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

Shiwani Singh¹, Fei Jiang¹, Takeshi Tsuji¹
International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University,
744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

Abstract

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. The transport of fluid depends largely on geometry and structure of pores. In recent years, geological trapping of CO₂ by injecting it between the grains in the rock emerged as a viable solution to reduce the CO₂ emission into the atmosphere. The typical length scale of pores ranges from micro-meter(μm) to nano-meter(nm). Especially the pore space of cap rock (e.g., mudstone) that seals the injected CO₂ is small (nm scale). 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 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 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). It has been routinely used to simulate the multiphase flows in porous medium to unravel the physics of flow of CO₂ and which in turn helps in prediction of optimal condition to increase the storage property inside the rock. However, in these descriptions, a no-slip boundary condition is used at the fluid-solid interface. In the regime where the pore-size ranges from μm-nm, 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 interface can be naturally obtained by the lattice Boltzmann method just by the applying appropriate kinetic boundary at the interface. One such boundary condition is proposed in Ref. [1], 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 shown to reproduces the correct slip velocity in high Kn flows.

Here, we use lattice Boltzmann simulation with appropriate kinematic boundary condition in order to study the role of slip effect on the hydrologic properties (e.g., permeability). Simple geometry like homogeneous pore network is considered first to study the slip effect using the kinetic boundary condition. Further, we apply same method to the digital-rock-model of natural sandstone derived from micro-CT-scanned images Ref. [2]. Finally, aiming to enhance the storage capacity and to evaluate sealing capacity of cap rock, the role of interfacial tension in the presences of slippage (in micro-pores) is discussed.

References: