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Original research article

Effect of Different Positions of Waveguide Port on the Coupled Model of Electromagnetic Wave and Heat Transfer in Microwave Heating of Coal

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ABSTRACT

Microwave heating has been used in coal processing for quite some time due to its low cost and time, and the ability to enhance the overall efficiency of the coal. Microwave ovens are widely used in microwave heating to understand the interaction between the microwaves and coal. A waveguide port, attached to the microwave oven, is responsible for the generation of the microwave radiation within the cavity. Its distance from the object placed inside the oven can affect the outcomes of the microwave heating. Therefore, it is important to study the effect of the waveguide position on the microwave heating of coal. In this paper, a coupled model of electromagnetic wave propagation and heat transfer is solved for a coal sample placed inside a microwave oven. The waveguide port is moved at a step of 10 cm for 15 positions, starting from the top of the left-side wall of the microwave oven up until above the glass table. Electric field intensity and temperature inside the microwave oven for each varied position of the waveguide port is calculated. An alternate pattern of increase and decrease in power absorption by the coal depending on the distance of the waveguide port has been observed. The highest power absorption occurs when the waveguide port is at one of the furthest positions from the coal.

Keywords: Coal; Electric field distribution; Microwave heating; Numerical simulation; Temperature distribution

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1. Introduction

Coal is one of the most abundant fossil fuels found around the world. It is also cheap and contributes to 42% of the world's electricity making it very popular in the developing countries [1, 2]. However, before its utilization, it is essential to process it in order to increase its efficiency and reduce some factors such as emission of greenhouse gases, etc. One technique that has been used lately and found very effective in processing the coal is microwave heating [3-6].

Microwave heating uses microwave radiation, which lies in the frequency range of 0.3-300 GHz. Microwave radiations have been used in many other fields such as telecommunications, industry, medicine, etc. [7, 8]. In microwave heating, the objects exposed to the microwave are categorized as insulators, conductors, and absorbers [9]. Insulators, such as sulphur, allow microwaves to penetrate them with no energy loss. Whereas, conductors such as copper do not let microwaves penetrate; instead they reflect them. Lastly, absorbers such as water absorb the microwave and then convert it into heat. Conventional heating methods not only heat the object but also the surrounding environment through conduction, convection, and radiation; also, they take a lot of time. Microwave heating is a fast technique and focuses only on the object that needs to be heated. The molecules of the object interact with the incident waves and a process of rotation and realignment happens which then leads to heat loss within the object [10, 11]. Due to its these advantages, microwave heating has been used in many other fields such as thawing [12], drying [13], sterilization [14], etc.

The simplest example of microwave heating is the microwave ovens used in our houses for heating food. However, to understand the overall process of microwave heating which includes the electric field distribution, temperature distribution in the oven and in the food, numerical analysis has been found very effective [15-17].

Microwave heating of coal processing is a wide field which includes drying [18], cooking [19], increasing grindability [20], desulphurization [21], flotation [22], etc. Microwave heating has been found to increase coal permeability, pore size, and fracture [23], thus increasing its overall efficiency. It has been shown that increasing the power in microwave heating increase the thermal heterogeneity of the coal [6]. There have also been studies to determine the effect of coal size, microwave frequency, microwave power, and coal permittivity on its thermal response to heating inside a microwave oven [4-6]. However, the effect of the position of the waveguide port on the microwave heating of coal has not been studied.

Li et al. [24] used two waveguide ports in a single microwave oven for coal heating. Huang et al. [6] used a microwave oven where the waveguide port was placed somewhere in the middle of the right wall of the oven. Pitchai et al. [25], and Liu et al. [26] used the microwave with a waveguide port on the upper wall of the microwave oven. The position of the waveguide port will affect the microwave heating and a comparison of its different positions on the microwave heating of the coal is an interesting analysis to conduct.

In this paper, a coupled model of electromagnetic wave propagation and heat transfer is solved by using FEM. The effect of the position of the waveguide port on the electric field distribution and temperature distribution inside the microwave oven is studied. To our knowledge, this is the first time when the effect of the waveguide port position on coal's response to the microwave heating is studied.

