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Simulation of Fluid Penetration with High Density Ratio in Layered Porous Media with Lattice Boltzmann Model by Using Equations of State

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ABSTRACT

In this study, drop penetration with high density ratio in layered porous medium is simulated with pseudo-potential lattice Boltzmann model. Due to inherent weakness of this model in simulation of flows with high density ratio, equations of state as Redlich-Kwong and Peng-Robinson are employed in the simulation. The influence of temperature in surface tension is also studied. Drop penetration is investigated in a layered porous medium which is made of four different sections. Effects of different factors like porosity, hydrophobicity/ hydrophilicity of surfaces on the penetration rate and pattern is studied. The results illustrate that by decreasing the porosity, the penetration rate is changed. In hydrophilic situation, the penetration pattern is piston-type and in hydrophobic one, the penetration is similar to the finger or finger-type. The penetration pattern in different capillary numbers, viscosity ratios and different regimes are analyzed. The change of penetration pattern by consideration of non-homogenous hydrophilicity is also studied.

KEYWORDS:

Two Phase Model, Equations of State, Fluid Penetration, Layered Porous Medium.

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1- INTRODUCTION

In recent years, the lattice Boltzmann method (LBM) has emerged as an attractive computational approach to simulate isothermal multiphase fluid flow problems. Since LBM has many advantages to simulate complicated fluid dynamic problems, it has been widely used to solve multiphase problems. Yuan and Schaefer [1] incorporated some given equations of state (EOS) of non-ideal gas into Shan & Chen model [2] to achieve high-density ratios. Kupershtokh et al. [3] proposed a new pseudo-potential based model by integrating reduced equations of state. Liu et al. [4] extended a lattice Boltzmann high-density-ratio model which uses diffuse interface theory to describe the interfacial dynamics, to simulate immiscible multiphase flows in porous media. They have validated capability and accuracy of this model by simulations of equilibrium contact angle, dynamic capillary intrusion and gas displacement of liquid in a homogenous two dimensional pore network consisting of uniformly spaced square obstructions. This paper focuses on the incorporation of various EOS in the S-C single component multiphase LB model and simulates drop penetration into layered porous medium with high density. The influences of porosity and hydrophobicity/hydrophilicity of surfaces on the penetration rate and pattern are studied.

2- METHODOLOGY

In this study, Redlich-Kwong (R-K) and Peng-Robinson (P-R) equations of state are implemented. A drop with initial diameter d_0 is placed tangent to the surface of porous media; after several thousand iteration for stabilization of the droplet, the gravity force acts on and drop with initial velocity, u_0 , and the droplet penetrates into the porous medium. The most important geometric characteristic in this study is porosity which is defined as $\phi = V_{pores}/V_{total}$, that V_{pores} is volume of pores and V_{total} is total volume, of course in 2D simulations it is defined as number of fluid nodes to total nodes in porous area. Random distribution of solid blocks is chosen, since there is no regular distribution of particles in the media. The main property of this method is not just random choosing of nodes, which have to be filled, also is the porous media being consist of several similar layers with the same porosity so that it would remain constant in the whole domain. Each layer is constructed from 3×3 square which placed randomly. Therefore, a random generator program is utilized to fill some percentages of domains that have

two properties; First, it distributes solid rods in each layer and whole domain monotonously, i.e., it gives an equal filling chance to every grid and would produce desired porosity. Second, its porous generation differs in its different runs, which cause different configurations for every porosity.

To better investigation of the penetration rate quantitatively, dimensionless parameters are defined as: $h^* = h/L$ and $v^* = v/V$.

The computational domain is surrounded by wall and the full bounce back boundary condition is used.

3- RESULTS

3- 1- Evaluation of surface tension

In order to obtain surface tension in the D2Q9 model, a series of droplet tests with various radii is performed in a 100×100 lattice system. The relationship between the radii and pressure difference is expressed by Laplace's law $\Delta p = \sigma/R$, that σ is surface tension, R and Δp are radius and pressure difference. Regarding different temperatures ratios, surface tensions are determined, respectively, and no external force such as gravity is applied. Periodic boundary condition is imposed on each direction of the domain. Initially, different sizes of droplet are placed in the center of the lattice system, respectively, and then after a while, steady droplets of different radii can be obtained. The pressure inside and outside of the droplet is measured at the lattice that is far away from the interface, because the value of pressure may change sharply near the interface. The radius of the circle, on which the density of fluid 1 and fluid 2 are identical, is chosen as the radius of droplet at steady state. The relationship of Δp and $1/R$ are plotted in Figure 1. As shown, it is clear that the pressure difference inside and outside of the droplet is indeed proportional to the reciprocal of the droplet radius for all the cases. The excellent agreement between the LBM simulation results and the ones based on the Laplace's law proves that the code can be used to conduct the following simulations. As shown in Figure 1, by increasing the temperature ratios, surface tension is decreased. This test has done for P-R equation.

