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Effects of material properties on heating processes in two-layered porous media subjected to microwave energy

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ABSTRACT

Microwave heating of double-layer porous medium is numerically investigated using a proposed numerical model. A two-dimensional domain composed of two porous layers is considered. The two porous layers have different particle sizes, porosities, thermal and dielectric properties. The generalized non-Darcian model developed takes into account of the presence of a solid drag and the inertial effect. The transient Maxwell's equations are solved by using the finite difference time domain (FDTD) method to describe the electromagnetic field in the waveguide and in the media. The temperature profile and velocity field within the media are determined by solution of the momentum and energy equations given by the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. This study focuses on effects of diameter, porosity, position and types of particles that have different thermal and dielectric properties. The computed results agree well with the experimental results. While the particle size and porosity mainly affect fluid flow within porous media, the thermal and dielectric properties strongly influence heat transfer mechanism in each layer of porous media.

1. Introduction

Microwave heating of a porous medium is widely implemented in industries, such as heating food, ceramics, biomaterials, concrete manufacture, etc., since microwave energy has many advantages such as short time process, high thermal efficiency, environmentally friendly credentials and high product quality. Microwave radiation penetrates into a material and heats it by a dipolar polarization that occurs millions times per second.

A number of previous works have focused on the drying of unsaturated porous media in which heat and mass transfers were modeled [1–6] however most of these dealt with solid materials and focused on heat conduction within a medium. Some works studied a natural convection induced by microwave heating of fluids, since a complex distribution of electromagnetic waves is shown to be a complicate effect on flow field [7–11]. The effects of natural convection and dielectric properties on liquid layers were studied numerically and experimentally. The heating kinetics strongly depended on the dielectric properties [7]. Natural convection due to buoyancy force strongly affects flow patterns within the water layer during the microwave heating process, and clearly enhances temperature distribution in the layer [8]. Recently, Chaum et al. [8] experimentally investigated the heating process within a packed bed filled with glass beads and water and found that the location of the sample relative to that of heat source had an important effect on the pattern of heating. Other recent works focused on microwave driven convection in pure liquids [9–11]. While the previous studies were based on pure liquids, we pay attention to heating induced by microwave energy in a fluid-saturated porous medium with two layers. One of the apparent applications for microwave heating of fluid-saturated porous medium involves food sterilization or pasteurization [12].

Furthermore, all the previous investigations referred did not account for the effect of variable porosity in the vicinity of the impermeable wall. A region of higher porosity near the wall forms due to the packing of the porous spheres near the column wall is not as efficient as that away from the wall towards the column center [13]. Benenati and Brosilow [14] found a distinct porosity variation with a high porosity region close to the wall in packed beds. Values of porosity those are high close to an impermeable wall decrease to an asymptotic value at about four to five sphere diameters away

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Nomenclature

C_p	specific heat capacity (J/(kg K))
E	electric fields intensity (V/m)
f	frequency of incident wave (Hz)
g	gravitational constant (m/s^2)
H	magnetic field intensity (A/m)
P	power (W)
p	pressure (Pa)
Q	local electromagnetic heat generation term (W/m^3)
s	Poynting vector (W/m^2)
T	temperature (°C)
t	time (s)
$\tan\delta$	dielectric loss coefficient (–)
u,w	velocity component (m/s)
Z_H	wave impedance (Ω)
Z_I	intrinsic impedance (Ω)
Greek letters	
ϕ	porosity (m^3/m^3)
α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
η	absolute viscosity (Pa s)
ε	permittivity (F/m)
ε'	dielectric constant (F/m)
ε''	dielectric loss factor (F/m)
λ	wavelength (m)
μ	magnetic permeability (H/m)
υ	velocity of propagation (m/s)
ν	kinematics viscosity (m^2/s)
ρ	density (kg/m^3)
σ	electric conductivity (S/m)
ω	angular frequency (rad/s)
ξ	surface tension (N/m)
Subscripts	
0	free space
∞	ambient condition
a	air
f	fluid
j	layer number
in	input
p	particle
r	relative

