Advances in Geo-Energy Research

Vol. 6, No. 4, p. 357-358, 2022

Research highlight

A new upscaling method for microscopic fluid flow based on digital rocks

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Keywords:
Upscaling
microscopic flow
digital rock
permeability

Cited as:
Liao, Q., Xue, L., Wang, B., Lei, G. A new upscaling method for microscopic fluid flow based on digital rocks. Advances in Geo-Energy Research, 2022, 6(4): 357-358.
https://doi.org/10.46690/ager.2022.04.10

Abstract:
This report presents our new findings in microscopic fluid flow based on digital rocks. Permeability of digital rocks can be estimated by pore-scale simulations using the Stokes equation, but the computational cost can be extremely high due to the complicated pore geometry and the large number of voxels. In this study, a novel method is proposed to simplify the three-dimensional pore-scale simulation to multiple decoupled two-dimensional ones, and each two-dimensional simulation provides the velocity distribution over a slice. By this decoupled simulation approach, the expensive simulation based on the Stokes equation is conducted only on two-dimensional domains, and the final three-dimensional simulation of Darcy equation using the finite difference method is very cheap. The proposed method is validated by both sandstone and carbonate rock samples and shows significant enhancement in the computational speed. This work sheds light on large-scale microscopic fluid flow based on digital rocks.

Permeability is a key parameter for quantifying fluid flow in porous media (Liu et al., 2022). As permeability on the macroscale is related to its microstructure, it is necessary to accurately simulate microscopic fluid flow based on microscale properties (Mostaghimi et al., 2013). The equivalent permeability can be obtained via upscaling process, i.e., converting rock properties from fine scales to coarser scales (Liao et al., 2019). Digital rock analysis is an effective technology for core analysis, and has been widely used in sandstone, carbonate, shale and other core analysis fields (Wang et al., 2022). It is based on two-dimensional (2D) scanning electron microscope image or three-dimensional (3D) computed tomography scan image, using computer image processing technology, through a certain algorithm to complete the reconstruction of digital core. The Navier-Stokes equation is probably the most well-known equation for fluid flow simulations (Zhang and Sun, 2021). For modeling single-phase incompressible flow in porous media, the inertial forces can be neglected, and the momentum conservation equation reduces to the steady-state Stokes equation, while the mass conservation equation reduces to the incompressibility equation (Fig. 1(a)). The lattice Boltzmann method (LBM) is intrinsically a mesoscopic computational fluid dynamics approach based on the evolution of statistical distribution on lattices (He and Luo, 1997). It has achieved considerable success in simulating fluid flows and associated transport phenomena. However, the associated computational effort can be enormous for large-scale models.

In this study, an efficient method is developed for computing the equivalent permeability of digital rocks by simplifying the Stokes equation to Darcy equation. The method is based on the idea that a 3D digital core can be approximated by the combination of multiple 2D slices/layers, and the property of each layer is governed by the Stokes equation (Fig. 1(a)). Specifically, to mimic the 2D fine-scale velocity solved from the Stokes equation, a local permeability is assigned according to the velocity for each voxel. By this means, the 3D Stokes equation can be simplified to multiple 2D cases that provide the local permeability distribution for the 3D Darcy equation

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Received June 10, 2022; revised June 19, 2022; accepted June 22, 2022; available online June 24, 2022.

Yandy Scientific Press

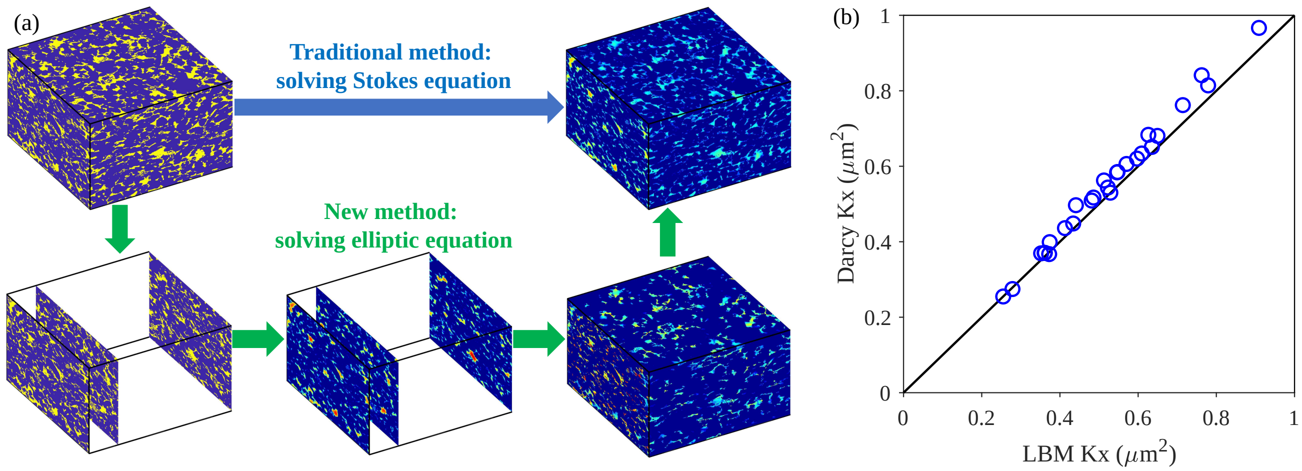

Fig. 1. (a) Traditional method: directly solving 3D Stokes equation, and proposed new method: converting Stokes equation to elliptic Darcy equation; (b) Results comparison of the upscaled permeability from LBM and the proposed method.

(elliptic equation that can be solved easily using algebraic multigrid method), and thus the computational cost can be significantly reduced.

Case studies have been conducted on various samples to validate our method. A Berea sandstone rock sample of full size 960^3 voxels was cut into $3^3 = 27$ cubes, each 320^3 voxels. The equivalent permeability is computed for all three directions using both the traditional LBM and the proposed method. Fig. 1(b) shows the results for x-direction, in which the blue circles indicate the permeability values of the 27 subsamples, while the results for y and z-directions show similar performance. The results demonstrate that the computed 3D permeabilities using finite difference method based on the Darcy equation agree well with those using lattice-Boltzmann method based on the Stokes equation with only 8% error, and a speedup factor of about 750 is achieved. The method was also applied to carbonate rocks for fast estimation of block permeability.

In sum, a new method is proposed for digital rock upscaling of permeability based on the idea of converting Stokes equation to Darcy equation. Simulation results show that this method is sufficiently accurate and very efficient, compared to the results from lattice-Boltzmann method. Possible extensions including flow in fractured porous media, multiphase flow and stress-dependent problem are being investigated (e.g., Cai et al., 2017; Lei et al., 2021; Xue et al., 2022). This work makes it possible to perform large-scale simulations and helps to provide insights into how microstructure effect the pore-scale fluid flow.

Acknowledgement

This work was supported by Science Foundation of China University of Petroleum, Beijing (No. 2462022QNXZ002).

Conflict of interest

The authors declare no competing interest.

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