3- 2- EFFECT OF FIGURE POROSITY

To examine the porosity effects, Porosity values are set to 0.81, 0.85, 0.87, 0.9 and 0.96 respectively. With reduction in the porosity, the droplet will spread on the surface and its penetration rate decreases. The results are shown in Figure 2 and 3.

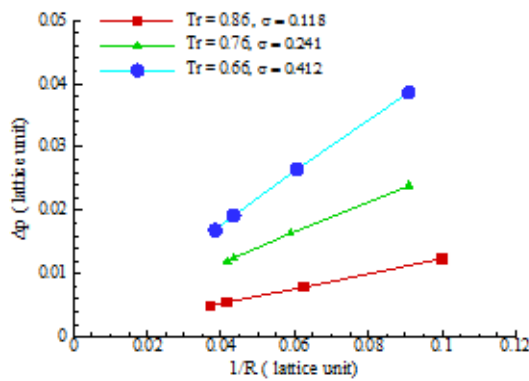


Figure 1. Relationships between Δp and l/R

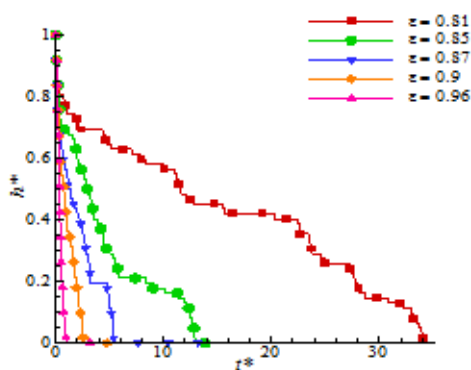


Figure 2. Plot of h^* versus dimensionless time t^* , at different porosities

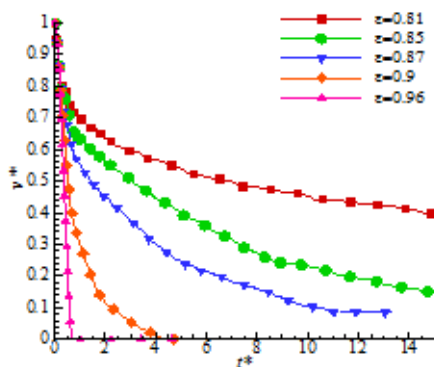


Figure 3. Plot of v^* versus dimensionless time t^* , at different porosities

As shown in Figure 2 penetration in height of porous medium occur completely but as illustrated in Figure 3, in low porosities some of penetrating fluid would not penetrate in and speared on the surface of porous medium.

3-3- HYDROPHILIC AND HYDROPHOBIC SOLID CELLS

The patterns of penetration for two cases are shown in Figure 4. As shown in hydrophilic situation droplet

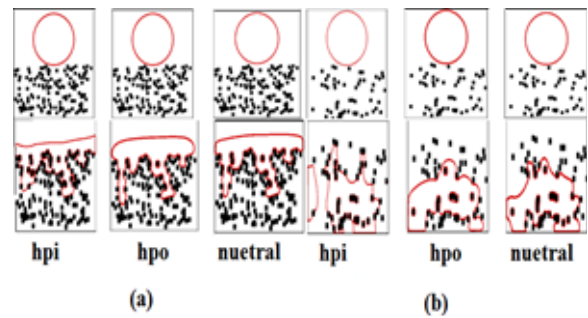


Figure 4. Pattern of penetration in three cases for (a) $\varepsilon=0/83$ (b) $\varepsilon=0/93$

wet more lattice and colony penetration is done, as it called piston-type.

In hydrophobic one droplet penetrates as it contains minimum numbers of lattice and just run away like a finger such that it called finger-type pattern. It is clear in low porosities.

4- CONCLUSION

In this study, drop penetration with high density ratio in layered porous medium was simulated with lattice Boltzmann model. The equations of state were also employed in the model. Drop penetration was investigated in a layered porous medium and the effects of hydrophobicity/ hydrophilicity of the porous surfaces on the penetration pattern were studied. The change of penetration pattern in the case of non-homogenous hydrophilicity was also analyzed.

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