions were:

- The solid soot was used as a dielectric material.
- In the electromagnetic model, the perfect electric contactor was used as boundary conditions for the walls of microwave cavity and waveguide with TE_{10} mode as an incident port and no boundary conditions was used for the interface of dielectric material and metallic electrodes.
- Convection thermal boundary was considered for the dielectric material.
- The simulation did not consider the chemical reaction. A command in ANSYS, was used to remove the elements having temperature exceeded the oxidation temperature.

The geometric model included a microwave cavity having dimensions of 0.10922 m × 0.05461 m × 0.07386 m and dielectric properties of $\mu_r = 1$, and $\varepsilon_r' = 1$. The cavity contained soot as a dielectric material having dimensions of 0.018 m × 0.05461 m × 0.012 m and dielectric properties of $\mu_r = 1$, $\varepsilon_r' = 8.6$, and $\varepsilon_r'' = 7.4$ [18]. The soot contained three cylindrical aluminum rods having dimensions of 0.001 m diameter, and 0.01 m length and properties of $\mu_r = 1$, $\varepsilon_r' = 1$, and $\sigma = 1.4\times10^7$ S/m for each rod. The soot was located in the cavity center on *x*- axis, along *y*-axis, and 20% of the distance on *z*-axis. The rods were inserted vertically at a distance of 0.088 m on *x*-axis and 0.002 m on and *z*- axes measured from the right corner of the soot leaving two gaps between the rods. The upper gap between the upper and middle rods was 0.0015 m and the lower gap between the middle and lower rods was 0.0005 m as shown in Figure-1. The microwave cavity was supplied with a frequency of 2.45 GHz and electromagnetic power of 1500 W.

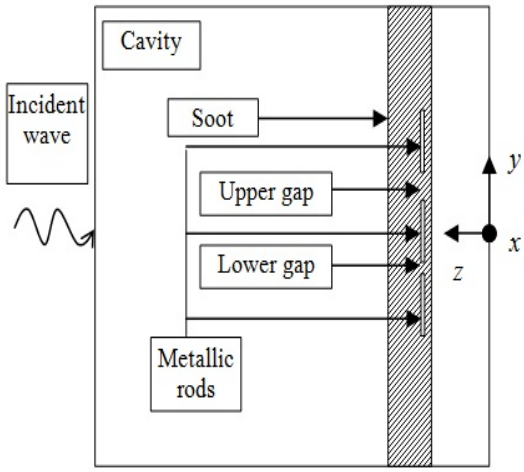


Figure-1. Side section in the cavity containing dielectric material and 3 metallic rods.

The simulation results were based on the mesh independency test of 10 elements per each dimension for the cavity, 20 elements per each dimension for the soot, and 0.0002 m element size for the metallic rods.

RESULTS AND DISCUSSION

The electric field in a microwave cavity, generated heat, temperature distributions and weight removal in the soot as a dielectric material by using microwave heating and multiple metallic electrodes were simulated. The discussion of the simulation results are as follows.

The intensity of electric fields inside the soot was 106665 V/m and 34609 V/m at the lower and upper gaps respectively as shown in Figure-2. While, it was 3000 V/m at the same positions in the soot without the presence of metallic electrodes. The high electric field induced in the lower and upper gaps was due to the effect of inserting metallic rods inside the soot. The intensity of induced electric field could be controlled by changing the length of gap between the metallic electrodes.

The effect of the metallic electrodes insertion for heat generation within the soot is displayed in Figure-3 and Figure-4, where the values of heat generated within the soot were about 2.5×10^{10} W/m^3 and 10^{10} W/m^3 at the lower gap and upper gap respectively. While the generated heat in the same positions inside the soot not containing the metallic electrodes was 1.3×10^{8} W/m^3. This was because the generated heat was increased with increasing electric field according to Equation. (2).

