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Convective Flow and Distribution of Concentration in Porous Media Subjected to Electromagnetic Field (Computation Based on Local Thermal Non-Equilibrium Models)

Prempreeya Montienthong [1], Phadungsak Rattanadecho [2,*], and Waraporn Klinbun [3]

[1,2] Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), 99 moo 18, Klong Luang, Pathum Thani 12120, Thailand
[3] Panyapiwat Institute of Management, 85/1 Moo 2, Chaengwattana Rd., Bang Talad, Pakkred, Nonthaburi, 11120, Thailand
Corresponding Author: ratphadu@engr.tu.ac.th, 02564-3001 #3153

Abstract

This paper is carried out on the simulation 2D model of convective flow in porous media subjected to electromagnetic field. This study focuses on effects of input power of electromagnetic wave and input velocity of fluid on convective flow and distribution of concentration in porous media. The mathematical models based on LTNE consist of Maxwell's equations, momentum equation, fluid phase energy equation, solid phase energy equation and concentration equation. In numerical simulation, these mathematical models are solved by using finite difference time domain method (FDTD) for electromagnetic field and finite control volume method (FVM) for heat, flow fields and concentration. The effects of input power of electromagnetic wave i.e. 500, 800, 1000 and 1600 W were investigated. Distribution of temperature, velocity field and distribution of concentration during saturated flow inside porous media were discussed. This investigation provides the essential aspects for a fundamental understanding of convective flow and distribution of concentration within porous media while experiencing an applied electromagnetic field such as applications related to the transport of concentration in microwave food.

***Keywords**:* Distribution of concentration, Electromagnetic field (mode TE_{10}), Local thermal non equilibrium (LTNE) models.

1. Introduction

Microwave has the important role in the industry. The advantages of producing heat from microwave are high efficiency, has ability to select receiving heat and has energy penetration that makes heat can distribute uniformly through the object. Ordinary, the heat transfers in porous media such as means some examples, such as boiled eggs in salt water, oil on the beach, impurities in water that has been heated by the sun. All these are porous materials with contaminants are heated under forced convection and natural convection. Applications of electromagnetic waves are widely implemented in food industries and packaging in food microwave. And thermal natural convection combined electromagnetic wave in porous media is normally seen in environment such as water movement in geothermal reservoirs, underground spreading of chemical wastes and other pollutants, grain storage, thermal insulation, evaporative cooling and solidification [1]. Concentration or mass diffusion in the porous media is frequently found in daily life. For example, the infiltration of contaminants and fertilizer through soil layers, contaminants in food, catalytic converters in car and crystal growth. One of mass diffusion or concentration applications is sintering process; process of heating a material to just below the melting point so that it forms one solid mass to create a solid material such as metal and ceramic powders etc. [2].

Karimi-Fard et al [2] indicated a numerical study of double-diffusive natural convection in square cavity which was filled in the porous medium. This research focused on the influence of the Lewis number on the inertial and boundary effects which affected on the double-diffusive convection. Khanafer and Vafai [1] presented a numerical study of mixed-convection heat and mass transport in a lid-driven square enclosure which was filled in a non-Darcian fluid-saturated porous medium. The results were the buoyancy ratio, Darcy number, Lewis number and Richardson number had profound effects on the double-diffusive phenomenon. Jena et al. [3] presented the study which focused on an analyze buoyancy opposed double diffusive natural convection in a square porous cavity having partially active thermal and solutal walls. Trevisan and Bejan [4] studied the natural convection phenomenon occurring inside a porous layer with both of heat and mass transfer from the side. The natural circulation was driven by a combination of buoyancy effects with temperature and concentration variations. Nishimura et al [5] showed the effect of buoyancy ratio on the flow structure which was investigated numerically for a binary mixture gas in a rectangular enclosure. Weaver and Viskanta [6] presented the influence of augmenting, opposing thermal and solutal buoyancy forces on binary gases natural convection. Nithiarasu et al [7] indicated the double-diffusive natural convective flow within a rectangular enclosure. Heat and mass transfer in microwave heating processes, including natural convection in liquid have been investigated. Saltiel and Datta [8] investigated heat transfer in liquid at any point of solid and fluid temperature by using Local Thermal Equilibrium model.

Investigation of heat transfer in microwave heating processes and natural convection in porous media are complicated. Many researchers have been carried out in this problem such as Wessapan and Rattanadecho [9], Saneewong Na Ayuttaya et al. [10] and Makul et al. [11].

Previous researches are based on invoking the Local Thermal Equilibrium model (LTE) based on the assumption that the solid phase temperature is equal to fluid phase temperature everywhere in the porous media. Two different models are used for analyzing heat transfer in a porous media i.e. Local Thermal Equilibrium model (LTE) and Local Thermal Non-Equilibrium model (LTNE). In recent years, the LTNE model has received more attention to demonstrate the heat transport in porous media because LTE model is not suitable for a number of physical situations such as the fluid flows at a high speed through the porous media.

Heat transfer in microwave heating processes and natural convection in porous media under Local Thermal Non-Equilibrium were studied by Keangin et al. [12]. The influences of blood velocities, porosities, input microwave powers and positions within the porous liver on the tissue and blood temperature distributions have been investigated.

Klinbun et al. [13] also studied heat transfer in the microwave heating processes and forced convection in porous media under the Local Thermal Non-Equilibrium model. The effect of electromagnetic field on forced convection in a fluid-saturated porous medium is analyzed. The effects of the dimensionless electromagnetic wave power and dimensionless electromagnetic wave frequency on the dimensionless temperature field and nusselt number distribution are discussed. This research found temperature and nusselt number values increase substantially with an increase in the electromagnetic power.

In the same way, Nakayama et al. [14], Quintard [15], Amiri and Vafai [16] and Kuznetzov [17] also researched about heat transfer in porous media by used local thermal Non-equilibrium model, but the difference in microwave is not related to their research.

It seems that LTE model is not considered the temperature difference between the solid and fluid phases within the porous media which the temperature difference significantly influence on the heat transfer. Therefore, this research chooses the LTNE model to analyse the effect of electromagnetic field on distribution of temperature, velocity and concentration during saturated flow in porous media.

However, a few studies concentrated energy equations, momentum and concentration equations of porous media subjected to electromagnetic fields under LTNE model. Therefore, to approach reality, modeling of heat transport, momentum and concentration in porous media is must be cooperating with the modeling of electromagnetic in order to completely these analysis. In addition, there are various effects related to the solid and fluid temperature and flow field, such as input velocities and input microwave powers that still not well understood.

In this study, investigates the distribution of solid and fluid temperatures, concentration and flow field within porous media under electromagnetic wave based on LTNE model. Distribution of temperature, velocity field and concentrated contaminants during convective flow in porous media were discussed. Mathematical model of the porous media approach is proposed, which uses transient energy, momentum and concentration equations coupled with Maxwell's equation. The coupled nonlinear set of governing equations as well as initial and boundary conditions are solved using the finite control volume and finite difference time domain method.

2. Analysis

Convective flow through a packed bed of spherical particles subjected to an electromagnetic field as shown in Fig. 1. is considered. The configuration consists of a porous media that fills inside a rectangular waveguide. The assumptions are as follows. Walls of the guide are assumed to be made of metal which approximates a perfect electrical conductor. The monochromic wave in fundamental mode (TE_{10}) is applied in the x-direction. The domain in which the electromagnetic field is analyzed includes the entire region enclosed by the walls of the guide. For temperature and flow fields the computational domain is limited to the region enclosed by the container. The horizontal walls of container are kept at a constant temperature.

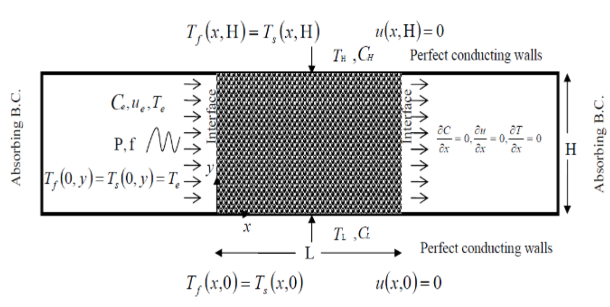

Fig. 1. Schematic diagram (2D) of the problem under consideration and the corresponding coordinate system.

