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A Coupled Discrete Unified Gas-Kinetic Scheme for Convection Heat Transfer in Porous Media

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Abstract. In this paper, the discrete unified gas-kinetic scheme (DUGKS) is extended to the convection heat transfer in porous media at representative elementary volume (REV) scale, where the changes of velocity and temperature fields are described by two kinetic equations. The effects from the porous medium are incorporated into the method by including the porosity into the equilibrium distribution function, and adding a resistance force in the kinetic equation for the velocity field. The proposed method is systematically validated by several canonical cases, including the mixed convection in porous channel, the natural convection in porous cavity, and the natural convection in a cavity partially filled with porous media. The numerical results are in good agreement with the benchmark solutions and the available experimental data. It is also shown that the coupled DUGKS yields a second-order accuracy in both temporal and spatial spaces.

AMS subject classifications: 82B40, 76S05, 76E06

Key words: Coupled discrete unified gas-kinetic scheme, generalized Navier-Stokes equations, porous media, convection heat transfer.

1 Introduction

Convection heat transfer in porous media has long been a subject of research due to its extensive applications in engineering, such as heat exchangers, electronic cooling instruments, and pollutant diffusion [1–4]. Over the past several decades, considerable investigations and applications have been devoted to the convection heat transfer in porous media through various traditional numerical methods, such as the finite volume method, the finite difference method, and the finite element method.

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In general, the modelling of porous flow can be classified into two categories, i.e. the pore-scale model and the representative elementary volume (REV) scale model. In the pore-scale study, the detailed geometric information of the pores should be known, and each pore requires sufficient grid resolution in the simulations. Thus, the computational domain size cannot be too large in view of the limited computer resources. An alternative approach is to investigate the averaged quantities at the REV scale. At this scale, a number of models based on some semi-empirical relations have been developed. Up to date, most investigations at the REV scale are based on the Darcy law [5, 6] as the Reynolds number based on pore diameter is smaller than 1 [7] such that inertial effect can be ignored. For flows with larger Reynolds numbers, various extended Darcy models have been proposed. For instance, the Darcy-Brinkman model [8,9], which considers the viscous dissipation introduced by solid boundary, allows to study high-porosity porous flows, while the Darcy-Forchheimer model [10,11] includes an additional nonlinear resistance term (Forchheimer term), and a generalized model was further developed in which both the Brinkman and Forchheimer effects are included [12, 13], such that the flows in wide range of flow regimes can be described. Based on this generalized model, a number of flow and heat transfer problems in porous media have been studied [14–16]. For example, Arpino et al. studied the transient natural convection in partially porous annuli, and clarified impacts on both porous medium properties and geometrical characteristics of the domain [17].

In the past years, several types of kinetic methods, which can be viewed as alternative numerical tools to traditional ones, have been successfully employed for porous media flows based on generalized model [18–20]. Particularly, the lattice Boltzmann method (LBM) has been recognized as a powerful tool for such flows. Guo et al. proposed a LBM with the Bhatnagar-Gross-Krook collision operator (LBGK) for flow and heat transfer at the REV scale [21], and a model with multiple-relaxation-time (MRT) model was subsequently proposed to improve the numerical stability [22,23]. In addition to the standard LBM, a finite-volume LBM was also developed for thermal flows in porous media [24]. Although the LBM models mentioned above have gained much success, some limitations still exist. For example, the computational time step and grid size are coupled, so that the flexibility of relaxation time and the numerical stability are very limited [25].

Recently, another kinetic method, a discrete unified gas–kinetic scheme (DUGKS) has been presented for both hydrodynamic and rarefied flows [26–30]. As a finite-volume method, the DUGKS can be easily implemented on non-uniform or unstructured meshes to satisfy the local accuracy requirement [25, 31, 32]. Although DUGKS was originally developed for multiscale flows beyond continuum regime, it can also be applied to continuum flows on which the LBM focuses. Under such circumstances, the DUGKS exhibits several distinctive features in comparison with LBM. In fact, several comparative studies of the standard LBM and DUGKS have been preformed systematically for laminar flows [25, 33], turbulent flows [34, 35], and natural convection flows [36, 37] in previous work. Generally, for flows without solid boundaries, for example the decaying turbulent flow, the accuracy of standard LBM is slightly better than the DUGKS [34], while