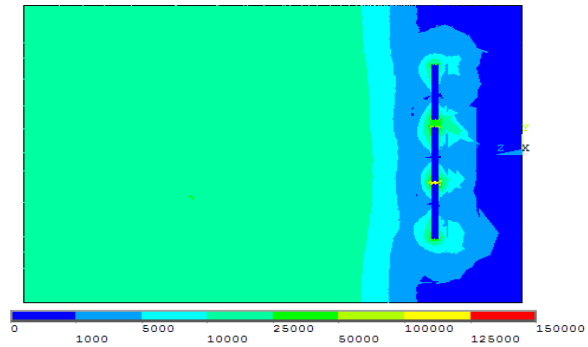


Figure-2. Contours of electric field in the cavity containing soot and metallic electrodes.

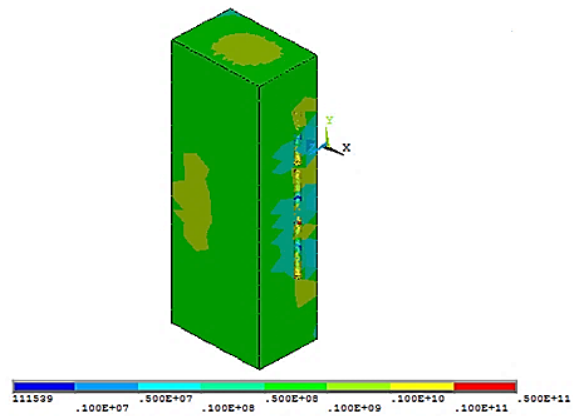


Figure-3. Contours of heat generated in the soot containing electrodes.

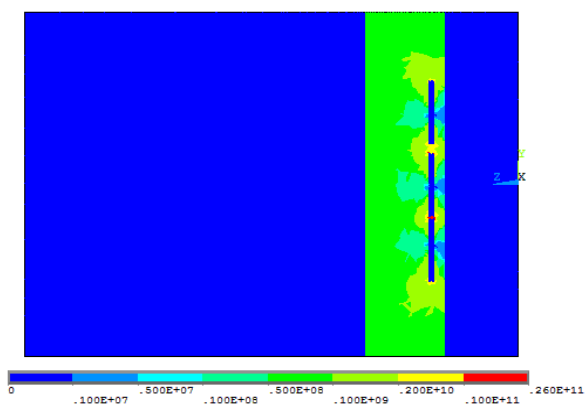


Figure-4. Contours of heat generated in soot containing metallic electrodes inside the cavity.

In order to simulate the temperature against the time of microwave heating, four points were chosen on the *x-y* face of the soot as shown in Figure-5. Points 1 and 2 were positioned in the lower and upper gaps that separate the three metallic electrodes. Points 3 and 4 were positioned on the opposite side to the points 1 and 2, which not contained the metallic electrodes.

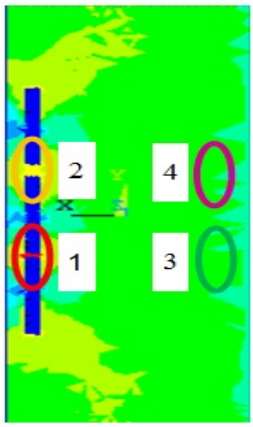


Figure-5. Location of the four points in the soot on *x-y* face.

The simulation of temperature behavior with microwave heating time for the four points is shown in Figure-6. The temperature of point 1 was increased from 298 K to about 1000 K at less than 1 second due to the electric field induced by the metallic electrodes existed inside the soot exposed to electromagnetic wave. Then after 2 seconds, the soot was oxidized upon reaching the temperature of 1350 K due to the continuous microwave heating. The temperature of point 2 increased from 298 K to about 900 K at less than 1 second due to the induction of the electric field and attained to the oxidation of 1064 K after 2 seconds of the microwave heating. The temperature at points 3 and 4 rose from 298 K to 340 K for 1 second of microwave heating. The temperature at points 3 and 4 rose slowly to the oxidation of 961 K and 946 K respectively after 14 seconds of microwave heating.