Table. 1 Thermal and dielectric properties used in the computations. [13]

Material property	Air	Water	Soda lime
Density, $\rho\left(\text{kg m}^{-3}\right)$	1.1	989	2225
Specific heat, $C_p\left(\text{J kg}^{-1}\ \text{K}^{-1}\right)$	1008	4180	835
Thermal conductivity, k $\left(\text{Wm}^{-1}\ \text{K}^{-1}\right)$	0.028	0.640	1.4
Viscosity, μ $\left(\text{kg m}^{-1}\text{s}^{-1}\right)\times 10^5$	1.9	57.7	-
Dielectric constant, γ_r	1.0		7.5
Loss tangent, tan δ	0.0		0.0125

Dielectric constant and Loss tangent of water are $88.15-0.414T+(0.131\times10^{-2})T^2$ $-(0.046\times10^{-4})T^3$and $0.323-(9.499\times10^{-3})T+(1.27\times10^{-4})T^2$ $-(6.13\times10^{-7})T^3$ respectively.

2.1 Analysis of the electromagnetic field

Maxwell's equations for TE_{10} mode are solved to obtain the electromagnetic field inside a rectangular waveguide and the enclosed porous medium [13].

$$E_z, H_x, H_y \neq 0 \tag{1}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\gamma}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z\right) \tag{2}$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\varphi}\left(\frac{\partial E_z}{\partial y}\right) \tag{3}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\varphi}\left(\frac{\partial E_z}{\partial x}\right) \tag{4}$$

where E and H are the electric and magnetic fields, γ is electric permittivity, φ is magnetic permeability, and σ is electric conductivity.
Boundary and initial conditions:
1) Perfect conduction condition is utilized at the inner walls surface of waveguide. Therefore, normal components of the magnetic field and tangential components of the electric field vanish at these walls:

$$H_{\text{n}} = 0, E_{\text{t}} = 0 \tag{5}$$

Where subscripts t, n denote the components of tangential and normal directions, respectively.
2) The first order absorbing condition by Mur [17] are used at the both ends of the waveguide:

$$\frac{\partial E_x}{\partial t} = \pm c\frac{\partial E_x}{\partial x} \tag{6}$$

where $\pm$ is represented forward and backward direction and is denotes the phase velocity of the propagation wave.

3) The input microwave source is simulated by the equations (Ratanadecho et al., 2002):

$$E_z = E_{zin}\sin\left(\frac{\pi y}{a}\right)\sin\left(2\pi ft\right) \tag{7}$$

$$H_y = \frac{E_{zin}}{Z_H}\sin\left(\frac{\pi y}{a}\right)\sin\left(2\pi ft\right) \tag{8}$$

where f is the frequency of microwave, y is the width of the rectangular waveguide, Z_H is the wave impedance, E_{zin} and is the input value of the electric field intensity. By applying the Poynting theorem, the input value of the electric field intensity is evaluated by the microwave power input as:

$$E_{zin} = \sqrt{\frac{4Z_H P_{in}}{A}} \tag{9}$$

where P_{in} is the microwave power input and A is the area of the incident plane.

4) The continuity conditions at the interface between different materials are given by:

$$E_t = E_t^{'}, H_t = H_t^{'} \tag{10}$$
$$D_n = D_n^{'}, B_n = B_n^{'} \tag{11}$$

5) Initial conditions:

$$E, H = 0 \quad ; t = 0 \tag{12}$$

2.2 Analysis of flow , temperature field and concentration

To reduce the complicate of the problem, the following assumptions are applied:
1) The fluid is an incompressible Newtonian fluid.
2) Phase change does not occur.
3) The Boussinesq approximation is applied.

4) The porous medium is isotropic.
5) The effect of magnetic field on heating is negligible.
6) Thermal dispersion is omitted.
The governing equations for analysis flow and heat transfer in this study areas following:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (13)$$

Momentum equation:

$$\frac{1}{\varepsilon}\left(\frac{\partial u}{\partial t}\right)+\frac{1}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)= -\frac{1}{\rho_f}\left(\frac{\partial p}{\partial x}\right)+\frac{\mu}{\varepsilon}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) -\frac{\mu u}{\kappa}-\frac{F\mu}{\sqrt{\kappa}}\left(u^2+v^2\right)^{1/2}u \quad (14)$$

$$\frac{1}{\varepsilon}\left(\frac{\partial v}{\partial t}\right)+\frac{1}{\varepsilon^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)= -\frac{1}{\rho_f}\left(\frac{\partial p}{\partial y}\right)+\frac{\mu}{\varepsilon}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) -\frac{\mu v}{\kappa}-\frac{F\mu}{\sqrt{\kappa}}\left(u^2+v^2\right)^{1/2}v +g\beta_T\left(T-T_0\right)+g\beta_C\left(C-C_0\right) \quad (15)$$

The geometric F function, and κ permeability, [13]

$$F=\frac{1.75}{\sqrt{150\varepsilon^3}} \quad (16)$$

$$\kappa=\frac{\varepsilon^3 d_p^2}{150\left(1-\varepsilon\right)^2} \quad (17)$$

In addition, the variation of porosity near the impermeable boundaries can be expressed as [13].

$$\varepsilon=\varepsilon_\infty\left[1+a_1\exp\left(-\frac{a_2 y}{d_p}\right)\right] \quad (18)$$

a_1, a_2 are empirical constants

Fluid phase energy equation:

$$\varepsilon\left(\rho C_p\right)_f\frac{\partial T_f}{\partial t}+\left(\rho C_p\right)_f\left(u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}\right)= k_{feff}\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}\right)+h_{sf}a_{sf}\left(T_s-T_f\right)+\varepsilon Q_f \quad (19)$$

Solid phase energy equation:

$$\left(1-\varepsilon\right)\left(\rho C_p\right)_s\frac{\partial T_s}{\partial t}=k_{seff}\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}\right) -h_{sf}a_{sf}\left(T_s-T_f\right)+\left(1-\varepsilon\right)Q_s \quad (20)$$

where Q is the local electromagnetic heat generation term, which is a function of the electric field and defined as:

$$Q=2\pi f\gamma_0\gamma_r'\left(\tan\delta\right)\cdot\left(E_z\right)^2 \quad (21)$$

$$\tan\delta=\frac{\gamma_r''}{\gamma_r'}=\frac{\sigma}{\omega\gamma_r'\gamma_0} \quad (22)$$

Concentration equation:
The concentration transport equation is utilized [1,2]

$$\varepsilon\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \quad (23)$$

Boundary and initial conditions:
From Fig.1, no slip boundary conditions are applied at all the solid walls which are kept at a constant temperature. Thus, the boundary conditions are as follows:

$$T_f\left(0,y\right)=T_s\left(0,y\right)=T_e=27\ °C$$
$$T_f\left(x,\mathrm{H}\right)=T_s\left(x,\mathrm{H}\right)=T_\mathrm{H}=67\ °C$$
$$T_f\left(x,0\right)=T_s\left(x,0\right)=T_\mathrm{L}=15\ °C$$
$$u\left(0,y\right)=u_e\ ,\mathrm{Re_p}=\rho_f u_e d_p/\mu$$
$$u\left(x,\mathrm{H}\right)=0$$
$$u\left(x,0\right)=0$$
$$C\left(0,y\right)=C_e=30, 0.03\ \mathrm{mol/dm^3}$$
$$C\left(x,\mathrm{H}\right)=C_\mathrm{H}=20\ \mathrm{mol/dm^3}$$
$$C\left(x,0\right)=C_\mathrm{L}=10\ \mathrm{mol/dm^3}$$

From Fig.1, Outlet boundary conditions are used for model flow exits where the details of the flow velocity and pressure are not known prior to solution of the flow problem. There are appropriate where the exit flow is close to a fully developed condition, as the outlet boundary condition assumes a zero normal gradient for all flow variables except pressure.

$$\frac{\partial C}{\partial x}=0, \frac{\partial u}{\partial x}=0, \frac{\partial T}{\partial x}=0$$

Initial conditions are as follows:

$$T = T_0 = 27\,°C$$
$$u = u_0$$
$$C = C_0 = 0\,\text{mol/dm}^3 \qquad ; t = 0$$

3. Numerical simulations

Maxwell's equations are solved using the finite-difference time-domain (FDTD) method. The electric (E) and magnetic (H) field components are discretized using a central differencing scheme (second-order) in both space and time domains. The equations are solved using the leap-frog methodology; the electric field is solved at a given time step, the magnetic field is solved at the next time step, and the process is repeated sequentially. The fluid flow and heat transport within a porous medium are coupled to Maxwell's equations. These equations are solved numerically using a finite control volume approach along with the SIMPLE algorithm. The proposed discretization conserves the fluxes and avoids generation of a parasitic source. The basic strategy for the finite control volume discretization method is to divide the computational domain into a number of control volumes and then integrate the conservation equations over this control volume within an interval of time [t, t + Δ t]. At the boundaries of the computational domain, integrating over half the control volume and taking into account the boundary conditions discretizes the conservation equations and at the corners a quarter of the control volume is utilized. The fully implicit time discretization finite difference scheme is used to arrive at the solution in time. To insure stability of the time-stepping algorithm Δt is chosen to satisfy the courant stability condition.

$$\Delta t \le \frac{\sqrt{(\Delta x)^2 + (\Delta y)^2}}{c} \tag{24}$$

and the spatial resolution of each cell satisfies:

$$\Delta x, \Delta y \le \frac{\lambda_g}{10\sqrt{\gamma_r}} \tag{25}$$

where λ_g is the wavelength of microwave in the rectangular waveguide and γ_r is the relative electric permittivity.

