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Heat transfer characteristics in random porous media based on the 3D lattice Boltzmann method

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ABSTRACT

This paper examines the randomness of porous structure composed by cubes or spheres and particle size level in flow and heat transfer characteristics using the 3D lattice Boltzmann method. The simulation results show that randomness has significant effects on permeability and the Nusselt number when the number and size of spheres or cubes are fixed. As the particle size level increases, normalized permeability increases, but the Nusselt number decreases. When the particle size level increases to five, permeability and the Nusselt number cease to change. Furthermore, the effect of porosity for the porous structure with the least number of particle size level on the Nusselt number is the most significant.

1. Introduction

Fundamental studies on fluid flow and heat transfer through porous media have become the most widespread problem in many scientific and engineering fields, such as packed-bed reactors, catalytic chemical particle beds, solid-matrix heat exchangers, energy conservation in building, biomass pyrolysis, and petroleum exploitation [1–10].

Zukauskas [1] obtained the heat transfer correlation between gases and viscous liquids (viscous stress exists between liquids) flow through single tubes and the banks of tubes of various arrangements. The paper also emphasizes the influence of physical properties of fluids on heat transfer. Whitaker [2] analyzed heat transfer and flow through random packed-bed and compact staggered tube bundles. The obtained correlation was widely used in the related design calculation for many years and later modified by Kreith et al. [3] for a larger range of porosity and a variety of shapes of filler. Based on the analogy of heat and mass transfer, Wakao and Kaguei [4] obtained a new correlation of convective heat transfer coefficient for wider application. Chen and Wung [5] studied convective heat transfer and pressure drop in flow past aligned tube array and staggered tube array using the finite analytic method, and obtained the average convective heat transfer coefficients with the corresponding arrangement. Kuwahara et al. [6] employed the two-energy equation model to determine the interfacial convective heat transfer coefficient in porous media. In consideration of the periodically fully developed temperature profiles, this study performed a numerical experiment using a single structural unit. A universal correlation for the Nusselt number was established using the results obtained for a wide range of porosity, Prandtl and Reynolds numbers. The correlation established purely from a theoretical basis agreed well with available experimental data and was suitable for laminar flow in porous media. Pallares and Grau [7] modified the correlation found by Kuwahara et al. [6] to make the results of the three numerical studies comparable and in agreement with the experimental data. Jiang et al. [8] experimentally examined the heat transfer between solid particles and fluid in a sintered bronze porous media with an average particle diameter of 0.2 mm. Gamrat et al. [9] presented a numerical simulation of heat transfer over banks of square rods in aligned and staggered arrangements with porosity of 0.44–0.98 and low Reynolds number (0.5–40); constant wall temperature and constant volumetric heat source were also investigated. Nakayama et al. [10] proposed a general set of interstitial heat transfer coefficients in both consolidated and unconsolidated porous media. Liu and Wu [11] studied fluid flow and heat transfer in reconstructed porous media using micro-tomography images from a micro computed tomography (micro-CT) scanner using the double-population thermal lattice Boltzmann equation (LBE). The correlations for flow and heat transfer in the specific porous media sample were derived according to the numerical results.

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In these equations, ε is the porosity, μ_f is the fluid dynamic viscosity, μ_w is the fluid dynamic viscosity in wall temperature, $Re_d = Ud/v$, $Re_K = UK^{0.5}/v$, U is the velocity, v is the kinematic viscosity, d is the particle diameter and K is the permeability of porous media.

As mentioned above, the heat transfer coefficient correlations in different porous media differ widely, see Table 1. These studies yield contradictory conclusions. Nakayama et al. [10] and Yang et al. [12] found that heat transfer coefficient increases with the increase in porosity. However, Whitaker [2], Kreith et al. [3], Kuwahara et al. [6], Pallares and Grau [7], and Gamrat et al. [9] concluded that heat transfer coefficient decreases with the increase in porosity. The correlation between heat transfer coefficient and porosity developed by Jiang et al. [8] is convex upward, and the symmetry axis is $\varepsilon = 0.304$. Clearly, the study of heat transfer in porous media is of great academic value. Previous research did not examine the effect of particle location randomness and particle size distribution on heat transfer characteristics for 3D porous media. Thus, this paper aimed to predict the effect of randomness and multi-sized particle on permeability and Nusselt number through the lattice Boltzmann method. In the simulations reported in this study, Pr was set to 0.71.

2. Numerical method

2.1. Porous media

To investigate the influences of pore structure on fluid flow, porous media should be generated first. The current methods of generating a porous structure mainly include reconstruction of real materials by X-ray micro-CT [13,14] and artificial generation [15]. The reconstruction of real materials can obtain real pore information, but the cost is high. We employed artificial generation in this study. The algorithm for generating a random porous structure is described as follows:

Step 1. The computational region, particle size, and particle number are given.
Step 2. Three random numbers, which serve as the coordinates of the first particle center, are generated.
Step 3. Three random numbers, which serve as the coordinates of the N particle center, are generated.
Step 4. The coordinates are tested. If the new particles do not overlap with other particles that were previously placed, then the particle coordinates are recorded; otherwise, step (3) is repeated.
Step 5. Steps (3) and (4) are repeated until the particle number meets the requirement.

