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Simulation of Flow in Multi-Scale Porous Media Using the Lattice Boltzmann Method on Quadtree Grids

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Abstract. The unified lattice Boltzmann model is extended to the quadtree grids for simulation of fluid flow through porous media. The unified lattice Boltzmann model is capable of simulating flow in porous media at various scales or in systems where multiple length scales coexist. The quadtree grid is able to provide a high-resolution approximation to complex geometries, with great flexibility to control local grid density. The combination of the unified lattice Boltzmann model and the quadtree grids results in an efficient numerical model for calculating permeability of multi-scale porous media. The model is used for permeability calculation for three systems, including a fractured system used in a previous study, a Voronoi tessellation system, and a computationally-generated pore structure of fractured shale. The results are compared with those obtained using the conventional lattice Boltzmann model or the unified lattice Boltzmann model on rectangular or uniform square grid. It is shown that the proposed model is an accurate and efficient tool for flow simulation in multi-scale porous media. In addition, for the fractured shale, the contribution of flow in matrix and fractures to the overall permeability of the fractured shale is studied systematically.

AMS subject classifications: 76S05, 76D05, 65Y10

Key words: Quadtree grid, unified lattice Boltzmann method, permeability, fractured porous media.

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1 Introduction

Flow in porous media usually occurs across multiple length scales. One example is gas flow in shale. The pore size of shale ranges from nanometers to micrometers, and the size of natural and hydraulic fractures varies from microns to centimeters, even meters. Therefore, multi-scale models are needed both to capture flow details in the finest length scale, and to handle the large scale of practical interest. The lattice Boltzmann method (LBM) [1], with a mesoscopic origin, is a promising numerical model for simulating flow in multiscale porous media. In recent years, the LBM has been successfully applied to a variety of fields, such as flows in porous media [2], chemical reactions [3, 4], heat transfer [5], particle suspensions [6], dissolution and precipitation [7–9], and multiphase and multicomponent flows [10, 11].

Because of its advantage in dealing with complex geometries/boundaries, the applications of the LBM to porous media have been mainly focused on the pore scale, with individual pores/grains fully resolved. However, some efforts have been devoted to extending it to flow simulation at the REV (representative elementary volume) scale. The basic idea is to introduce a resistance force to alter the local flow velocity, which was adopted in early work on lattice gas automata [12]. Spaid and Phelan [13] proposed a model based on the Brinkman equation for single-component flow in porous media. Later, Freed [14]extended the above model, rendering it to recover flow through a resistance field with arbitrary values of the resistance tensor components. In the model, the usual computational nodes were replaced with porous media nodes in the volume supposed to be occupied by a porous medium. However, due to the linear velocity dependence of the dimensionless resistance, the influence of Mach number is qualitatively different than that due to true inertial effects. Guo and Zhao [15] proposed a model for isothermal incompressible flow in porous media with linear and nonlinear matrix drag components as well as the inertial and viscous forces taken into account, by introducing the porosity into the equilibrium distribution and adding a force term to the evolution equation. By extending Freed's model into nonuniform grids, Kang *et al.* [16] developed a unified lattice Boltzmann model (ULBM) applicable to systems of various length scales, as well as to systems where multiple length scales coexist. The length of the scales can be as small as pore scales (on the order of microns), as large as field scales (on the order of meters to kilometers), or a mixture of various scales. The ULBM can recover Brinkman's equation or Darcy's equation under different situations. The ULBM treats the porous medium nodes, pore nodes, and wall nodes in the same way, even though they are at different length scales. There are no internal boundaries in the simulation. However, because the nonuniform meshes used in their model are rectangular, the applications of the ULBM have been very limited. For example, in simulation of flow through a fractured system, the fracture has to have smooth surface and has to be in parallel with the coordinates.

Therefore, to expand the applications of the ULBM, it is necessary to extend it to more general meshes. In fact, to increase numerical efficiency, several efforts have been made