The following set of simulation parameters are used to satisfy conditions given by Eqs. (24) and (25):
(1) Grid size: $\Delta x = 1.0$ mm and $\Delta y = 1.0$ mm.
(2) Time steps: $\Delta t = 2\times10^{-12}$ s is used corresponding to electromagnetic field and $\Delta t = 0.01$ is used corresponding to temperature field, velocity field and concentration calculations.
(3) Relative error in the iteration procedures is ensured to be less than 10^{-6}

4. Results and discussions

4.1 Validation

The computational results are displayed in fig.2., The results are in excellent agreement with the results given by Klinbun [13]. This model can be used to describe the fundamental attributes of convective flow in a porous medium subject to electromagnetic field.

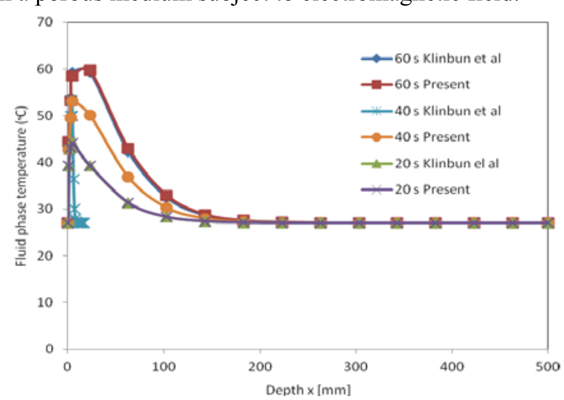

Fig 2. Comparisons of fluid phase temperature for the present work versus the results of Klinbun et al.

In order to verify the accuracy of present model, the numerical results for the case without a concentration transport are validated againt the analytical results with the same conditions obtained by Klinbun [13].

Overall, our results in the present study are in excellent agreement with the analytical result by Klinbun [13]. This highly favorable comparison lends confidence in the accuracy of the present numerical model.

4.2 Analysis of electromagnetic field

Fig. 3. shows simulation of electric field at microwave frequency of 2.45 GHz, microwave power of 500 W, Particle Reynolds number (Re_p= $\rho_f u_e d_p / \mu$) = 0.1, where the center of the porous media can be seen that large amplitude and gradually decreases as wave moves into the porous media. Most waves are reflected back from the surface and

resonance with large amplitude, while the electric field in the material gradually decrease and disappear because of wave penetration.

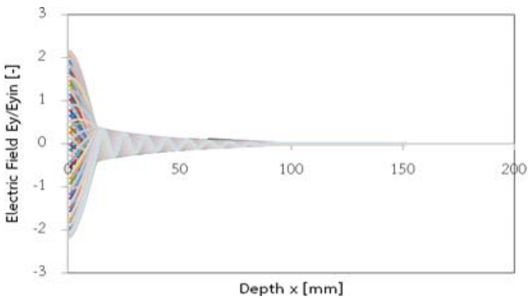

Fig. 3. Simulation of the electric field along porous packed bed at microwave frequency of 2.45 GHz, microwave power of 500 W Reynolds number (Re_p) = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3

4.3 The influence of microwave power on distribution of temperature, velocity and concentration of fluid in porous media

Distribution of temperature

Relate to the problem of the process of the heat from microwave that is related to the electromagnetic and the distribution of the temperature. This study estimate the electromagnetic which are indicate the power of microwave inside dielectric materials and also tell that it's gradually decreased. This means the power of the wave transfers into another form that we called heat. In other words, the power of the microwave is slightly decrease, because the power has been absorb by the dielectric materials and changes the wave into the heat form which is called the Internal Heat Generation. In contrast, the properties of the electric materials strongly effect to the microwave by drop off the power generator of the microwave.

Fig. 4. and 5 display the effect of variations in the microwave power on the distribution of temperature. The results show that the highest temperatures values do correspond to the highest microwave power. The highest temperature values, for the cases considered here, correspond to microwave power of 1600 W, while microwave power of 800 W produces the lowest values of the temperature. Since the power of the microwave has more intense than the electromagnetic field. Therefore, the materials can absorb a huge energy from the microwave power. At the middle of porous media, it has most absorption, because the high density of the electromagnetic field around the center of porous media which makes this area becomes highest temperature. Distribution of temperature happened on the left side that takes the microwave wave has high temperature and slowly decrease along with the x-axis. From the figure, you can see the upper boundary of distribution of temperature is higher than the lower because this study specified the upper one to have the high temperature.

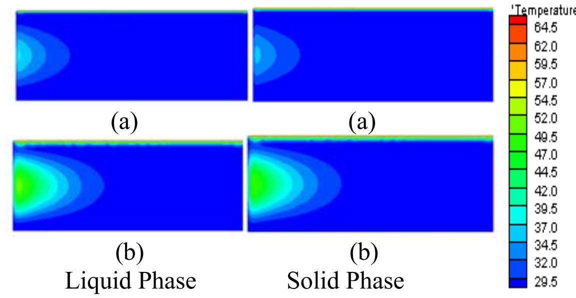

Fig. 4. Distribution of temperature in porous media (ºC) with elapsed times: (a) 20 s (b) 60 s at microwave power of 800 W (microwave frequency of 2.45 GHz, Reynolds number (Re_p) = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3)

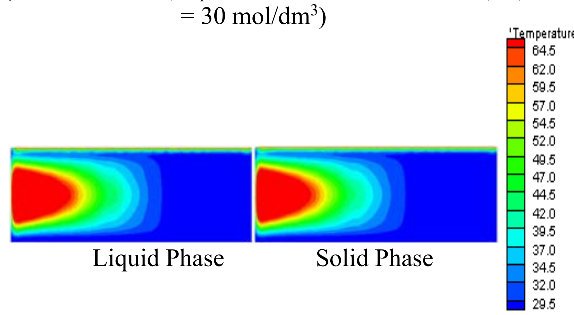

Fig. 5. Distribution of temperature in porous media (ºC) with elapsed times: 60 s at microwave power of 1600 W (microwave frequency of 2.45 GHz, Reynolds number (Re_p) = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3)

To classify the outcome on qualitative ratings for LTE assumption, this may be expressed in the following form

$$\%\text{LTE} = \left(\frac{T_{f(i,j)} - T_{s(i,j)}}{T_{f(i,j)}} \right) \times 100 \qquad (26)$$

Compare the distribution of temperature on x-y axis at the 60 second. Obviously, the left side has high temperature and gradually down along the depth. After all, the mechanism process of the high absorption of porous media as we called High Lossy Material. Most of that wave that is incident on the material always absorb by the porous media, except some of them that have reflect out to the surface. Also, the wave that transmits through the layer of the porous media is less.

Fig. 6. Compares the percentage difference of distribution of temperature of fluid phase and solid phase at 0-60 s on x-axis equal 25 mm, y-axis equal 99 mm, at microwave frequency of 2.45 GHz, microwave power 500, 800, 1000 and 1600 W. At time 10 s to see that the percentage difference of distribution of temperature of the fluid phase and solid phase have the highest at microwave power 1600 W (% LTE = 14).

At microwave power 500, 800 and 1000 W have % LTE about 3 – 8. As can be seen the local thermal equilibrium assumption deteriorate as microwave power increase. The local thermal equilibrium assumption is suitable in the case microwave power of 1600 W.

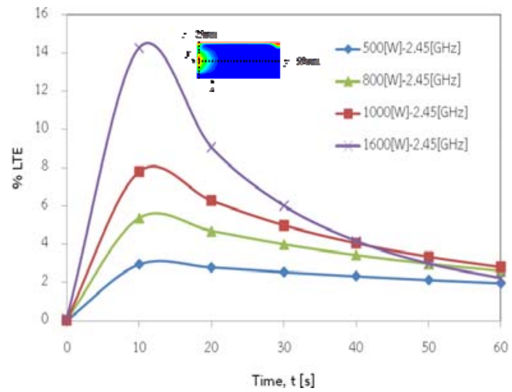

Fig. 6. Percent difference of distribution of temperature of solid and fluid phase at x-axis = 25 mm, y-axis = 99 mm at different microwave power with elapsed times. (microwave frequency of 2.45 GHz ,inlet concentration (C_{in}) = 30 mol/dm^3)