2. Problem Formulation

A geometrical model of the microwave oven with coal inside it is shown in Fig. 1. Electromagnetic wave propagation and heat transfer are solved by using FEM. The dimensions of the oven are given in the figure. Coal has a radius of 25 mm and height 60 mm [5]. The microwave is excited by 1[kW] power through the waveguide port. The waveguide port is first placed at 170cm above the ground on the left wall of the microwave oven and then moved down in decrements of 10 cm for 15 positions (explained in detail in section 3.3). The heating time for each position of the waveguide port is 60 seconds. Electric and thermal properties of the microwave oven and the coal are shown in Table 1.

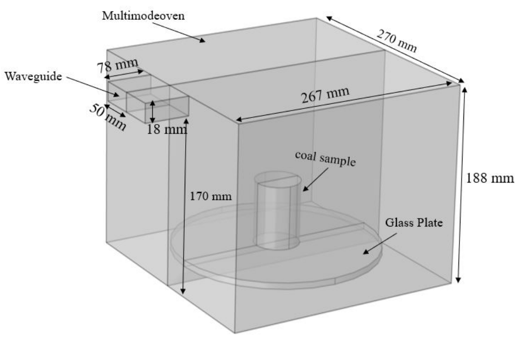


Fig. 1. Geometrical model of the microwave oven with coal sample inside it

3. Mathematical Model

To solve the coupled model of electromagnetic wave propagation and heat transfer analysis in the coal following assumptions have been made:

1. The dielectric and thermal properties of the model are constant throughout the simulation.
2. Any sort of chemical reaction, phase change, and energy exchange within the model are neglected.
3. The coal sample used in the study is homogenous and isotropic.
4. Heat transfer is only considered in the coal.

3.1 Equations for electromagnetic wave propagation analysis

To solve the EM wave propagation inside the microwave oven and coal, Maxwell's equations in frequency domain have been solved [5, 27]:

$$\nabla \times \mu_r^{-1}\left(\nabla \times E\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0, \tag{3.1}$$

where μ is the permeability, E is the electric field (V/m), k_0 is the free space wave number (m^{-1}), ε_r is the relative permittivity, $j = \sqrt{-1}$, σ is the electrical conductivity (S/m), ω is the angular frequency (rad/s), and ε_0 is the permittivity of vacuum.

k_0 can be defined as:

$$k_0 = \frac{\omega}{c_0}, \tag{3.2}$$

where c_0 is the speed of light in a vacuum (m/s).

Relative permittivity ε_r can be defined as:

$$\varepsilon_r = \varepsilon' - j\varepsilon'', \tag{3.3}$$

where ε' is the dielectric constant which shows the material's capability of storing EM field, and ε'' is the dielectric loss factor which determines the conversion of EM energy into heat energy.

EM waves generating from the wave guide propagate inside the microwave oven and interact with the dielectric materials inside it; this results in a conversion of EM energy into thermal energy, expressed as

$$Q_e = Q_{rh} + Q_{ml}, \tag{3.4}$$

where Q_{rh} are the resistive losses

Table 2. Dielectric and thermal properties of coal and microwave oven [5].

Material	ε_r	σ (S/m)	k (W/m·K)	ρ (kg/m³)	C (J/kg°K)
Coal	2.5-0.15*j	0.02	0.478	1300	4186.8
Glass	2.55	0	-	-	-
Nitrogen	1	0	0	-	-
Copper	1	5.998e7	400	8960	385

$$Q_{rh} = \frac{1}{2}\mathrm{Re}\left(J \cdot E^*\right) \tag{3.5}$$

where J is the current density *(A/m^2)* and Q_{ml} are the magnetic losses

$$Q_{ml} = \frac{1}{2}\mathrm{Re}\left(i\omega B \cdot H^*\right), \tag{3.6}$$

where B is the magnetic flux density (*Wb/m^2),* and H is the magnetic field intensity *(A/m).*

3.1.1 Boundary conditions for electromagnetic wave propagation analysis

EM waves are supposed to penetrate a small distance outside the microwave oven Hence, impedance boundary conditions are applied on the walls of the microwave oven, defined as

$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r - j\sigma/\omega}}\, n \times H + E - (n \cdot E)n = (n \cdot E)n - E_s, \tag{3.7}$$

where E_s is source electric field, used to specify the source current on the boundary *(V/m).*

The EM wave generating from the waveguide is in TE mode, meaning it does not have an electric field component in the direction of the propagation. In waveguides, EM waves propagate in some specific modes depending on the dimensions of the waveguide and the frequency. In this study, a rectangular waveguide is used and the cutoff frequency for different modes is defined by

$$(v_c)_{mn} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}, \tag{3.8}$$

where m and n are the mode numbers (*m=1, n =0)* and *a* and *b (a= 78mm, b = 18mm)* are the depth and width of the wave guide, respectively.

The port has a propagation constant, expressed as

$$\beta = \frac{2\pi}{c}\sqrt{v^2 - v_c^2}, \tag{3.9}$$

where v is the microwave frequency and v_c is the cutoff frequency.

3.2 Equation for heat transfer analysis

Electromagnetic losses (Q_e) from Eq. (4) are used as a heat source to calculate the temperature in the materials

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T\right) + Q_e, \tag{3.10}$$

where ρ is the density (kg/m³), C_p is the specific heat capacity *(J/kg.K)*, k is the thermal conductivity *(W/(m.K))*, and T is temperature *(K).*

3.2.1 Boundary condition for heat transfer analysis

The heat transfer is only considered in the coal, not in the surrounding region. Hence, a thermal insulation boundary condition is applied on the outer surface of the coal, expressed as

$$n\cdot(k\nabla T)=0. \quad (3.11)$$

3.3 Varying positions of the waveguide port and numerical procedure

The waveguide port is first placed 170 cm from the ground of the microwave oven, as shown in Fig. 2. The port is decremented in steps of 10 cm for total 15 positions until it reaches the final position of P15, which is 30 cm above the floor of the microwave oven. The last position of the port (P15) was chosen because it is right above the glass table of the oven. Going further would make the port go below the glass table, which is not reasonable for microwave heating.

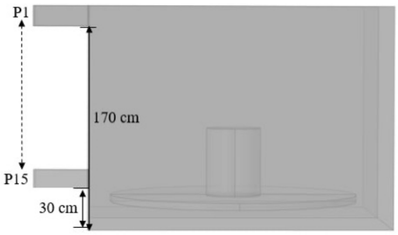


Fig. 2. Microwave oven showing the different positions of the waveguide port from P1 to P15.

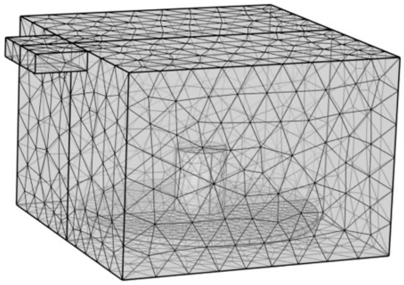


Fig. 3. Three-dimensional FEM mesh of the microwave oven used for microwave heating of coal.

FEM has been used to calculate the electric field and temperature distribution inside the microwave oven. FEM works by meshing the whole domain in small elements (Fig. 3), and then performing the numerical calculation. It is very important for the results obtained to be independent of the mesh elements. Fig. 4 shows the mesh convergence graph for the temperature when the waveguide is at P3 position. As can be seen, at 45000 elements the temperature calculated becomes independent of the mesh elements.

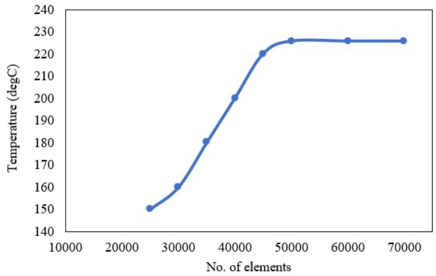


Fig. 4. Mesh convergence.

