EFFECTS OF WETTABILITY ALTERNATION SIMULATION BY LATTICE BOLTZMANN IN POROUS MEDIA

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Abstract

The microscopic wettability state of porous media plays a great role in controlling the location, flow and distribution of fluids in a reservoir rock. In this paper, the wettability influences of two immiscible fluids in porous media are studied by applying the Lattice Boltzmann method (LBM) based on the Shan-Chen Pseudo-potential model. Firstly, wettability of two immiscible fluids is described in terms of the relative importance of external force and surface tension, respectively. The effects of the wetting hysteresis on the flow behavior of fluids are investigated in the case with the external force, compared with the simulated results without the external force. Then taking the formation anisotropy into account, the porous media are divided into two sections characterized as mixed and fractional wettability. The effects of the different wettability on fluid behaviors are simulated in the porous models. Similarly, two more models are employed to reveal the influence of the mixed wettability on flow behaviors in the mixed-wet-small (MWS, small pores are oil wet) and mixed-wet-large (MWL, large pores are oil wet) porous media. The numerical results show (1) the external force would decrease the wettability of the wetting fluid on the surface significantly, even leading to wettability reversal; (2) the flow behaviors of two immiscible fluids are related to wettability of the porous media. Water-wet and intermediate-wet are relatively favorable in water flooding, and the order of relative oil permeability in diverse wettability rocks are intermediate-wet> water-wet >oil wet; (3) in mixed-wet rocks, water flooding is a more efficient method in MWS model to achieve a good displacing performance. It is because the oil would be trapped in the oil-wet small pores in the MWL model. This paper provides a good understanding of the wettability impacts from a microscopic point of view, which is key information for planning resource extraction. In addition, it confirms that the LBM is a promising tool for investigating and dynamically monitoring the flow behavior.

Introduction

The microscopic wettability state of porous media plays an important role in controlling the location, flow and fluid distributions in a reservoir rock with direct influence on oil recovery (see references [1-3]). Many experimental investigations have been completed for the impact of wettability. However, wettability of reservoir rocks and the fluid behaviors at the pore scale are uncertain and difficult to observe in the laboratory.

Lattice Boltzmann Method (LBM) is proven to be an effective and promising method for modeling fluid flows in porous media. During the last few years, LBM has been used widely in modeling multiphase flow through porous media because of its algorithm simplicity and accuracy in modeling the complex pore configurations [4-6]. The Shan-Chen Pseudo-potential model is especially popular for multiphase flows in porous media [7-9]. It provides a convenient means to approximate the real flow in a porous medium system for both single-fluid and multiphase flow. It is based on an idealization of the discrete physical system in both space and time.

In this paper, we employ the 2D Shan-Chen model to study the wettability effects on flow behaviors in porous media. First, wettability alternation of two immiscible fluids is discussed in terms of the external force and surface tension, the effects of which are investigated on wetting hysteresis. Then the porous media are divided into two types: mixed and fractional wettability. The effects of the different wettability on fluid behaviors are simulated in the porous media models. The wettability distributions in these models are the water-wet, oil-wet and intermediate-wet, separately. Moreover, two more models are adopted to reveal the influence of the mixed wettability on flow behaviors in mixed-wet-small (MWS, small pores are oil-wet) and mixed-wet-large (MWL, large pores are oil-wet) porous media.

THEORIES of LBM

LBM is a relatively recent technique evolved from lattice gas (LG) automata, and can be considered as a special finite difference scheme for the kinetic equation of the discrete-velocity distribution function. The particles' movements are separated into two influencing parts: collision and propagation, by the following equation:

$$f_i(x+e_i,t+1) = f_i(x,t) + \Omega_i(f(x,t)) \tag{1}$$

where the $f_i(x,t)$ represents the particle distribution at the position x along the direction *i* at the time t, e_i is the local particle velocity, $\Omega_i(f(x,t)$ is the collision operator which represents the rate of change of f_i resulting from collision. The most general two-phase flow model was proposed originally by Shan and Chen [11]. They suggested the use of microscopic interaction potential among particles in LBM. The cohesive force F_f added to the nearest neighbor fluid particles and the adhesive force F_s between the fluid and solid wall are given by