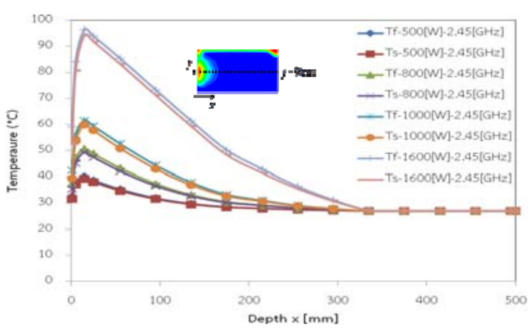

Fig. 7. Distribution of temperature of the solid and fluid phase at difference microwave power along x-axis at y-axis = 99 mm (microwave frequency of 2.45 GHz at time 60 s inlet concentration (C_{in}) = 30 mol/dm^3)

Fig. 7. shows relationship of temperature of the fluid and solid phase at operating inlet microwave power (P = 500, 800, 1000 and 1600 W) on the x-axis, y-axis equal 99 mm, frequency 2.45 GHz at 60 s. The temperature increased and reached a maximum on x-axis about 25 mm and then gradually decreased as along x-axis. The temperature decreases in direction of wave, consistent with conditions of resonance of standing wave. Microwave energy is changed into heat energy in porous media. The maximum temperature in porous media is approximately 40, 51, 63 and 97 ºC at 500, 800, 1000 and 1600 W microwave power, respectively at microwave frequency of 2.45 GHz.
This study proves distribution of temperature in the porous media, in case that more power has higher distribution of temperature. With the middle of the porous has constantly distribution of temperature. The influences of the fluid (Marangoni Effect) that makes the heat move from the middle to the surrounding surface. Including, this figure also shows that the temperature inside the porous media is slightly increasing at the beginning of the heat process. After that, temperature is gradually reduced. Since, the action of the Dielectric Loss Factor is decrease when the temperature is increasing.

Flow Pattern

Velocity fields within porous media at t =60 s are discussed, one sees that the microwave power has important effects on the velocity field. This study has three powers i.e. 500, 800, and 1600 W. The physical data are: f = 2.45 GHz, Re_p = 0.1 and C_{in} = 0.3 mol/l Figs. 8 and 9 show the flow field inside porous media when the porous media is inserted in the waveguide during microwave heating with operating power of 800 and 1600 W, respectively. Fluid flow fields are in the same direction but the magnitudes of velocity are clearly different in the case microwave power of 1600 W, the density of electric field in porous media is higher than case microwave power of 800 W. Upstream region has strong velocity fields, because the upper layer porous receive strong incident wave. The vectors are rigorous near the upper right corner and the velocity fields have a trend corresponding to that of distribution of temperature.

Velocity vector has moved from the left because difference of temperature in the left and the right on porous media, have a different in density. The volumetric expansion of the fluid and buoyancy force driving fluid motion as shown. In Figure, the upper boundary of distribution of velocity is similar to distribution of temperature due to set on the edge of the area with high temperatures. Difference of temperature with area causes velocity vector moves away from this position.

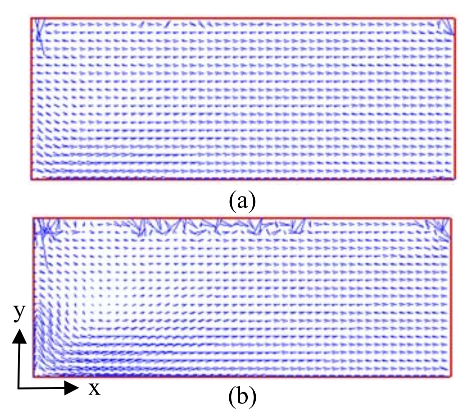

Fig. 8. Flow field with elapsed times: (a) 20 s (b) 60 s at microwave power of 800 W (microwave frequency of 2.45 GHz, Re_p = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3))

Figs. 8. and 9, flow field explained more of the processing that at the very beginning of the heat is less influence to the heat convection but more effective in heat conduction. By increase the time, the difference between the surfaces of the porous media makes the process become convection fluid. Therefore, the fluid flow moves from the heat area into the cooler surrounding surface. This situation becomes the incidence that the heat convection process is very important in this procedure.

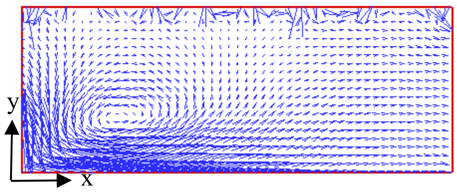

Fig. 9. Flow field with elapsed times: 60 s at microwave power of 1600 W (microwave frequency of 2.45 GHz, Re_p = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3)

Distribution of concentration

Fig. 1. Determine schematic diagram of the problem under consideration has higher concentration than the downward, then the diffuse is expand from the high to low. To consider the spread of the concentration from the left to the right by input fluid to the left, then the concentration of fluid is slowly decrease until it is constantly at 55mm and the concentration of fluid is max at top and right of porous media at 500 mm on the x-axis and 199 mm on the y-axis. Therefore, it shows the distribution of concentration at 199mm (y-axis).

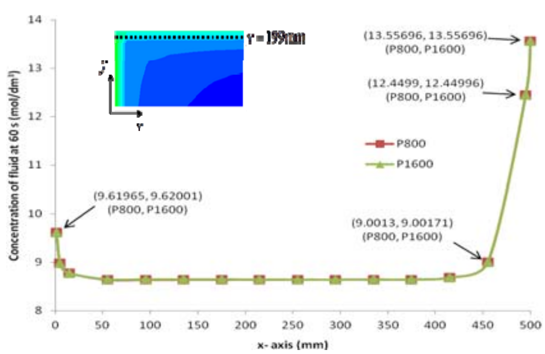

Fig. 10. Distribution of concentration with elapsed time 60 s at difference microwave power in the range of y-axis is 199 mm Reynolds number (Re_p) = 0.1, inlet concentration (C_{in}) = 30 mol/dm^3.

Distributions of concentration within porous media at elapsed time of 60 s operating 800 and 1600 W of microwave power and microwave frequency of 2.45 GHz are displayed in Fig. 10. At 1600 W of microwave power, is distributed higher concentration, such as at the x-axis 455 mm elapsed time 60 s at 1600 and 800 W of microwave power has concentration 9.00171 and 9.00130 mol/ dm^3 respect to the high microwave power and high density of the electric field. In case of 1600 W microwave power, diffusion rate of concentration is better than case of 800 W microwave power. Distribution of concentration caused by diffusion, the movement of solutes from areas of high concentration to areas of low concentration and stop movement when concentration on equilibrium.

5. Conclusions

The effect of an electromagnetic field on transportation through a porous medium is analyzed in this research. The transient Maxwell's equations are utilized to describe the electromagnetic field distribution inside the waveguide and the porous medium while the flow field is simulated by using the Brinkman–Forchheimer and Darcy model. Furthermore, the local thermal non-equilibrium (LTNE) model extended concentration equation is employed to express the heat transport phenomena in a porous medium.

The following summarizes the conclusions arrived at in this work:

The model was developed to describe the flow behavior, distribution of concentration and distribution of temperature in a porous media. The magnitude of electromagnetic wave power has a substantial impact on the temperature of porous media. An increase in the electromagnetic wave power produces a higher porous temperature and enhances a larger temperature difference between solid and fluid phase. The high microwave power (1600 W), the most influence to distribution of temperature, flow fields and distribution of concentration of the fluid within porous media during saturated flow. Our results show that an imposed electromagnetic field has substantial effect in altering the LTE between solid and fluid phases in porous media.

6. Nomenclature

A	area (m^2)
C_p	specific heat capacity $(\mathrm{J/kgK})$
D_p	penetration depth (m)
E	electric field (V/m)
f	electromagnetic wave frequency (Hz)
H	magnetic field strength (A/m)
h	heat transfer coefficient (W/m^{2}K)
P	power (W)
Q	heat generation term (W/m^3)
Re_p	particle Reynolds number, $\rho_f u_e d_p / \mu$
T	temperature (°C)
$\tan\delta$	loss tangent
t	time (s)
u, v	velocity (m/s)

Greek letters

ε	porosity
ρ	density $(\mathrm{kg\ m^{-3}})$
β_T	coefficient of thermal expansion
β_C	coefficient of concentration expansion
ϕ	magnetic permeability (h/m)
ω	angular frequency (rad/s)
σ	electric conductivity $(\mathrm{Wm^{-1}\ K^{-1}})$
γ_0	dielectric constant
$\gamma_r^{'}$	relative dielectric constant
$\gamma_r^{''}$	relative dielectric loss factor

Subscripts

f	fluid
s	solid
x, y, z	coordinate

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8. References

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