4. Results and Discussions

4.1 Numerical validation

To validate the accuracy of the results obtained from the present study, a numerical simulation has been performed by following the steps included in the previous published paper of [5]. Coal is placed in the microwave oven, where it is exposed to a microwave radiation of 2.45 GHz frequency at 1kW power for 600 s. The temperature distribution along an arc length is shown in Fig. 5. As can be seen, the calculated results are similar to the previous published work. The highest temperature obtained from the calculated result is 1558˚C and from the Lin et al. it is 1520 ˚C.

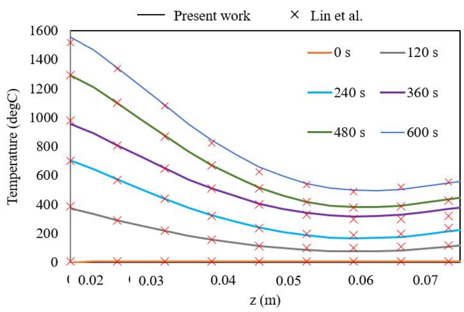


Fig. 5. Comparison between the calculated temperature distribution inside the coal with the literature [5].

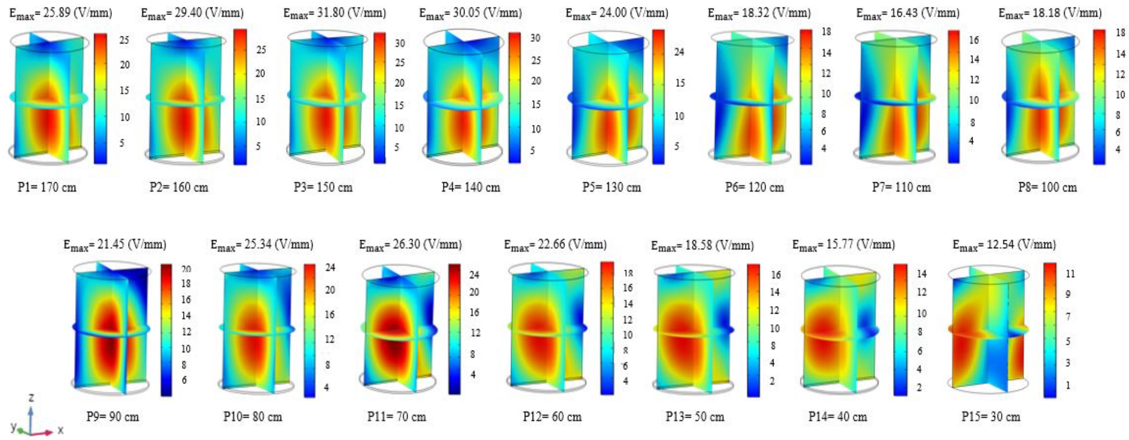
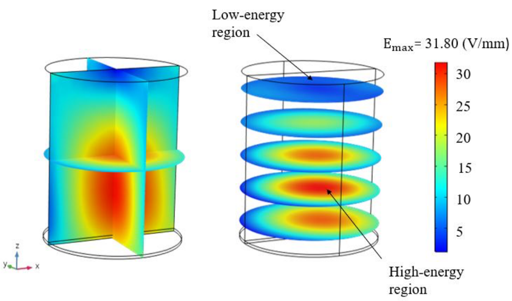


Fig. 6. Electric field distribution in the coal for all 15 positions (P1-P15) of the waveguide port.



(a) (b)

Fig. 7. Electric field intensity for P3 position of waveguide port (a) multi-slice plot and (b) slice plot.

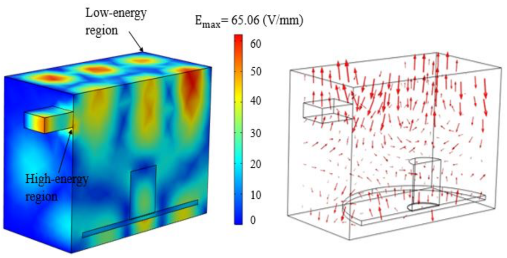


Fig. 8. Electric field intensity distribution in the oven for P3 position of waveguide port.

The temperature then gradually decreases as the arc-length approaches the bottom of the coal. The results show good agreement with the literature and, hence, give confidence in simulating the present work.

4.2 Electric field distribution in the coal

Microwaves travel from the waveguide port in the microwave oven cavity onto the coal placed on the glass table. The waves penetrate the coal and the energy gets absorbed. Electric field intensity inside the coal for different positiond of the waveguide port is calculated and shown in Fig. 6. The highest power absorption by the coal occurs when the waveguide port is at P3 position, which is 150cm from the floor of the microwave oven. This higher power absorption leads to higher value of electric field intensity inside the coal. High-energy and low-energy regions are generated, denoting higher and lower power absorption in the coal, respectively (Fig. 7). High and low energy regions on the coal move depending on the positions of the waveguide port. When the value of electric field intensity is higher, the high-energy region seems to be concentrated in the middle region of the coal. Whereas, when the value of electric field intensity is low, the high-energy region spreads out on the outer side of the coal. Moreover, a pattern of increase-decrease-increase-decrease in power absorption is observed for different positions of the waveguide port. The coal's electric field intensity first gradually increases for P1-P3 positions. It then drops for P4 - P7 positions before going up again

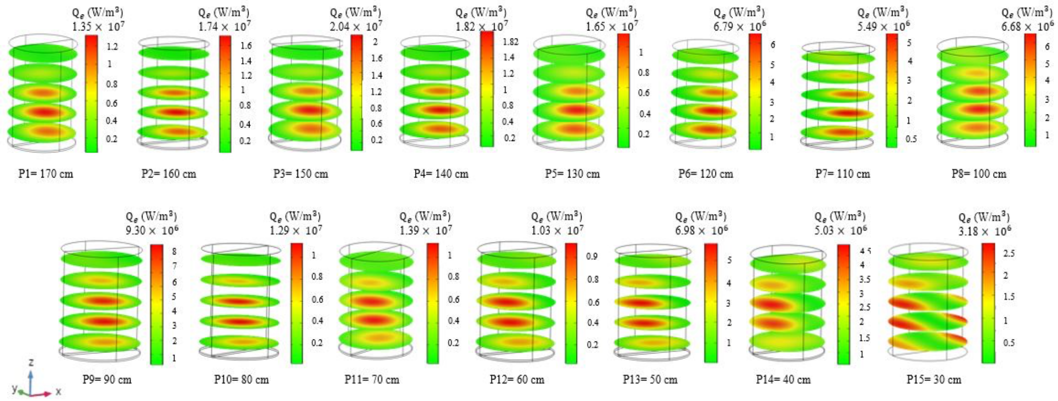


Fig. 9. Electromagnetic power loss density in the coal for all 15 positions (P1-P15) of the waveguide port.

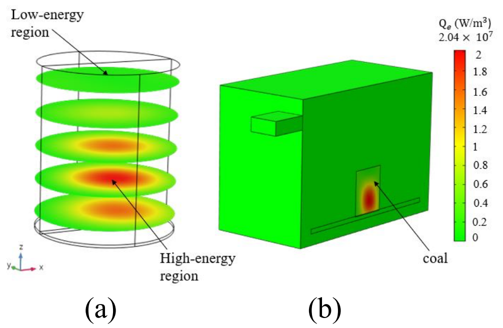


Fig. 10. Electromagnetic power loss density for P3 position of waveguide port (a) slice plot and (b) cross-section view of microwave oven.

for P8-P11. Finally, it again drops for P12-P15. Fig. 7 shows the highest value of electric field intensity as 31.80 (V/mm) obtained in the coal for P3 position. Fig. 7(a) shows the multi-slice and Fig. 7(b) shows the slice plot of the coal. As can be seen, the high-energy region for the higher value of electric field intensity is concentrated towards the middle of the coal. Fig. 8 shows the cross-sectional view of the electric field intensity distribution inside the oven for the P3 position of the waveguide port. The high-energy region is found on the waveguide port while the low-energy region is found on the far upper right side of the oven. As can be seen, the higher value of electric field intensity is on the upper area of the microwave oven in front of the waveguide port and above the coal. Some part of the electric field gets absorbed by the coal and some is reflected by the metallic walls of the oven. The absorbed energy in the coal then is converted into heat as explained in the further sections.

