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Lattice Boltzmann simulations of convection heat transfer in porous media

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HIGHLIGHTS

- A non-orthogonal MRT-LB method is developed to study convection heat transfer in porous media.
- The proposed LB method is based on the generalized non-Darcy model.
- Two different LB models are constructed: one is constructed in the framework of the DDF approach, and the other is constructed in the framework of the hybrid approach.
- The proposed LB method can be served as a numerically accurate and computationally efficient numerical method for convection heat transfer in porous media.

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ABSTRACT

A non-orthogonal multiple-relaxation-time (MRT) lattice Boltzmann (LB) method is developed to study convection heat transfer in porous media at the representative elementary volume scale based on the generalized non-Darcy model. In the method, two different LB models are constructed: one is constructed in the framework of the double-distribution-function approach, and the other is constructed in the framework of the hybrid approach. In particular, the transformation matrices used in the MRT-LB models are non-orthogonal matrices. The present method is applied to study mixed convection flow in a porous channel and natural convection flow in a porous cavity. It is found that the numerical results are in good agreement with the analytical solutions and/or other results reported in previous studies. Furthermore, the non-orthogonal MRT-LB method shows better numerical stability in comparison with the BGK-LB method.

1. Introduction

Fluid flow and convection heat transfer in porous media have attracted considerable attention due to their fundamental nature and broad range of applications in many fields of science and engineering. Consequently, fluid flow and convection heat transfer in porous media have been studied extensively by using theoretical, experimental, and numerical methods [1,2]. Fluid flow and convection heat transfer in porous media usually involve three scales, i.e., the domain scale, the representative elementary volume (REV) scale, and the pore scale. In the last several decades, various traditional numerical methods have been developed to study convection heat transfer processes in porous media at the REV scale based on some semi-empirical models, such as the Darcy model, the Brinkman-extended Darcy model, the Forchheimer-extended Darcy model, and the generalized non-Darcy model (also called the Brinkman–Forchheimer-extended Darcy model) [2–6].

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The lattice Boltzmann (LB) method [7–11], as a mesoscopic numerical approach originated from the lattice-gas automata (LGA) method [12], has achieved great success in simulating fluid flows and modeling physics in fluids [13–22]. Unlike traditional numerical methods based on a direct discretization of macroscopic continuum equations, the LB method is based on mesoscopic kinetic equation for single-particle distribution function. As reported by Succi [23,24], the LB method has some attractive advantages over traditional numerical methods due to its kinetic background: (i) non-linearity (collision process) is local and non-locality (streaming process) is linear, whereas the transport term $\mathbf{u} \cdot \nabla \mathbf{u}$ in the Navier–Stokes equations is non-linear and non-local at a time; (ii) streaming is exact; (iii) the strain tensor and the fluid pressure can be calculated locally; (iv) complex boundary conditions can be easily formulated in terms of the elementary mechanical rules; (v) nearly ideal for parallel computing with very low communication/computation ratio.

The LB method has also been successfully applied to study fluid flow and heat transfer in porous media. The LB models for fluid flow and heat transfer in porous media can be generally classified into two categories, i.e., the pore scale method [25–29] and the REV scale method [30–39]. In fact, the LB method was already applied to study three-dimensional porous flows at the pore scale by Succi et al. in 1989 [25]. Later studies [26–28] demonstrated the reliability of the LB method in modeling fluid flows in porous media. Very recently, Prestininzi et al. [29] have brought factual evidence that the Bhatnagar–Gross–Krook (BGK) LB model is capable of modeling Darcy flow through arrays of equal spheres within a few percent accuracy. In the pore scale method, fluid flow and heat transfer in the pores of the medium is directly modeled by the standard LB method, and the interaction between solid and fluid phases is realized by using the no-slip bounce-back rule. The detailed flow information of the pores can be obtained, which can be utilized to investigate macroscopic relations.

In the REV scale method, an additional term accounting for the presence of a porous medium is incorporated into the LB equation by using some appropriate forcing schemes based on some semi-empirical models (e.g., Darcy model [33], Brinkman-extended Darcy model [30–32], and generalized non-Darcy model [34–39]). Based on the generalized non-Darcy model [6], Guo and Zhao [34] developed a generalized LB model for studying incompressible porous flows. In the generalized LB model, the porosity is incorporated into the equilibrium distribution function, and a forcing term is added into the LB equation to account for the linear and nonlinear matrix drag forces. Subsequently, the generalized LB model was extended to study convection heat transfer in porous media [36,37]. After nearly two decades of development, the REV scale method has been developed into a numerically accurate and computationally efficient numerical method for studying fluid flow and convection heat transfer in porous media on large scales.

In the LB community, the BGK model [10,11] is still the most popular one owning to its simplicity. However, the single-relaxation-time assumption of the BGK model obviously comes with several limitations, e.g., it usually suffers from numerical instability at low viscosity (the relaxation time is close to 0.5), and it is restricted to fluids with isotropic diffusion coefficient. One way to overcome the defects of the BGK model is to use the multiple-relaxation-time (MRT) model proposed by d'Humières in 1992 [40], which is an important extension of the matrix LB method developed by Higuera et al. [9]. Actually the basic idea of any MRT scheme is originated from the work of Higuera et al. [9]. It has been widely accepted that the MRT model can significantly improve the numerical stability of the LB schemes by carefully separating the relaxation rates of the hydrodynamic (conserved) and kinetic (non-conserved) moments [41–44]. In addition, the number of tunable parameters in the MRT model is sufficient to handle problems with anisotropic diffusion coefficient [45,46]. In our previous study [39], a thermal MRT-LB model was developed for simulating convection heat transfer in porous media at the REV scale in the framework of the double-distribution-function (DDF) approach. In the model, the MRT-LB equations are proposed based on orthogonal transformation matrices. However, as reported in Refs. [47,48], the transformation matrix of the MRT-LB model is not necessary to be an orthogonal one, i.e., the MRT-LB model can be developed based on non-orthogonal transformation matrix, which results in the so-called non-orthogonal MRT-LB model. In the non-orthogonal MRT-LB model, the Gram–Schmidt orthogonalization process is not needed. Compared with the orthogonal transformation matrix, the non-orthogonal transformation matrix contains more zero elements, which makes the non-orthogonal MRT-LB model simpler and more efficient than the classical orthogonal MRT-LB model [41].

In this paper, we aim to present a non-orthogonal MRT-LB method for convection heat transfer in porous media at the REV scale. In the method, two different LB models are constructed: one is constructed in the framework of the DDF approach [48–51], and the other is constructed in the framework of the hybrid approach [42]. The rest of this paper is organized as follows. The macroscopic governing equations are briefly described in Section 2. The non-orthogonal MRT-LB method is presented in Section 3. The numerical results and some discussions are given in Section 4. Finally, a brief conclusion is made in Section 5.

2. Macroscopic governing equations

For fluid flow and convection heat transfer in a homogeneous, isotropic and fluid-saturated porous medium at the REV scale, based on the generalized non-Darcy model, the macroscopic governing equations under local thermal equilibrium condition can be written as follows [2,6]:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\left(\frac{\mathbf{u}}{\phi}\right) = -\frac{1}{\rho_0}\nabla(\phi p) + \upsilon_e \nabla^2 \mathbf{u} + \mathbf{F}, \tag{2}$$

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