$$F_f(x) = -\varphi^{\sigma}(x)\sum_i G_f \cdot \varphi^{\bar{\sigma}}(x+e_i)e_i \tag{6}$$

$$F_{s\sigma}(x) = -\varphi^{\sigma}(x)\sum_i G_s \cdot s(x+e_i)e_i \tag{7}$$

where s represents the pore distribution in the porous media value for 0 (structure) and 1 (pore), and G_f and G_s are interaction strengths of components σ and $\bar{\sigma}$, respectively. Parameter $\varphi^{\bar{\sigma}}$ means a function related to the density of the component $\bar{\sigma}$. A positive (negative) value of adhesive parameter is used for wetting (non-wetting) fluid in LBM simulation. Introducing the forces into the collision operator LBM achieves a new local velocity for local equilibrium distribution function. It is attractive that phase separation takes place spontaneously in this model and its ability to simulate multiphase fluids is potent.

SIMULATIONS AND DISCUSSIONS

Effects of the External Force on Wettability

In a series of numerical simulations for wettability, we modify wettability by adjusting the contact angles between the fluids and the solid surface. A pure rectangle of 20*20 (in lattice units) is placed in a square of 100*200 (in lattice units) with periodic boundaries, i.e., the fluid particles left from the right side would return to the left side. The densities functions of the fluids are 2 and 0.06, respectively. Figure 1a represents the fluid distributions at the stable state only under the interfacial tensions. The contact angle is about 120 degree. From Figure 1*b* to Figure 1*d* the fluid distribution evolutions under the same external force (1e-5) are presented with the time development. With the growing time, the distributions of the droplet are constantly changing and the non-wetting is increasing. In the same way in a square of 100*100 (in lattice units) with periodic boundaries, the fluid behaviors are illustrated in Figure 2 to present the variation under the difference external forces. It is different to measure the contact angles due to the asymmetry of the droplet, thus we qualified the wettability by the droplet height. When the height is higher, the contact angle is bigger. It is clearly that the non-wetting is stronger and stronger with the increasing forces. It shows the external force would increase non-wetting, resulting in wettability hysteresis. In addition, it proved that LBM is easier to observe the dynamic evolution of the wettability variation than the laboratory.

Effects of Different Wettability on Fluid Behaviors

Assumption in a porous media model as the first subfigure in Figure 3, the white pores are full of oil, the black rounds represent the pore structure, and the pore volume of the porous media is unit. In the process of water flooding, the advancing interface evolutions are shown in the Figure 3. The rows illustrate the water displacing interface profiles in the water-wet, oil-wet and intermediate-wet models from top to bottom separately. In the displacement process, the water (grey fluids in Figure 3) moves into the big pores first in the oil-wet model. It does not move into the small pores even after the flow channels have been formed. A significant viscous fingering is presented. The interface profiles in the water-wet model are similar with that in the intermediate model. Comparison of the saturation profiles vs. the entered volume is shown in the Figure 4. The water saturation is the lowest in the oil-wet model. There is more oil trapped in the small pores than the other two models. Thus, the water displacing efficiency are the best in the intermediate-wet model, next is in the water-wet model and the third is in the oil-wet model. The reason is that the remaining oil is caused by the capillary forces and the model heterogeneity. In the intermediate-wet model, the capillary force is the relative weak; in the water-wet mode, the capillary force is reduced by the wettability hysteresis due to the fluid flow. So they got the less oil trapped. However, the capillary force is the resistant of water flooding in the oil-wet model and is increased by the wettability hysteresis, which results in the more oil trapped in the small pores. The Figure 5 illustrates the profiles of the relative permeability vs. water saturation in the water flooding process for the three models. The biggest oil relative permeability appeared in the intermediate model too, the followed is the water-wet and oil-wet model. That is to say, the water-wet and intermediate-wet are relatively favorable in water flooding, and the order of relative oil permeability in diverse wettability rocks are intermediate-wet> water-wet >oil wet.

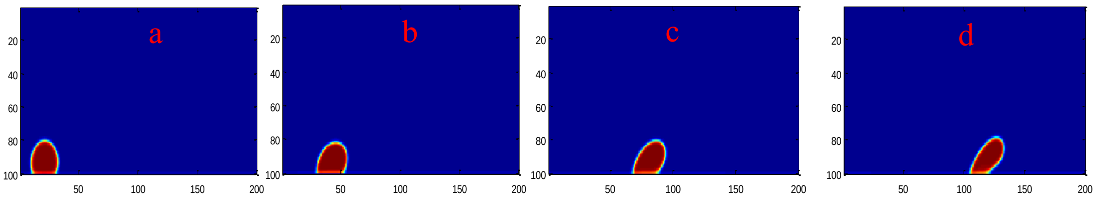

Figure 1. Fluid distribution profiles in a 100*200 lattices with periodic boundary at the different time step 1000, 3000, 5000 and 7000 in turn.

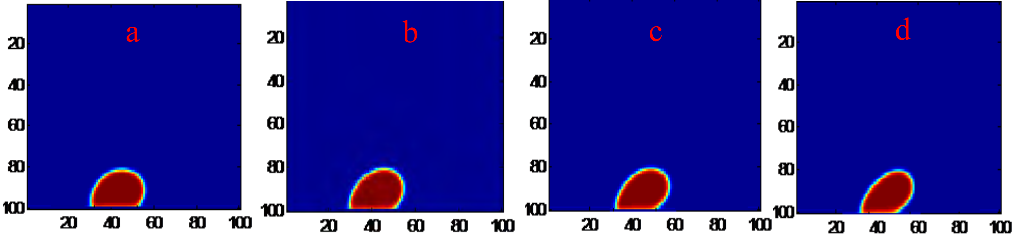

Figure 2. Fluid distribution profiles in a 100*100 lattices with periodic boundary at the different external forces 1e-6, 3e-6, 5e-6 and 1e-5 at the same time in turn.

Effects of Mixed Wettability on Fluid Behaviors

The pores and channels with different diameters have the mixed wettability in reservoir rocks. Generally the pore could be characteristic of MWS and MWL according to the wettability pattern. We have carried out the simulations for the immiscible flow behaviors in mixed-wet porous media as illustrated in Figure 6. In this figure, the white parts represent the pore full of oil. The grey parts mean the displacing water to occupy the spaces between the black round-shaped matrix grains in porous media. Figure 6 represents how the fluid distributions evolved in the MWS model (the bottom row) in the MWL model (the top row) at a specified growing time interval of 1000, respectively. It can be seen at the beginning that the areas invaded by water are purely characteristic of large pores in both models. In the MWL model, water prefers to keep away from the small pore. It did not occupy the small pores even after the flow channels are established among the big pores from inlet to outlet. Lot of oil is trapped in relatively small pores. However, in the MWS model, water moves to occupy the big pores easily, at the same time small pores are invaded too. The displacing interface is more stable in the MWS model and the viscous fingering is not as salient as shown in the MWL model. It is the capillary force that would block the water flow in the MWS model. As a consequence, water is kept away from the smaller pores and oil is trapped there Therefore, water flooding is a more efficient method in MWS model to achieve a good displacing performance.

