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Discussion

Effect of random structure on permeability and heat transfer characteristics for flow in 2D porous medium based on MRT lattice Boltzmann method

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ABSTRACT

Flow and heat transfer through a 2D random porous medium are studied by using the lattice Boltzmann method (LBM). For the random porous medium, the influence of disordered cylinder arrangement on permeability and Nusselt number are investigated. Results indicate that the permeability and Nusselt number for different cylinder locations are unequal even with the same number and size of cylinders. New correlations for the permeability and coefficient $b'D_{en}$ of the Forchheimer equation are proposed for random porous medium composed of Gaussian distributed circular cylinders. Furthermore, a general set of heat transfer correlations is proposed and compared with existing experimental data and empirical correlations. Our results show that the Nu number increases with the increase of the porosity, hence heat transfer is found to be accurate considering the effect of porosity.

1. Introduction

Flow and heat transfer through porous medium are undoubtedly encountered in many science and engineering fields because of unique structures and characteristics. The domain of application is widely spread, ranging from hydrology, civil, and mechanical engineering to chemical and petroleum engineering, the thermal management of electronic cooling, and improvement of performance of heat transfer systems [1–4]. Usually, fluid flows in a porous medium obey the Darcy law, i.e., the linear relation between the average velocity and the pressure gradient. As the Reynolds number increases to a critical value, the relationship becomes nonlinear. Over the last several decades, fluid flows and heat transfer in porous medium have been studied experimentally and theoretically by many authors.

Coulaud et al. [5] and Lee and Yang [6] carried out calculations for two-dimensional (2D) flows across banks of circular cylinders to examine flow characteristics and devise drag correlations. Kuwahara et al. [7] investigated a collection of square rods to develop a permeability–porosity relationship that ranges from zero to unity. Nakayama et al. [8] presented Nusselt number expressions for the interstitial heat transfer coefficients on both consolidated and unconsolidated porous media.

A number of issues arise when simulating the pore-scale flow field with the traditional Navier–Stokes solver, such as extensive computational time, poor convergence, and numerical instability, which result from the narrowness of the flow passage. In recent years, lattice Boltzmann method (LBM) has drawn considerable attention as a promising tool for simulating flows through a complex geometry. Succi et al. [9] and Cancelliere et al. [10] used LBM to estimate the permeability of a three-dimensional (3D) porous media with randomly distributed inclusions. Nabovati et al. [11] simulated the random porous media by placing identical rectangles with a random distribution and free overlapping. The simulations clearly indicate that the random porous media is less permeable than the regularly ordered medium for the same porosity. Fluid flow in random fibrous media is simulated using LBM and a semi-empirical constitutive model is developed for the permeability as a function of their porosity and of the fiber diameter [12]. Chai et al. [13] investigated the non-Darcy effect on incompressible flows through disordered porous media. As an extension to the common empirical expressions, a general correlation was proposed to include the non-Darcy effect. Cai et al. [14] studied the fluid–solid coupling heat transfer in fractal porous medium. A numerical simulation was conducted to investigate the influences of pressure

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Nomenclature

c	lattice streaming speed .... m/s	K_e	effective permeability
f_i	stream distribution function	h	average convective heat transfer coefficient
g_i	temperature distribution function	Re	Reynolds number
D_{en}	effective diameter .... m	t	time .... s
K	Darcy permeability	U_{in}	inlet velocity of impinging jet flow .... m/s
Nu	Nusselt number	C_L	lift coefficient
Pr	Prandtl number		
T	temperature .... K	*Greek symbols*	
C_D	drag coefficient	α	thermal diffusivity .... m^2/s
St	Strouhal number	ε	porosity
x, y	Cartesian coordinates	ν	kinematic viscosity .... m^2/s
f_i^{eq}	equilibrium distribution function for f_i	λ	thermal conductivity .... W/m K
g_i^{eq}	equilibrium distribution function for g_i		

drop and porosity on fluid flows and the effect of the thermal conductivity ratio of solid matrix to fluid on heat transfer.