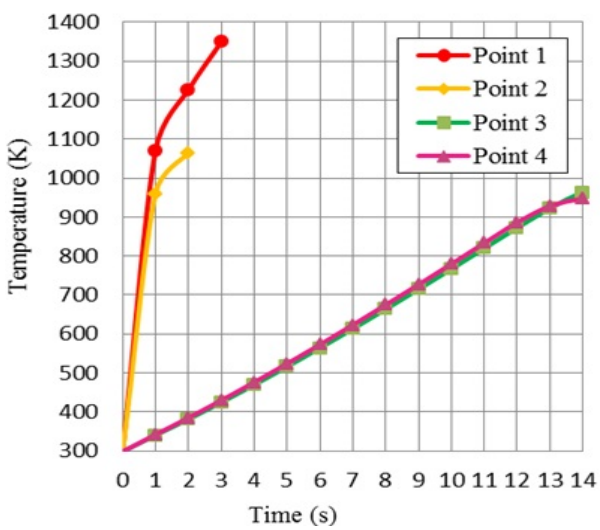
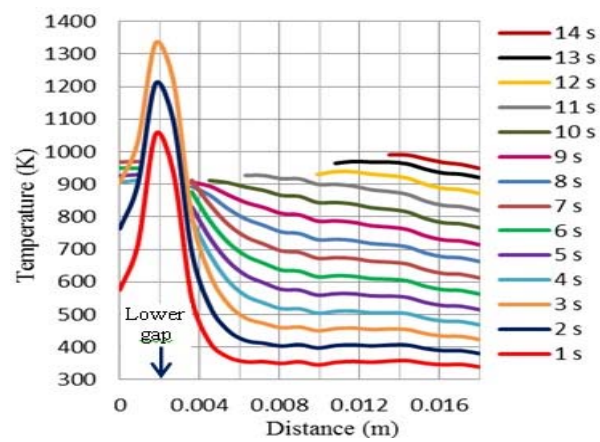
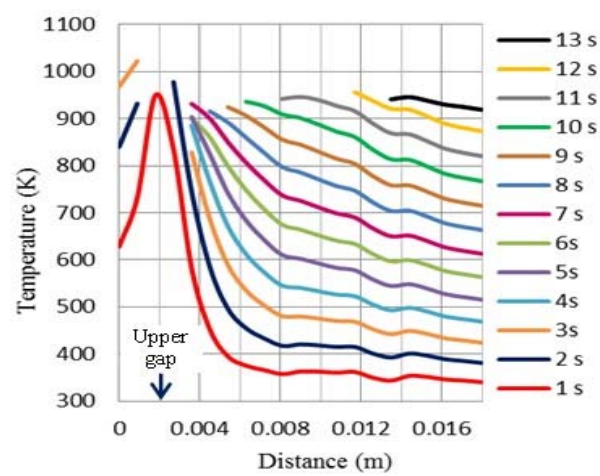


Figure-6. Temperature against microwave heating time for four points chosen inside the soot.

Figure-7 shows the temperature behavior against distance along *x*-axis within the soot across the lower and upper gaps at different times. The two gaps were positioned at 0.002 m distance from the left edge of soot sample along *x*-axis. The curve at 1 second showed a severe rise in the temperature to 1040 K and 940 K at lower gap and upper gap respectively due to the high electric field induced in the gap between two electrodes. The temperature reduced to 340 K at 0.018 m distance measured from the left soot edge along *x*-axis due to the reduction in the effect of electric field that was induced in the gaps. With time increase from 1 second to 14 seconds and 13 seconds, the temperature rose and temperature curves reduced in distance and focused at right side as shown in Figure-7 (a) and (b) respectively, due to the rapid soot oxidation at the left side close to the metallic electrodes. The results showed that the time required for microwave heating to raise the soot temperature from 298 K to 900 K (i.e. temperature rise of 602 K) was reduced from 12 seconds to less than 1 second due to the presence of multiple metallic electrodes in the soot.