4.3 Electromagnetic power loss density distribution in the coal

The absorbed energy in the coal then is converted into heat, according to Eq. 4. Fig. 9 shows the electromagnetic power loss density in the coal for all 15 positions of the waveguide port. As can be seen, the power loss density is also highest for the P3 position of the waveguide port. The formation of the high-energy and low-energy region also corresponds to the electric field intensity. The high-energy region is concentrated towards the center when the value of power loss density is higher. The pattern of increase-decrease-increase-decrease in power loss density has also been observed in the coal for the same positions of the waveguide port as found in electric field intensity.

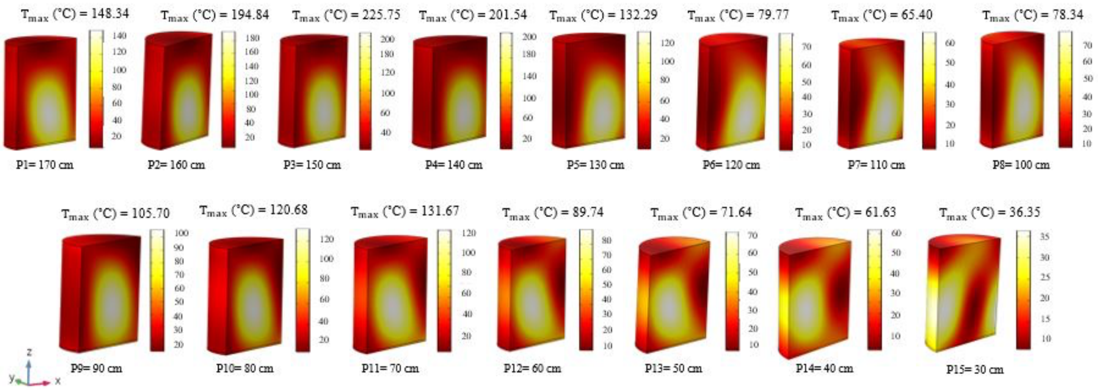
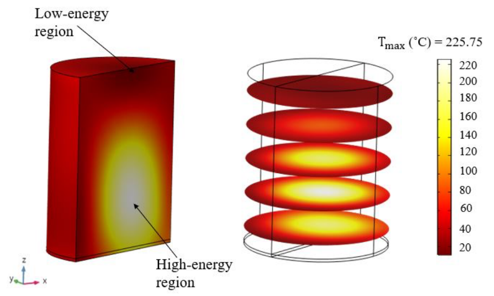


Fig. 11. Temperature distribution in the coal for all 15 positions (P1-P15) of the waveguide port.



(a) (b)

Fig. 12. Temperature distribution in the coal for P3 position of waveguide port (a) cross-section and (b) slice plot view.

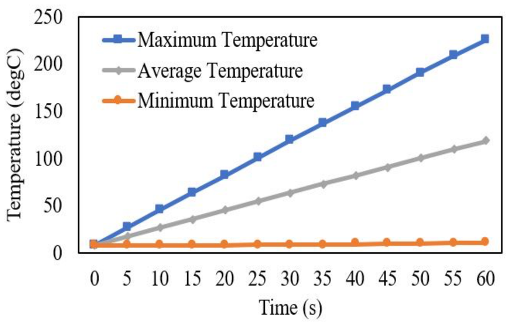


Fig.13. Temperature vs time graph of maximum, minimum, and average temperature in the coal for P3 position of the waveguide port.

Fig. 10 shows the power loss density for the highest value found at the P3 position. The power loss density in the microwave oven is zero, as the heat generation is only considered in the coal.