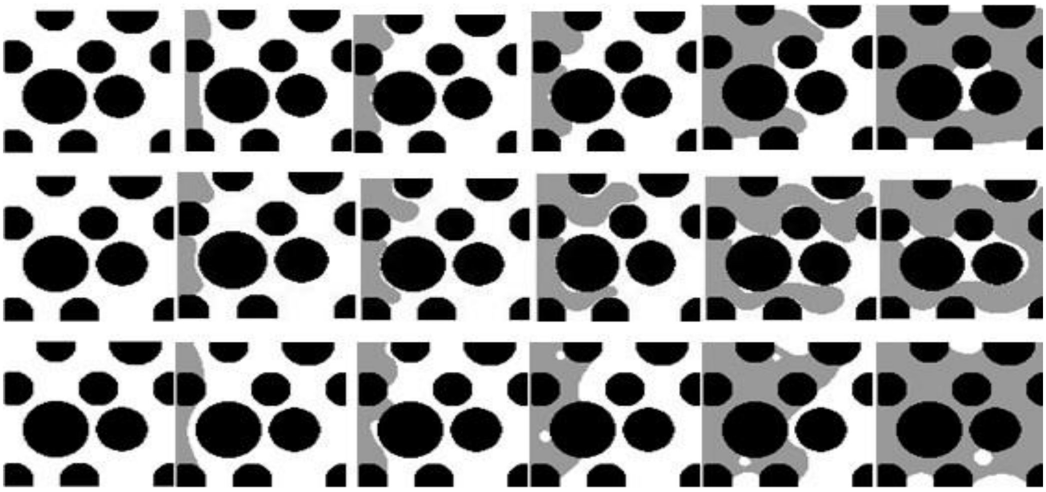

Figure 3. Displacing interface profiles in the water-wet (top row), the oil-wet (second row) and the intermediate-wet (third row) models.

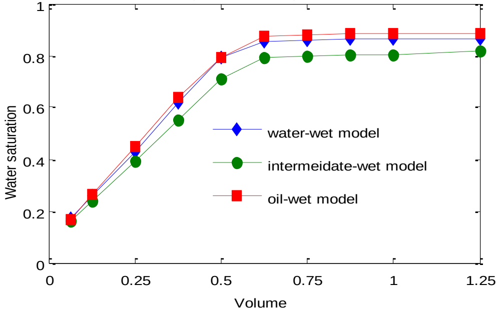

Figure 4. Water saturation vs. injected volume.

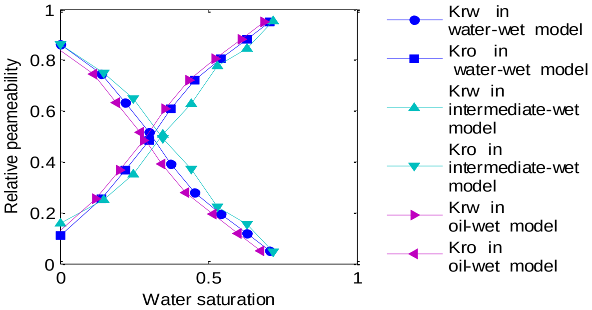

Figure 5. Relative permeability profiles vs. water saturation in three models

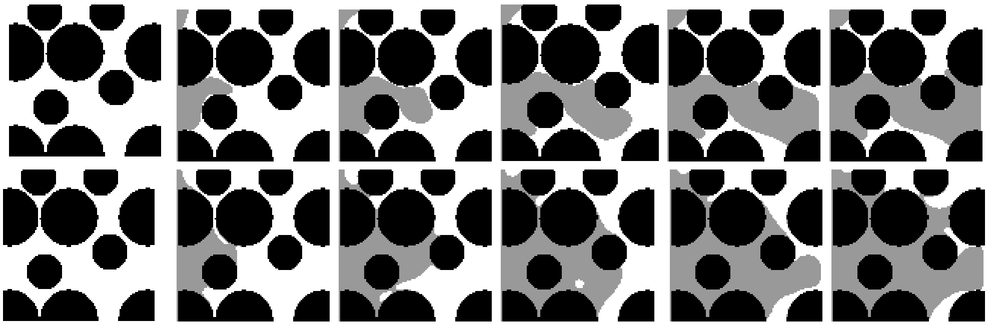

Figure 6 Fluid distributions in the MWL (top row) and in the MWS (bottom row) model

CONCLUSION

In this paper, the wettability influences of two immiscible fluids are studied by applying Shan-Chen Pseudo-potential LBM. The numerical results show (1) the external force would decrease the wettability of the wetting fluid on the surface significantly, even leading to wettability reversal; (2) the flow behaviors of two immiscible fluids are related to wettability of the porous media. Water-wet and intermediate-wet are relatively favorable in water flooding, and the order of relative oil permeability in diverse wettability rocks are intermediate-wet> water-wet >oil wet; (3) in mixed-wet rocks, water flooding is a more efficient method in MWS model to achieve a good displacing performance. It is because the oil would be trapped in the oil-wet small pores in the MWL model. This paper provides a good understanding of the wettability impacts from a microscopic point of view, which is key information for planning resource extraction. In addition, it confirms that the LBM is a promising tool for investigating and dynamically monitoring the flow behavior.

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