In practice, the structure of porous medium is random and irregular. Literature dealing with permeability is vast, but most methodologies, and in particular those based on experimentally-based correlations, suffer from lack of generality primarily due to the assumptions that they embody and randomness of porous medium. Detailed studies on various porous structures, shapes of composed materials, and porosities remain limited, and few studies focus on heat transfer through random porous medium with different cylinder sizes. Meanwhile, it is difficult to carry out the experiment and traditional numerical simulation at pore level for random porous medium with Gaussian distributed circular cylinders. A novel double distribution function approach leaning on the MRT-LBE with D2Q9 for solving the mass and momentum conservation equations, and the MRT-LBE with D2Q5 for simulating the temperature is validated by Moussaoui et al. [15,16]. Therefore, the objectives of this paper are two-fold. The first objective is to extend the permeability correlation and coefficient $b'D_{en}$ of the Forchheimer equation to the random porous medium with Gaussian distributed circular cylinders using double MRT relaxation time Lattice Boltzmann method. The second objective is to obtain the heat transfer correlations considering the effect of porosity on random porous medium with Gaussian distributed circular cylinders using double MRT relaxation time Lattice Boltzmann method.

2. Numerical methods

2.1. D2Q9-MRT model for fluid flow

The collision operator of the MRT model can be generalized as,

$$f_i(x+e_\alpha\Delta t, t+\Delta t) - f_i(x,t) = -\Omega\big(f_i(x,t) - f_i^{eq}(x,t)\big). \quad (1)$$

The parameter Ω is the collision matrix, $f = (f_0, f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8)^T$, and T denotes the transpose operator. This model can conveniently accomplish the collision process in the moment space. Hence, Eq. (1) transform to the following form:

$$\begin{aligned} &f_i(x+e_\alpha\Delta t, t+\Delta t) - f_i(x,t) \\ &\quad = -M^{-1}\mathbf{S}\big(\mathbf{m}(x,t) - \mathbf{m}_i^{eq}(x,t)\big), \end{aligned} \quad (2)$$

where M is a 9×9 matrix that transforms f_i and f_i^{eq} into the moment space with $\mathbf{m} = \boldsymbol{M}\boldsymbol{f}$ and $\mathbf{m}^{eq} = \boldsymbol{M}\boldsymbol{f}^{eq}$, respectively. Matrix M is expressed as

$$M = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -4 & -1 & -1 & -1 & -1 & 2 & 2 & 2 & 2 \\ 4 & -2 & -2 & -2 & -2 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & -2 & 0 & 2 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \\ 0 & 0 & -2 & 0 & 2 & 1 & 1 & -1 & -1 \\ 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \end{pmatrix}$$

The inverse of matrix M is

$$M^{-1} = \frac{1}{36}\begin{pmatrix} 4 & -4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & -1 & -2 & 6 & -6 & 0 & 0 & 9 & 0 \\ 4 & -1 & -2 & 0 & 0 & 6 & -6 & -9 & 0 \\ 4 & -1 & -2 & -6 & 6 & 0 & 0 & 9 & 0 \\ 4 & -1 & -2 & 0 & 0 & -6 & 6 & -9 & 0 \\ 4 & 2 & 1 & 6 & 3 & 6 & 3 & 0 & 9 \\ 4 & 2 & 1 & -6 & -3 & 6 & 3 & 0 & -9 \\ 4 & 2 & 1 & -6 & -3 & -6 & -3 & 0 & 9 \\ 4 & 2 & 1 & 6 & 3 & -6 & -3 & 0 & -9 \end{pmatrix}$$

The moment vector $\mathbf{m}$ is $\mathbf{m} = (\rho, e, \varepsilon, j_x, q_x, j_y, q_y, p_{xx}, p_{xy})^T$. The equilibrium of moment $\mathbf{m}^{eq}$ is as follows:

$$\begin{aligned} m_0^{eq} &= \rho \\ m_1^{eq} &= -2\rho + 3\big(j_x^2 + j_y^2\big) \\ m_2^{eq} &= \rho - 3\big(j_x^2 + j_y^2\big) \\ m_3^{eq} &= j_x \\ m_4^{eq} &= -j_x \\ m_5^{eq} &= j_y \\ m_6^{eq} &= -j_y \\ m_7^{eq} &= \big(j_x^2 - j_y^2\big) \\ m_8^{eq} &= j_x j_y \end{aligned} \quad (3)$$

$\boldsymbol{S}$ is a diagonal relaxation matrix:

$$\boldsymbol{S} = \mathrm{diag}(1.0, 1.4, 1.4, s_3, 1.2, s_5, 1.2, s_7, s_8)$$

where $s_7 = s_8 = 2/(1+6\upsilon)$, and s_3 and s_5 arbitrary, can be set to 1.0.

The macroscopic fluid variables, namely, density and velocity, are defined by sums over the distribution functions: