Numerical analysis of the CO_2 displacement in the wet-heterogeneous porous media at the pore scale

Heng Zhou[1, a,*], Dayong Wang[1, b]and Wenqiang Li[1, c]

[1]School of Energy and Power Engineering, Dalian University of Technology, Dalian, 116023, China.

[a,]*15230239298@163.com,[b]wangdy@dlut.edu.cn, [c]312816352@qq.com

Keywords: Wettability heterogeneity, Multiphase flow, Shan-Chen-type model, Saline aquifers.

Abstract. Comprehending deeply multiphase flow in saline aquifers is a precondition to solve the issues in the CO_2 geological sequestration and the wettability heterogeneity is one of the main factors affecting the CO_2 multiphase migration. In this paper, a Shan-Chen-type model (lattice Boltzmann method) is used to numerically investigate the effect of wettability heterogeneity on the CO_2 migration path and ultimate saturation with the two typical heterogeneous models. The results suggestthat the existence of wettability heterogeneity in porous media can thoroughly affect the flow path of CO_2 and the ultimate saturation, so it is the factor that cannot be ignored in the numerical simulation and experimental analysis for CO_2/brine systems.

Introduction

Saline aquifers are often chosen as preferred storage sites of CO_2geological sequestration because of its extremely largest potential storage capacity and widespread geographic distribution on the earth [1]. The multiphase flow in saline aquifers is a complex hydrogeological process.More comprehensive understanding of the multiphase flow process is a prerequisite for keeping the large storage capacity and safety of saline aquifers [2].

Due to the depositional environment, diagenesis,and tectonism, reservoirs are heterogeneous and moreover theseheterogeneitiesare significant factors influencing the multiphase flow process. The wettability heterogeneity of rock surfaces is a typicalrepresentationof the heterogeneity of reservoirs. To date, in the oil/water system, extensive experimental and numerical researches have been done to investigate the effect of heterogeneous wettability on capillary pressure [3], relative permeability [4], and the efficiency and displacement mechanisms of oil recoveryprocesses [5, 8].However, in the CO_2/brine system, the wettability heterogeneity is often ignored in researches [6, 7]. Due to the difference of the displacement mechanisms and the properties of the fluids between oil/water systems and CO_2/brine systems, and the importance of heterogeneous wettability, it is essential to investigate how heterogeneous wettability acts on the CO_2/brine system.

The stripeand lensmodels [8] representing two typical geological structures are often used to study the heterogeneity. In this paper, a Shan-Chen-type model developed by Porter [9] is used to numerically investigate the effect of wettability heterogeneity on the fluid flow path and the ultimate saturation during the immiscible displacement process of CO_2/brine at the pore scale in the two models mentioned above.

The lattice Boltzmann method

A Shan-Chen-type model developed by Porteris called the explicit forcing (EF)model. In the EF model,the lattice Boltzmann evolution equation is given by Eq. (1).

$$f_i^k(x+e_i\Delta t)-f_i^k=\frac{1}{\tau_k}\left[f_i^{eq,k}(x,t)-f_i^k(x,t)-\frac{\Delta t}{2}f_i^{F,k}\right]+\Delta t f_i^{F,k} \quad (1)$$

Where $f_i^k(x,t)$ denotes the distribution function of the *k*th fluid component in the*i*thvelocity direction at position x at time *t*; $f_i^{eq,k}(x,t)$ is the corresponding equilibrium distribution function;$\tau_k$denotes the dimensionless relaxation of the *k*th fluid component based on the kinematic viscosity by$\vartheta=(\tau_k-0.5)/3$;$f_i^{F,k}$represents the effect of external force.

The equilibrium distribution function $f_i^{eq,k}(x,t)$ is as follows:

$$f_i^{eq,k}(x,t) = \omega_i \rho_k \left[1 + \frac{e_i \cdot u_k^{eq}}{c_s^2} + \frac{(e_i \cdot u_k^{eq})^2}{2c_s^4} - \frac{u_k^{eq} \cdot u_k^{eq}}{2c_s^2}\right] \quad (2)$$

Where c_s equals to $1/\sqrt{3}$; The detail values of ω_i and e_i are introduced in Porter's paper.