4.4 Temperature distribution in the coal

Temperature distribution in the coal for all positions of the waveguide port is calculated for 60sec and shown in Fig. 11. The temperature distribution corresponds to the electric field intensity and power loss density (Figs. 6 and 9). This similarity in the pattern of energy distribution among electric field intensity, power loss density, and temperature in the coal was also reported by Lin et al. [5]. The highest value of temperature is found for the P3 position of the waveguide port (225.75˚C), shown in Fig.12. As was the case in Sections 4.2 and 4.3, the high-energy region is concentrated towards the center. Unlike electric field intensity and power loss density, heat transfer is a transient procedure. To clearly see how the increase-decrease-increase-decrease in power absorption occurs in the coal, graphs between temperature vs time have been plotted. Fig. 13 shows the temperature vs time graph for maximum, minimum, and average temperature in the coal obtained for the P3 position of the waveguide port. Fig. 14 shows temperature vs time graph for all positions of the waveguide port. A clear alternate behavior of temperature distribution can be seen here.

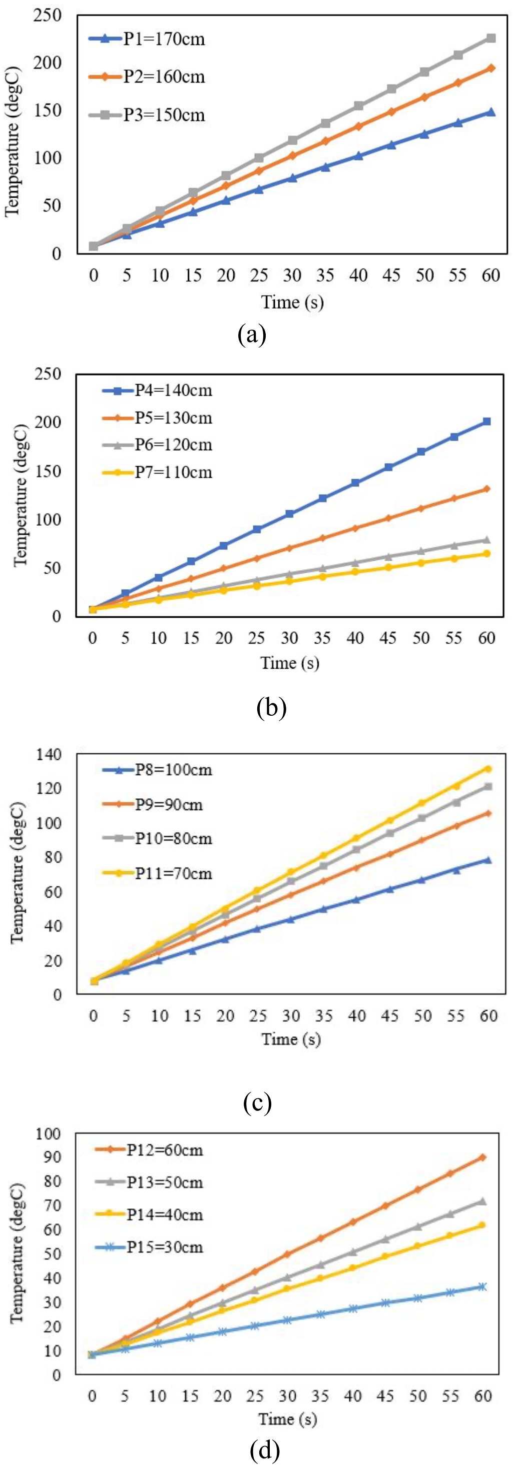


Fig. 14. Temperature vs time graph in the coal for waveguide position of (a) P1-P3, (b) P4-P7, (c) P8-P10, and (d) P11-P15.

5. Conclusion and Future Work

A coupled model of electromagnetic wave propagation and heat transfer is solved for microwave heating of coal. Effect of the different positions of waveguide port on the electric and thermal response of the coal has been studied. The position of the waveguide port has been found to significantly influence the results of microwave heating of coal. A pattern of increase-decrease-increase-decrease in power absorption in the coal for varied position of the waveguide port is observed. The hot and cold spot region on the coal moves according to the pattern of the power absorption of coal. Among all the waveguide port positions highest values of electric field intensity, electromagnetic power loss density, and temperature is found when the waveguide port are at P3 position (150cm from the microwave oven floor). In future, the positions of the waveguide port can be varied in three dimensions to further study the effect on the microwave heating of coal.

Acknowledgements

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