(a)



(b)

Figure-7. Temperature with time against distance along *x*-axis cross (a) lower gap, (b) upper gap.

It is noticed in Figure-8, that the weight removal of soot due to the radiation of microwave heating for 8 seconds was happened close to ends of the metallic electrodes. After 12 seconds of microwave heating, the total weight loss of soot was grown, but the weight loss was elevated close to electrodes. After 13 seconds of microwave heating, the soot was removed around the electrodes, but not totally removed in the opposite side as shown in Figure-9.

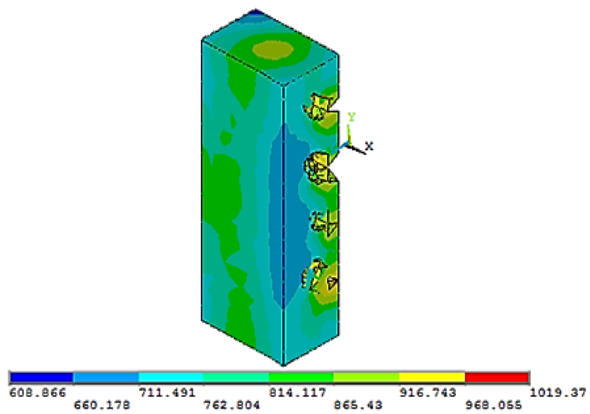


Figure-8. Contours of temperature in the soot after 8 seconds of microwave heating.

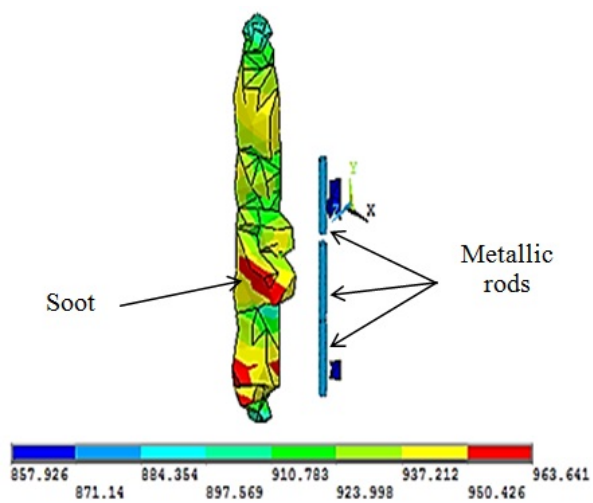


Figure-9. Contours of temperature in the soot after 13 seconds of microwave heating.

CONCLUSIONS

The conclusions from the simulation results refer that the time required to raise the temperature (to 900 K) of a dielectric material, which is soot, exposed to electromagnetic wave is minimized locally from 12 seconds to less than 1 second when accumulating the soot on multiple metallic electrodes. The accumulation of the soot on multiple metallic electrodes reduced the time of electromagnetic heating due to the high increase in the induced electric field, which generated high heat removed the soot around the electrodes rapidly. The maximum temperature was increased from 940 K to 1040 K (i.e. temperature rise was 100 K) when reduced the gap length between the electrodes from 0.0015 m to 0.0005 m.

For further applications of employing the concept of rapid microwave heating that was presented in this research work, metallic pieces could be inserted in the soot or waste accumulation to assist the microwave heating to burn the waste rapidly and save the consumed electromagnetic energy.

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NOMENCLATURE

c_p	Specific heat
dS	Surface integral
dV	Volume integral
h	Heat transfer coefficient
j	Imaginary part of a complex number
k	Thermal conductivity
t	Time
S	Surface area
T	Temperature
T_a	Ambient temperature
ε	Complex permittivity
ε_0	Permittivity of vacuum or air
ε_r'	Relative dielectric constant
ε_r''	Relative dielectric loss factor
μ_0	Magnetic permeability of vacuum or air
μ_r	Relative permeability
ρ	Density
ω	Angular frequency

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