On the basis of this method, the microstructure of packed porous media with a certain diameter distribution and particle shape can be generated randomly as shown in Fig. 1.

To obtain the effective diameter of multi-sized particles, information about the particle diameter probability distribution function [N(D)] is needed. The effective diameter is defined as follows [16]:

$$D_{en} = \frac{\int D^3 N(D) dD}{\int D^2 N(D) dD} \tag{1}$$

For cubic particles, the volume-equivalent spherical diameter is used as the single-particle diameter [17].

$$d = \left(\frac{6V_p}{\pi}\right)^{\frac{1}{3}} \tag{2}$$

where d is the volume-equivalent spherical diameter, and V_P is the actual value of the particle volume. For the multi-sized cubic particles, the effective diameter was obtained from Eq. (2).

2.2. D3Q19-LBE model for fluid flow

The evolution equation of LBM is as follows:

$$f_i(\boldsymbol{x} + \boldsymbol{e}_i \delta t, t + \delta t) - f_i(\boldsymbol{x}, t) = -\frac{1}{\tau}(f_i(\boldsymbol{x}, t) - f_i^{eq}(\boldsymbol{x}, t)) \tag{3}$$

where τ is the dimensionless relaxation time, f_i is the velocity distribution function, and f_i^{eq} is the corresponding equilibrium distribution function given by Eq. (4):

$$f_i^{eq} = \rho w_i \left[1 + \frac{\boldsymbol{e_i} \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e_i} \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{|\boldsymbol{u}|^2}{2c_s^2}\right] \tag{4}$$

where $\boldsymbol{u}$ is the velocity, ρ is the density in lattice units, $\boldsymbol{e}_i$ is the lattice discrete velocity, c_s is the lattice speed velocity, $c_s = 1/\mathrm{sqrt}(3)$, and w_i is the weight coefficient. For the D3Q19 model, $w_0 = 1/3$, $w_{1-6} = 1/18$, and $w_{7-18} = 1/36$, $\boldsymbol{e}_i$ is given by Eq. (5).

$$(e_0, e_1, \cdots e_{18}) = \left\{\begin{matrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \end{matrix}\right\} \tag{5}$$

The dimensionless relaxation time τ is related to the kinematic viscosity of the fluid v by

Table 1
Correlations of convection heat transfer for different porous media.

Reference	Heat transfer coefficient equation	Application scope
Zukauskas [1]	$Nu = 0.022 Re_d^{0.84} Pr^{0.36}$	Pr = 0.7–500, Re = 1–2 × 10^6
Whitaker [2]	$Nu = \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(aRe_d^{1/2} + bRe_d^{2/3}\right)Pr^{1/3}\left(\frac{\mu_f}{\mu_w}\right)^{0.14}$	$Re > 50$
Kreith et al. [3]	$Nu = \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(0.5Re_d^{1/2} + 0.2Re_d^{2/3}\right)Pr^{1/3}$	ε = 0.34–0.78, Re = 20–10^4
Wakao and Kaguei [4]	$Nu = 2 + 1.1Re_d^{0.6}Pr^{1/3}$	Re = 15–10^5
Chen and Wung [5]	$Nu = 0.8Re_d^{0.4}Pr^{0.37}$	Aligned, Re = 40–800
	$Nu = 0.78Re_d^{0.45}Pr^{0.38}$	Staggered, Re = 40–800
Kuwahara et al.[6]	$Nu = \left(1 + \frac{4(1-\varepsilon)}{\varepsilon}\right) + \frac{1}{2}(1-\varepsilon)^{1/2}Re_d^{0.6}Pr^{1/3}$	ε = 0.36–0.96, $Pr = 10^{-2}$–10^2 $Re = 3 \times 10^{-3}$–5×10^3
Pallares and Grau [7]	$Nu = 2\left(1 + \frac{4(1-\varepsilon)}{\varepsilon}\right) + (1-\varepsilon)^{1/2}Re_d^{0.6}Pr^{1/3}$	Re = 15–100, $Pr \approx 1$
Jiang et al. [8]	$Nu = (0.86 - 4.93\varepsilon + 7.08\varepsilon^2)Re_d^{1.15}Pr^{1/3}$	Diameter, 40–200 μm
Gamrat et al. [9]	$Nu = 3.02(1-\varepsilon)^{0.278}\exp(2.54(1-\varepsilon)) + ((1-\varepsilon)^n + 0.092)Re_d^{0.5}Pr^{1/3}$	ε = 0.44–0.98, Re = 0.05–40 Aligned, n = 0.44, Staggered, n = 1.09
Nakayama et al.[10]	$Nu = 0.124\left(\frac{3\pi\varepsilon}{4(1-\varepsilon)}\right)^{0.605}(Re_d \cdot Pr)^{0.791}$	Consolidated and unconsolidated
Liu and Wu [11]	$Nu = 0.012 + 0.0741Re_K^{0.25}$	Berea sandstone
Yang et al.[12]	$Nu = 0.057 \times (1-\varepsilon)^{-0.644} \cdot Re^{0.786} \cdot Pr^{1/3}$	Random cylinders