The macroscopic density ρ_k and velocity u_k of the kth component are defined as

$$\rho_k = \sum_i f_i^k \quad (3)$$

$$\rho_k u_k = \sum_i f_i^k e_i + \frac{\Delta t}{2} F_k \quad (4)$$

Where F_k denotes the total external forces, and $F_k = F_{k,f} + F_{k,w}$ ($F_{k,f}$: the fluid-fluid interaction force; $F_{k,w}$: the fluid-solid interaction force).

The forces F_{kf} and F_{kw} in the EF model are expressed as

$$F_{k,f}(x) = -c_0 \psi_k(x) \sum_{\bar{k}} g_{k\bar{k}} \nabla \psi_{\bar{k}}(x + e_i \Delta t) \quad (5)$$

$$F_{k,w}(x) = -\psi_k(x) \sum_i g_{ads,k} s(x + e_i \Delta t) \quad (6)$$

In Eq. (5), c_0 equals to 6 for D2Q9; $\psi_k = \rho_k$ for binary mixtures; $g_{k\bar{k}}$ is the interaction strength. In Eq. (6), $\psi_k = \rho_k$; $s(x + e_i \Delta t)$ is an indicator of a solid phase, which equals 1 for a solid phase and 0 for a pore; The $g_{ads,k}$ denotes the adhesion strength and it is positive when the surface is non-wet for the fluid, otherwise negative.

In EF model, F_k is discretized into $f_i^{F,k}$ for 9 velocity directions where $f_i^{F,k}$ is defined as

$$f_i^{F,k} = \frac{F_k \cdot (e_i - u_k^{eq})}{\rho_k c_s^2} \quad (7)$$

The equilibrium velocity u_k^{eq} and the total velocity u of the fluid in EF model are given as

$$u_k^{eq} = \sum_k \frac{\rho_k u_k}{\tau_k} / \sum_k \frac{\rho_k}{\tau_k} \quad (8)$$

$$u = \sum_k \rho_k u_k / \sum_k \rho_k \quad (9)$$

Results and discussion

In this section, the effect of wettability heterogeneity on the fluid flow and the ultimate saturation in two heterogeneous models are discussed in detail. Moreover, in order to reflect the effect more clearly, a model with the uniform wettability is designed as a reference case.

The Distributions of Wettability and the Initial Condition. In this paper, the simulation region is set to be the 2D dimensions of 1085*405 lattice units. The solid grains in the models have the same diameter of 30 lattice units, the pore throat is set to be 10 lattice units and the porosity is 0.45. The skeleton structures and the distributions of wettability of three models are shown in Fig.1.

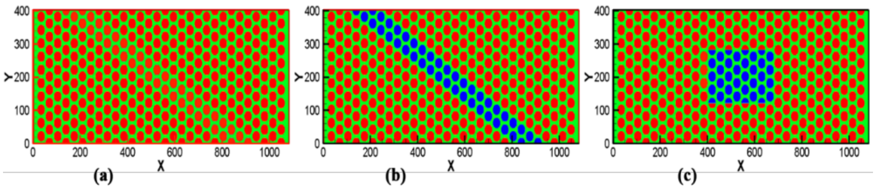

Fig. 1 The skeleton diagram, red grains are water-wet and blue grains are CO_2-wet, green color represents the flow channel, (a) the homogeneous model; (b) the stripe model; (c) the lens model

The properties of the fluids and some initial parameters are shown in Table 1. The half-way bounce back boundary condition is used at the solid surfaces including the upper and lower boundaries and the surfaces of the grains. Meantime, the left (inlet) and right (outlet) boundaries are set to be with a velocity boundary scheme by Zou and He [10].

Table 1 The parameters and initial values

density ratio	viscosity ratio	$g_{k\bar{k}}$	$g_{ads,k}$ for water-wet	$g_{ads,k}$ for CO_2-wet	inlet velocity
1:1	1:30(CO_2/H_2O)	0.32	0.05	-0.05	0.0005

Effect of Wettability Heterogeneity on the Flow Path. Fig. 2 has shown the various stages during the CO_2 flooding processes of the three models. As shown in Fig. 2, the displacement in the homogeneous wet modelis relatively even from the inlet to the outlet. By contrast, the flow patternsin two heterogeneous models arequite different from that in the homogeneous model, especially when CO_2 reaches the CO_2-wet region.In the stripe model, when CO_2 reaches the stripe, CO_2 preferentially flows along the stripe instead of towards the outlet, due to the lower CO_2 phase pressure in the stripe. All of the injected CO_2 reaches the stripe though three fine flow paths (remarked in Fig. 2), occupies the stripe region and acts as a barrier causing a considerable part of water in the region upstream of the stripe not to be displaced. In the lens model, due to the lower CO_2phase pressure, an over whelming majority of $CO_2$is sucked into the lens region, which restrains theflow of CO_2 in the surrounding regions of the CO_2-wet region. Meantime, it can be observed that all of the CO_2 flowing out from the outlet comes from the lens, which can severely affect the CO_2 distribution in the region downstream of the lens. Through the comparative analysis of three models, the difference between the homogeneous model and the heterogeneous ones shows that the existence of wettability heterogeneity can thoroughly change the flow path of CO_2, and the totally different flow patterns between the two heterogeneous models indicate that thedistributionof heterogeneity also has a very significant impact on the flow path.

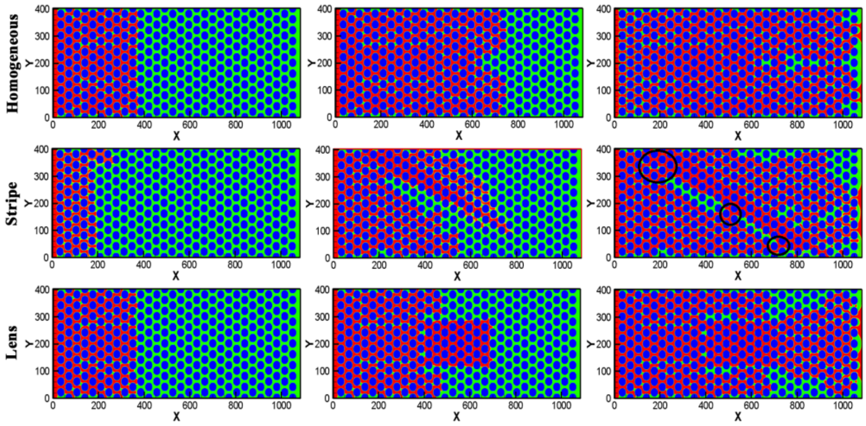

Fig. 2 The CO_2 flooding process where red color represents $CO_2$and green color represents water

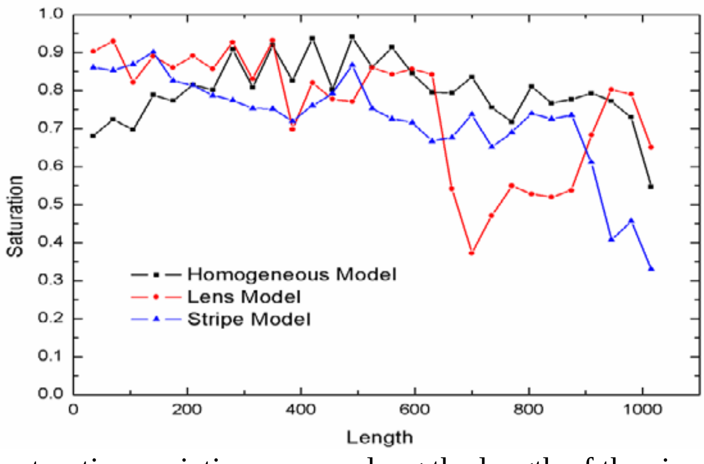

Fig. 3 TheCO_2 saturation variation curves along the length of the simulation region

Effect of Wettability Heterogeneity on the Ultimate Saturation. The variation curves of ultimate CO_2 saturation along the length of the simulation region for three models are also discussed. As shown in Fig. 3, the curves for the heterogeneous models are not consistent with the homogeneous model. At the beginning of the curves, the saturation in the homogeneous model is lower than the two heterogeneous ones. After that, in stripe model, the saturation curve is always lower than the homogeneous curve that is becausethe CO_2 cross-bedding in the stripe region causes a considerable part of water not to be displaced and the CO_2saturation to reduce.In the lens model, the fluctuation range of the saturation curve is quite large and totally different from the homogeneous model, especially in the region downstream of the lens. In general, due to the existence of wettability heterogeneity, the saturation curve has been dramaticallyinfluenced, thusthe wettability heterogeneity should betaken into consideration in researches of the CO_2/brine system.

Summary

Two kinds of typical heterogeneous models have been implementedto numerically investigate the effect of wettability heterogeneity on multiphase flow in the CO_2/brine system. By comparing their simulation results with the homogeneous model, the following conclusions can be obtained:

1) The existence of wettability heterogeneity can thoroughly change the flow path of CO_2, and the different distributions of wettability heterogeneity can result in different flow patterns.
2) The wettability heterogeneity is one of the important factors determiningthe CO_2saturation, and should be taken into consideration in researches of the CO_2/brine system

Acknowledgements

This work was financially supported by the National Science Foundation of China (No. 51376033 andNo. 41004031).

References

[1] C.M. White, B.R. Strazisar, E.J. Granite, J.S. Hoffman, H.W. Pennline, Separation and capture of CO_2 from large stationary sources and sequestration in geological formations—Coalbeds and deep saline aquifers, J. Air Waste Manag. Assoc. 53 (2003) 645–715.

[2] W. S.Han, S. Y. Lee, C.Lu, B. J.McPherson, Effects ofpermeability on CO_2 trapping mechanisms and buoyancy-driven CO_2migration in saline formations. Water Resour. Res. 46 (2010) W07510.

[3] S. K.Masalmeh, Studying the effect of wettability heterogeneityon the capillary pressure curves using the centrifuge technique. J. Pet. Sci.Eng. 33 (2002) 29–38.

[4] S. K.Masalmeh, The effect of wettability heterogeneity oncapillary pressure and relative permeability. J. Pet. Sci. Eng. 39 (2003) 399–408.

[5] R. A.Dawe, C. A.Grattoni, Experimental displacementpatterns in a 2 × 2 quadrant block with permeability and wettabilityheterogeneities: Problems for numerical modeling. Trans. Porous Media. 71 (2008)5–22.

[6] T. K.Tokunaga, and J. Wan, Capillary pressure and mineral wettability influences on reservoir CO_2capacity, Rev. Mineral. Geochem.77(2013)481–503.

[7] K.Chaudhary, M.B. Cardenas, W.W.Wolfe, J.A. Maisano, R.A. Ketcham, and P.C. Bennett, Pore-scale trapping of supercriticalCO_2 and the role of grain wettability and shape, Geophys. Res. Lett. 40(2013)3878–3882.

[8] A. Caruana, R.A. Dawe, Flow behaviour in the presence of wettability heterogeneities. Trans. Porous. Med.25(1996) 217–233.

[9] M.L. Porter, E.T. Coon, Q. Kang, J.D. Moulton, J.W. Carey, Multicomponent interparticle-potential lattice Boltzmann model for fluids with large viscosityratios, Phys. Rev. E 86 (2012) 036701.

[10] Q.Zou, X.He. On pressure and velocity boundary conditions for the lattice Boltzmann BGK model. Phys. Fluids. 9 (1997)1591-1598