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Effect of electromagnetic field on distribution of temperature, velocity and concentration during saturated flow in porous media based on Local Thermal Non-Equilibrium models (influent of input power and input velocity)

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ABSTRACT

The work presents the effect of electromagnetic field on distribution of temperature, velocity and concentration during saturated flow in porous media. The simulations of electromagnetic field (mode TE_{10}) are obtained by solving Maxwell's equations via the finite difference time domain method (FDTD). In addition, Darcy–Brinkman–Forchheimer's model are used to describe the pattern of fluid flow and intensity distribution in porous media where the finite control volume model and SIMPLE algorithm are used to solve these system of equations. The two energy equations for solid and fluid phases are proposed in model of Local Thermal Non Equilibrium condition (LTNE). The effects of input power of electromagnetic wave i.e. 500, 800 and 1600 W, input velocity i.e. Re_p 0.1, 0.5 and 10 were investigated. Distribution of temperature, velocity field and concentrated contaminants in transferred fluid inside of porous media were discussed. The results have also shown major issues on how high power of electromagnetic wave, significantly affects the distribution of temperature, concentration and the velocity field.

1. Introduction

Microwaves have an important role in industry. The advantages of producing heat from microwave are high efficiency, the ability to select receiving heat, and energy penetration, which causes the heat to be distributed uniformly through the object. Usually, heat transfer in porous media such as means some examples, such as boiled eggs in salt water, oil on the beach, or impurities in water that has been heated by the sun. All these porous materials with contaminants are heated under forced convection and natural convection. Applications of electromagnetic waves are widely implemented in food industry and packaging in microwave food. Thermal natural convection combined with electromagnetic waves in porous media is normally seen in environments such as the movement of water 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 porous media is frequently found in daily life, for example in the infiltration of contaminants and fertilizer through soil layers, contaminants in food, catalytic converters in cars and crystal growth. One of the applications of mass diffusion or concentration is the sintering process – the 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, and so on [2].

Karimi-Fard et al. [2] carried out a numerical study of double-diffusive natural convection in a square cavity filled in porous media. This research focused on the influence of the Lewis number on the inertial and boundary effects which affected 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 that the buoyancy ratio, Darcy number, Lewis number, and Richardson number had profound effects on the double-diffusive phenomenon. Jena et al. [3] presented a study that focused on analyzing the 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 heat and mass transfer from the side. The natural circulation was driven by a combination of buoyancy

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Nomenclature

A	area (m^2)
C_p	specific heat capacity (J/kg K)
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 ($kg\ m^{-3}$)
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 ($W\ m^{-1}\ K^{-1}$)
γ_0	dielectric constant
γ'_r	relative dielectric constant
γ''_r	relative dielectric loss factor

Subscripts

f	fluid
s	solid
x, y, z	coordinate

effects with temperature and concentration variations. Nishimura et al. [5] showed the effect of the 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 and opposing thermal and solutal buoyancy forces on natural convection in binary gases. Nithiarasu et al. [7] demonstrated double-diffusive natural convective flow within a rectangular enclosure.

Heat and mass transfers in microwave heating processes, including natural convection in liquids, have been investigated. Saltiel and Datta [8] investigated heat transfer in liquid at any point of the solid and fluid temperature by using the Local Thermal Equilibrium (LTE) model.

Investigations of heat transfer in microwave heating processes and natural convection in porous media are complicated. Many researchers have attempted to study this problem. Wessapan and Rattanadecho [9] carried out a numerical analysis of the specific absorption rate (SAR) and the heat transfer in a heterogeneous two-dimensional human eye model exposed to the TM-mode of electromagnetic (EM) fields of 900 MHz at various power densities. Cha-um et al. [10] presented the process of heating dielectric materials by microwave with a rectangular waveguide. The results show that the locations of sample have greater effects than the other parameters. Klinbun et al. [11] presented a numerical and experimental analysis of microwave heating in a saturated packed bed by using a rectangular waveguide (TE_{10} mode), where the mathematical is based on the LTE model.

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

Heat transfer in microwave heating processes and natural convection in porous media under the LTNE were studied by Keangin and Rattanadecho [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 microwave heating processes and forced convection in porous media under the LTNE model. The effect of an electromagnetic field on forced convection in a fluid-saturated porous medium was 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 the heat transfer in porous media by using the LTNE model, but the difference in microwave is not related to their research.

It seems that the LTE model does not consider the temperature difference between the solid and fluid phases within the porous media, but this temperature difference has a significant influence on the heat transfer. Therefore, for this research, the LTNE model was chosen to analyze the effect of an electromagnetic field on the distribution of temperature, velocity, and concentration during saturated flow in a porous media.

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

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

2. Analysis

Saturated flow through a packed bed of spherical particles subjected to an electromagnetic field as shown in Fig. 1 is considered.

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