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Study on the effect of micro geometric structure on heat conduction in porous media subjected to pulse laser

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Abstract

Based on fractal theory, different two-dimensional fractal structures were constructed to simulate the practical porous media. Effective thermal conductivity for porous media was calculated by means of the finite volume method. Theoretical analysis of thermal response in the porous media under various heating conditions was performed with a multi-layer hyperbolic heat conduction model with volumetric heat generation. The results obtained in this paper indicate that pore size and micro distribution have a far-reaching impact on the heat conduction in porous media. If we assumed that both the thermal conductivity and the heat capacity of the solid phase is larger than those of liquid phase, decreasing the pore size and porosity is helpful to enhance the heat transfer in porous media and the peak of temperature increases with pore size and porosity. With the same pore size and porosity, the effect of the pore micro-geometric distribution on heat conduction in porous media is obvious. The method presented in this paper may suggest a valuable approach to theoretically evaluate the effect of pore micro-geometric structure on heat conduction in porous media.

Keywords: Pulse laser; Porous media; Heat conduction; Fractal; Micro-geometric structure

1. Introduction

As is widely known, heat conduction in porous materials is usually described macroscopically by averaging the microscopic heat transfer processes over a representative elementary volume. Traditional treatment of heat conduction in porous media is based largely on the mixture theory, assuming local thermal equilibrium within the solid and liquid phases, so that the heat transfer in two phases can be lumped into a process described by a single heat conduction equation. The problem then becomes the construction of an appropriate composite model for the effective stagnant thermal conductivity of the mixture. However, the calculation of heat conduction in porous media is strongly dependent on the micro-geometry structure of pore. Especially when thermal event occurring in a very short time instant that can be comparable to (or even shorter than) the required period to re-establish thermodynamic equilibrium, the precise determination of the effect of micro-geometric structure on the heat conduction in porous media will become crucial. High-rate heating in porous materials has been encountered frequently in many engineering applications, such as laser surgery in biomedical engineering and impulse drying. It has been generally realized that the traditional models may not be applicable to the high-rate heating in porous media, especially for some micro-scale thermal cases. The traditional models have some limitations, which could not describe the heat conduction in microcosmic scope. In developing general models, the most difficult task is to incorporate appropriate morphological information into the models. Because most of the heat transfer takes place through solid-to-solid contact and solid-to-liquid in saturated systems, both the pore size and distribution influence heat conduction. In the past, several other approaches have been proposed (Smith, 1942; Mickley, 1951; Sahimi, 1995; Miller, 1969). In the literatures, a widely used assumption is that the porous medium morphology is a periodic array of spheres with wetting phase fluid occupying the space between the spheres (Tomkiewicz and Sen, 1985). Some authors used the

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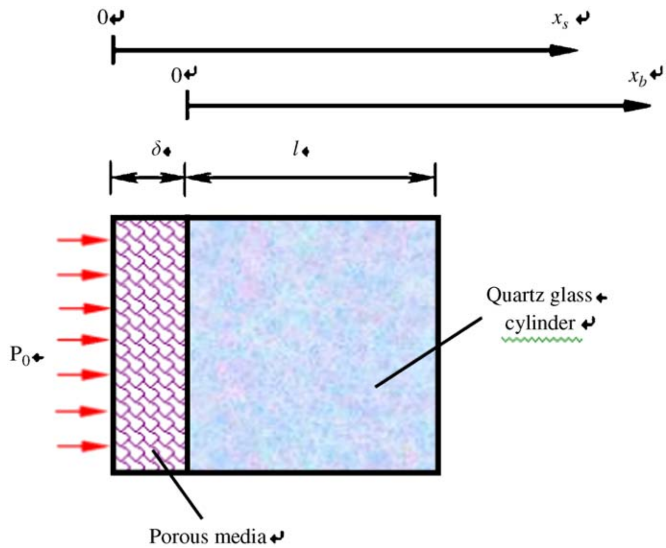

Fig. 1. Schematic of porous media subject to pulse laser.

statistical models (Torquato, 1987) to represent the fluid phases as spheres or ellipsoids similar to the grains. The Monte Carlo method is also used to simulate the heat transfer in heterogeneous porous media (Metzger et al., 2004). These models are found to be suitable for general heat transfer in porous media, but the mathematical expression derived for these calculations are rather complicated (Fig. 1).

Fortunately, the porous media have been proved to be fractal objects in nature (Katz and Thompson, 1985; Krohn and Thompson, 1986; Young and Crawford, 1991; Smidt and Monro, 1998). Fractal theory would offer a new sight on heat and mass transfer in porous media. Many authors have used it to analyze the heat and mass transfer in both saturated and unsaturated porous media (Yu and Li, 2001; Dathe and Thullner, 2005, Hunt, 2004a,b). Their results showed that many porous media are fractals and follow the fractal power laws. Several empirical correlations for heat conduction and permeability are also presented. Microstructure information and thermal response in porous media could be combined easily by fractal theory. In this paper, we will restrict our discussion to heat conduction in porous media saturated with fluids. Based on fractal theory, different two-dimensional fractal structures will be constructed to simulate the practical porous media. Effective thermal conductivity for porous media was counted by means of the finite volume method. Heat conduction in fractal porous media subject to high power short pulse laser is analyzed and simulated by a multi-layer hyperbolic heat conduction (HHC) model with volumetric heat generation. We will illuminate the effect of the pore micro-geometric structure on the thermal response of the porous media.

2. Theoretical model

2.1. Thermal model for temperature response in porous media

In order to explain the effect of pore micro-geometric structure on heat conduction in porous media, a finite medium $0 \leqslant x_s \leqslant \delta$ is placed on a larger base such as a quartz glass cylinder, $0 \leqslant x_b \leqslant l$ (as shown in Fig. 2). The heat transfer process in this case can be simplified as a one-dimension thermal problem. Both the finite medium and the base are initially at the room temperature T_0. At $t = 0$, the boundary surface of the medium $x_s = 0$ is subjected to a rectangular pulsed energy source (i.e., pulse laser). The other end of the medium $x_s = \delta$ is tightly contacted with one end of the base $x_b = 0$, which satisfies the continuous thermal condition while the other boundary surface of the base $x_b = l$ is kept insulated. The heat transfer in the porous media (finite medium) is considered as non-Fourier heat conduction and the HHC model is employed to describe it while the heat transfer in the base still compiles Fourier law and the classical parabolic heat conduction model is used to describe it. Governing equations including the initial boundary conditions can be obtained as follows.

2.1.1. Porous media

The governing equations for heat transfer in the porous media can be expressed as

$$\tau \frac{\partial q_s(x,t)}{\partial t} + q_s(x,t) = -\lambda_s(\varepsilon) \frac{\partial T_s(x,t)}{\partial x_s} \quad (0 < x_s < \delta), \tag{1}$$

$$\frac{\partial q_s(x,t)}{\partial x_s} = Q_r - (\rho c_p)_s \frac{\partial T_s(x_s,t)}{\partial t} \quad (0 < x_s < \delta), \tag{2}$$

where, T_s is the porous media temperature, x and t are space and time coordinate variables, λ_s, ρ_s, c_{ps}, δ are, respectively, the effective thermal conductivity, density, specific heat and thickness of the porous media, τ is the thermal relaxation time, q_s denotes the heat flux density, Q_r is the spatial heat generation due to absorption of pulsed laser heating, ε is the porosity of the porous media.

When a pulsed laser P_0 was applied on the porous media surface, one part $P_0 r_s$ was reflected by the porous media surface and the other part $P_0(1-r_s)$ would permeate the porous media. If the porous media were so thin that the laser could completely permeate, the laser would be reflected by the surface of the base. The porous media would absorb some of the reflected laser. For simplicity, only secondary absorbing will be considered in this paper. Assuming the heating flux decays exponentially with the distance from the porous media surface, the volumetric heating can be deduced as

$$Q_{rs} = -\frac{\partial q_{rs}}{\partial x} = \eta_s P_0 U(t)(1 - r_s)[\exp(-\eta_s x) + r_b \exp(-\eta_s(2\delta - x))], \tag{3}$$

$$Q_{rb} = -\frac{\partial q_{rb}}{\partial x} = \eta_b P_0 U(t)(1 - r_s) \times (1 - r_b) \exp(-\eta_s \delta) \exp(-\eta_b(x - \delta)), \tag{4}$$

where, η_s and η_b are the attenuation coefficients of laser in the porous media and the base, r_s and r_b are the reflectivity of the porous media and base's surface to the pulse laser, respectively,