from it [15,16]. Many researchers found that the variation of porosity might significantly affect flow patterns as well as heat transfer features [14,17–19]. The porosity of the bed exhibits sinusoidally damping decay especially at locations near wall [14]. This phenomenon leads to the channeling effect that could significantly modify flow patterns [15,20–22]. Hsiao et al. [18] reported that including the effects of variable porosity and thermal dispersion on natural convection in the region of the heated horizontal cylinder in an enclosed porous medium increased the average Nusselt number and reduced the error between the experimental data and their solutions. Thus, the effects of porosity variation should be taken into account in practice [17,23–25]. For works related to the two-layered porosity medium, Rattanadecho et al. [4] studied influence of time input energy for the microwave on particle size and initial moisture content. It is found that the capillary pressure increases when particle size is smaller and the rate of drying is faster. Prommas et al. [26] showed that the proportion of the benefits of energy and efficiency of exergy depended on the size of the particles, the hydrodynamic properties and the structure of the porous layer. Pakdee and Rattanadecho [27] proposed a mathematical model for the microwave heating of the saturated porous medium with variation-porosity based on distance from the wall of the packed bed. Effects of the size of the particles and the average porosity on the temperature and water flow profile were examined. Numerical results were reliable when compared with values obtained from experiments using a rectangular waveguide for the TE_{10} mode. Recently, effects of electromagnetic field on forced convection in porous media were investigated [28]. The energy separation between solid and fluid phases was modeled using local thermal non equilibrium (LNTE). The results showed that errors stem from assuming local thermal equilibrium the calculation is increased when the Darcy number or power of electromagnetic field or ratio of the thermal diffusivity of solid to fluid increases.

Most previous research studied heating processes in a uniform porosity medium due to microwave heating. Only few studies were interested in microwave heating in a multi-layered medium although microwave heating in a multi-layered saturated materials have been found in broad applications in food applications and hyperthermia system for the treatment of tumor [29,30]. Moreover, no work focusing on effects of material properties have been reported. Therefore, our study aimed to investigate effects of microwave on particle size, porosity and medium properties of particles including thermal and dielectric properties on heating process in two-layered porous materials. The present work particularly includes comparisons between the theoretical analysis, mathematical modeling and experimental results.

2. Experimental setup

Fig. 1 shows the experiment apparatus for microwave heating of a saturated porous medium using a rectangular waveguide. Actual image of the apparatus is shown in Fig. 1(a). The microwave system is a monochromatic wave of TE_{10} mode operating at a frequency of 2.45 GHz. Microwave power used is 300 W. From Fig. 1(b), magnetron (No. 1) generates microwaves and transmits them along the z-direction of the rectangular waveguide (No. 5) with inside cross-sectional dimensions of $109.2 \times 54.61\ mm^2$ that refers to a testing area (red circle) and a water load (No. 8) that is situated at the end of the wave guide. On the upstream side of the sample, an isolator is used to trap any microwaves reflected from the sample to prevent damage to the magnetron. The powers of incident, reflected and transmitted waves are measured by a wattmeter using a directional coupler (No. 6) (MICRO DENSHI., model DR-5000). Fiberoptic probes (No. 7) (LUXTRON Fluroptic Thermometer (model 790, accurate to ±0.5°C) is employed for temperature measurement. The probes are inserted into the sample, positioned on the XZ plane at Y = 25 mm. (see in Fig. 2). Due to the symmetry, temperatures are only measured on one side of the plane. The samples are saturated porous packed beds composed of glass beads and water. The container, with a thickness of 0.75 mm, is made of polypropylene which does not absorb microwave energy.

In our present experiment, the two-layer medium is examined. The glass beads of 0.15 mm and put on top of the glass beads of 0.4 mm in diameter is examined. The averaged (free stream) porosity of the packed bed corresponds to 0.385 and 0.371, respectively.