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Influence of slip flow at fluid-solid interface upon permeability of natural rock

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Abstract

The flows involving CO2 sequestration encounters pores of very small size usually in micro-meter range. At this scale, various small-scale flow effects associated with the fluid-solid interaction governs the hydrological properties. Hence, realizing the importance of appropriate boundary condition when dealing with the small scale flow is of extreme importance. One such effect is the occurrence of slip at the fluid-solid interface. The implementation of slip boundary condition, in lattice Boltzmann framework, is discussed in the present study. The effect of slippage on the bulk properties is obtained in channel flow using the slip boundary condition. Further, a homogeneous porous media is considered to show the effect of slip flow on bulk as well as local flow properties.

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Keywords: CO_2 Sequestration, porous media flow, lattice Boltzmann method, slip flow.

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1. Introduction

Understanding the transportation processes and fluid flow through the porous media helps in various engineering applications, for instance, shale gas transport, oil extraction and many more. In recent years, geological trapping of CO_2 by injecting it between the grains in the rock of used oil fields emerged as a viable solution to reduce the CO_2 emission into the atmosphere. This kind of fluid flow depends largely on geometry and structure of pores. The typical length scales of pores in the conventional oil field is of order of few micro-meter(μm). However, we should consider smaller pore space (less than micro-meter) in order to accurately model the CO_2 flow behaviour. Furthermore, with the advent of unconventional energy resources like tight gas, shale gas etc, small scale pores which are present in tight sandstones and shale rock became a viable option for CO_2 sequestration. The size of pores in these rocks ranges is of order of nano-meter(nm). At this level, the continuum approximations may break down and hence the plain Navier-Stokes solvers with no slip boundary conditions may not be valid. Although models based on Darcy Law are commonly used for large-scale simulations of the reservoir, various effects arising due to

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small-scale pore structure cannot be handled efficiently in these models. Hence, a fluid solver which can incorporate micro-scale effects is needed. The lattice Boltzmann (LB) method has shown a great success as a powerful alternative for solving the continuum flow with Kn<0.001 (Knudsen number Kn is the ratio of the molecular mean free path with respect to character macroscopic length)[1, 2]. It has already been used to simulate the multiphase flows in porous medium to unravel the physics of flow of CO_2 and which in turn helps in prediction of optimal condition to increase the storage property inside the rock [3]. However, in these descriptions, a no-slip boundary condition is used at the fluid-solid interface. In the regime where the pore-size are very small, it is well known that the slip flow occurs at the fluid-solid interface. This slip effect is known to significantly affect the micro-scale and nano-scale flow behaviour. For example, with the increase in the Knudsen number, the slip velocity increases and as a result the flow rate also increases. Hence, in order to accurately predict and optimize the storage property of rock, one need to appropriately handle this slip effect. Because of the kinetic origin of the method, the slip effect at the solid-fluid boundary can be naturally obtained by the lattice Boltzmann method just by the applying appropriate kinetic boundary. One such boundary condition is proposed in Ref. [4], where the discrete form of Maxwell diffusion boundary condition in the lattice Boltzmann framework is presented. Basically, in this condition, particles that reach the wall are redistributed in a way consistent with the mass-balance and normal-flux conditions. This boundary condition is used to produces the slip velocity in high Kn flows. Here, we use lattice Boltzmann simulation with appropriate kinetic boundary condition in order to study the role of slip effect on the hydrological properties (e.g., permeability). Simple geometry like homogeneous pore network (see Fig. 2) is considered to study the slip effect using the kinetic boundary condition.

2. **Method**

In the last two decades, the lattice Boltzmann method (LBM) has emerged as an alternate tool to simulate the hydrodynamics of Newtonian fluids following Navier Stokes equation. The lattice Boltzmann method can be understood as an approximate technique for solving Boltzmann BGK equation using a discrete velocity c_i, $i=1,2......N$. The fundamental quantity of interest is the discrete single particle distribution function $f_i(\mathbf{x},t)$ at the location $\mathbf{x}$ and time t. The required physical observables like density ρ, and momentum $\rho\mathbf{u}$, are obtained using appropriate moment of f_i, as:

$$\rho=\sum^{N} f_i; \qquad \rho u=\sum^{N} f_i c_i. \tag{1}$$

The dynamics of single particle distribution f_i is governed by the BGK-Boltzmann equation [5]:

$$\frac{\partial f_i}{\partial t}+c_i\frac{\partial f_i}{\partial x}=\frac{1}{\tau}\left(f_i-f_i^{eq}\right). \tag{2}$$

The right side of Eq. (2) signifies that each distribution function is relaxing to its equilibrium state, f_i^{eq},with a relaxation time, τ, which in turn is related to the viscosity of the fluid. In the present study, we use D2Q9 velocity-model (D stands for spatial dimension and Q discrete velocity). Furthermore, a regularization procedure introduced by Chen and co-workers [6] and Latt and Chopard [7] is also used for the stabilization of numerical procedure.

2.1. Conventional (no-slip) Boundary Condition

In a conventional LB scheme, a bounce-back boundary condition is used to mimic the no-slip wall boundary condition. The implementation requires the directions of incoming distribution functions to be reversed when they encounters the boundary node. This boundary condition works well in the continuum limit (low Kn). However, as the Knudsen number increases, slips velocity starts to increase at the boundaries and no-slip is not an accurate assumption.

2.2. Kinetic (Slip) Boundary Condition

The kinetic origin of LB method motivated Ansumali and Karlin [4] to propose a diffusively reflecting solid wall boundary condition. The basic idea behind this boundary condition is to redistribute the populations coming towards the wall such that it follows mass-balance and normal-flux conditions. The discrete version of this boundary condition is:

$$f_i(x_{wall},t)=K f_i^{eq}(\rho,u_{wall}) \tag{3}$$

where

$$K=\frac{\sum_{c_i\cdot n<0}\left|(c_i-u_{wall})\cdot n\right| f_i}{\sum_{c_i\cdot n>0}\left|(c_i-u_{wall})\cdot n\right| f_i^{eq}(\rho,u_{wall})} \tag{4}$$

with **n** being the unit normal direction. The term K can be understood as the the ratio of total outgoing flux to the wall and total incoming equilibrium flux from the wall.

3. Results

3.1. Channel Flow

We first consider the channel flow to check the competency of the kinetic boundary condition to reproduce flow properties of small scale flows. The volumetric flow rate is plotted with increasing Kn in Fig. 1. The Knudsen number for this flow is Kn= $\eta/(h\, c_s)$ where the kinematic viscosity, η, is tuned by relaxation time τ. The simulation performed using 500 grid points to discretize the channel height, h, in the lattice Boltzmann framework is presented.

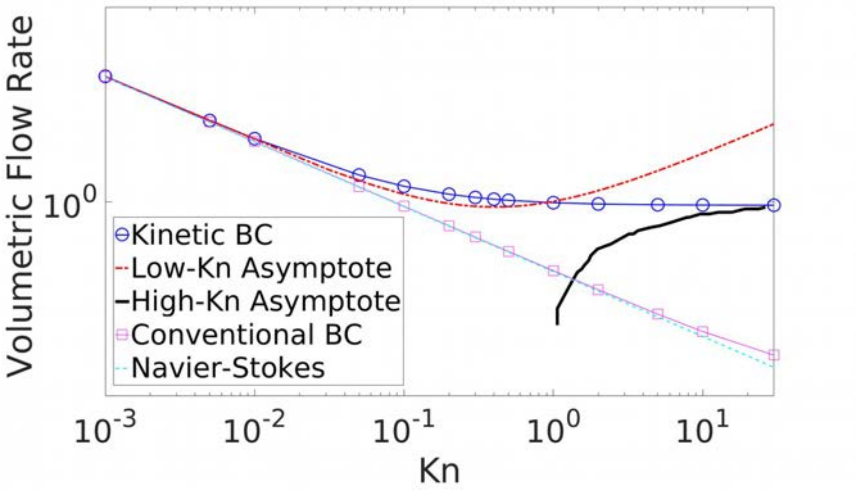


Fig. 1. Normalized mass flux as a function of Kn

As can be seen from Fig. 1, for continuum flow (Kn→0), mass flux evaluated from both conventional and slip boundary condition is same. However as Kn starts to increase, the conventional boundary condition is giving the same value of mass flow as predicted by Navier-Stokes with no-slip boundary condition for the full range of Kn. Furthermore, the kinetic boundary condition matches well with low as well as high Kn-asymptote. Hence, it can be concluded that the kinetic boundary condition is the minimal requirement to obtain the correct non-equilibrium behavior [8].

3.2. Porous Media Flow

The encouraging result described in the previous section motivated us to investigate the finite Knudsen effects in porous media flow. To test the usage of kinetic boundary condition in LB framework, we consider a simple connected porous media model between the parallel plate as shown in Fig. 2. The Knudsen number is defined by using the characteristic length to be pore-throat diameter, *d*, as shown in the figure. The permeability correction factor (PCF) which is defined as the ratio of apparent permeability (κ) with absolute permeability (κ_0) is plotted in Fig. 3. Here, the permeability is evaluated as:

$$\kappa=\frac{q\,\mu}{\nabla P} \tag{5}$$

with, q being the cross-sectional discharge, μ being the dynamic viscosity and ∇P being the pressure gradient. The absolute permeability is the permeability at very small Kn (Kn→0). The simulations were performed with 250 grid points in each direction.

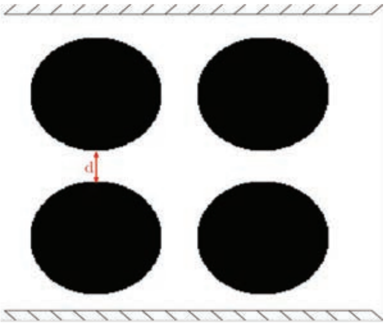


Fig. 2. Porous media with Pore throat diameter *d*

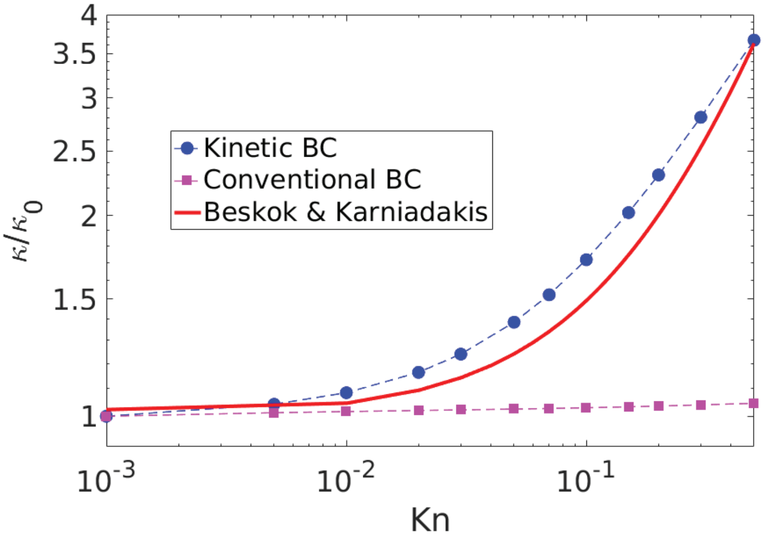
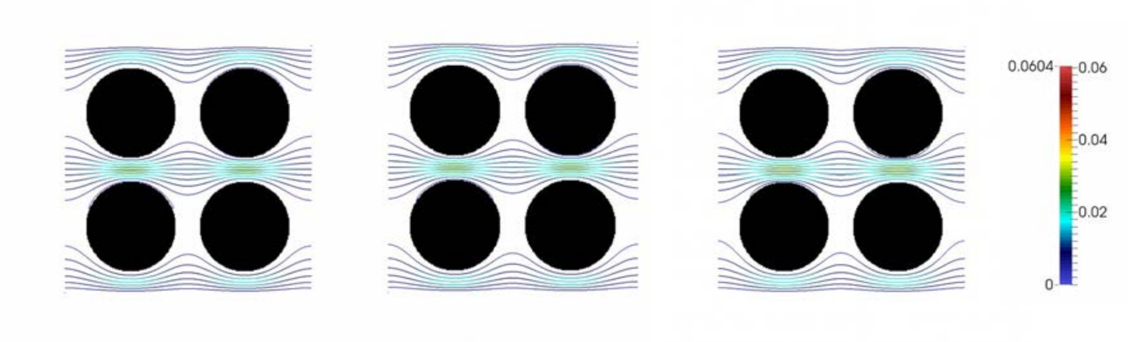


Fig. 3. Permeability correction factor with increasing Kn number

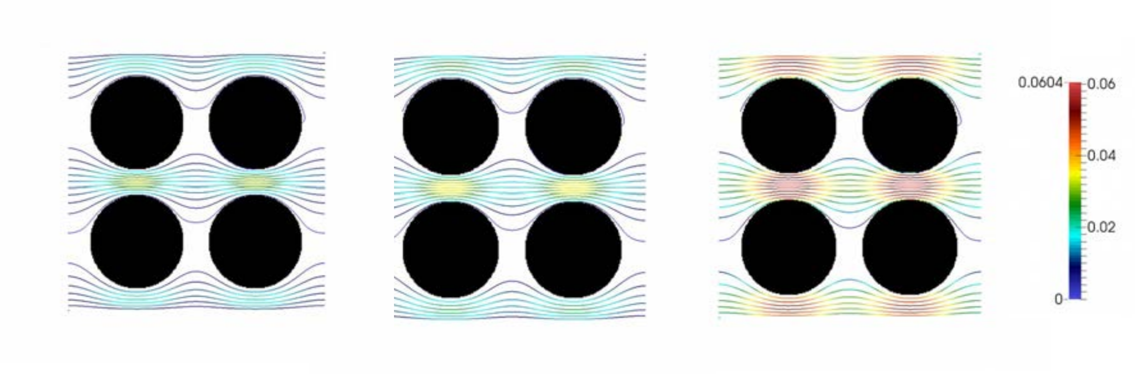
As can be seen from the Fig. 3, the conventional boundary condition does not show any significant increase in the PCF with increasing Kn number. On the other hand, the kinetic boundary condition not only show increasing PCF with Kn but also is in qualitative agreement with the analytical value given by Beskok et. al. [9]. The increase in the PCF with increasing Kn is attributed to the slip occurring at the fluid-solid intersection. Hence the next obvious thing to study is the profile of local velocity in this porous media set-up.

Finally, the steady state streamlines are plotted for the no-slip (conventional) and slip (kinetic) boundary condition in Fig. 4 for different Kn. As the Knudsen number is increased, the conventional boundary condition does not show any increase of velocity between the pores. However, the kinetic boundary condition shows an increase in velocity between the pore. The effect of slip is maximum inside the pore throat which is also evident from Fig. 4.



Kn=0.05 Kn=0.1 Kn=0.5

Conventional Boundary Condition



Kn=0.05 Kn=0.1 Kn=0.5

Kinetic Boundary Condition

Fig. 4. Streamlines with no-slip and slip boundary condition with different Kn

4. Conclusion

The CO_2 flow through porous media of pore-size in micro-meter falls under the slip-flow regime. However, in conventional numerical methods used to study CO_2 sequestration, the slip effect is usually ignored. In this study, using lattice Boltzmann simulation, we showed that in order to observe fundamental effects of small-scale flow (slip effect) in bulk properties like permeability, appropriate appropriate boundary condition is essential. This is importance because the slip boundary condition is shown to increase the permeability in finite Knudsen number flow in channel flow set-up. Further, using a simple homogeneous porous media, the role of slip velocity in the increment of permeability in small scale flow emphasized. In future, we intend to study the slip flow using realistic 3D rock pore model.

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