Numerical analysis of the CO2 displacement in the wet-heterogeneous porous media at the pore scale

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Abstract. Comprehending deeply multiphase flow in saline aquifers is a precondition to solve the issues in the CO2 geological sequestration and the wettability heterogeneity is one of the main factors affecting the CO2 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 CO2 migration path and ultimate saturation with the two typical heterogeneous models. The results suggest that the existence of wettability heterogeneity in porous media can thoroughly affect the flow path of CO2 and the ultimate saturation, so it is the factor that cannot be ignored in the numerical simulation and experimental analysis for CO2/brine systems.

Introduction

Saline aquifers are often chosen as preferred storage sites of CO2 geological 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 these heterogeneities are significant factors influencing the multiphase flow process. The wettability heterogeneity of rock surfaces is a typical representation of 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 recovery processes [5, 8]. However, in the CO2/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 CO2/brine systems, and the importance of heterogeneous wettability, it is essential to investigate how heterogeneous wettability acts on the CO2/brine system.

The stripe and lens models [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 CO2/brine at the pore scale in the two models mentioned above.

The lattice Boltzmann method

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

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

Where \( f_i^k(x, t) \) denotes the distribution function of the \( k \)th fluid component in the \( i \)th velocity 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 \( \theta = (\tau_k - 0.5)/3; f_i^{F,k} \) represents the effect of external force.
The equilibrium distribution function \( f_{i}^{eq,k}(x, t) \) is as follows:

\[
f_{i}^{eq,k}(x, t) = \omega_{i} \rho_{k} \left( 1 + \frac{e_{i}}{c_{s}^{2}} + \frac{e_{i}^{2}}{2c_{s}^{2}} - \frac{u_{ik}^{eq}}{2c_{s}^{2}} \right)
\]

Where \( c_{s} = 1/\sqrt{3} \); The detail values of \( \omega_{i} \) and \( e_{i} \) are introduced in Porter’s paper.

Themacroscopic density \( \rho_{k} \) and velocity \( u_{ik} \) of the \( k \)th component are defined as

\[
\rho_{k} = \sum_{i} f_{i}^{k}(3)
\]

\[
u_{ik} = \sum_{i} f_{i}^{k} e_{i} + \frac{\Delta t}{2} F_{k}(4)
\]

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 \( F_{k,f} \) and \( F_{k,w} \) in the EF model are expressed as

\[
F_{k,f}(x) = -c_{0} \psi_{k}(x) \sum_{k} g_{kk} \nabla \psi_{k}(x + e_{i} \Delta t)(5)
\]

\[
F_{k,w}(x) = -\psi_{k}(x) \sum_{i} g_{ads,k} s(x + e_{i} \Delta t) (6)
\]

In Eq. (5), \( c_{0} \) equals to 6 for D2Q9; \( \psi_{k} = \rho_{k} \) for binary mixtures; \( g_{kk} \) 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

\[
\frac{f_{i}^{eq,k}}{\rho_{k} c_{s}^{2}} = \frac{F_{k}(e_{i} - u_{ik}^{eq})}{\rho_{k} c_{s}^{2}} (7)
\]

The equilibrium velocity \( u_{ik}^{eq} \) and the total velocity \( u \) of the fluid in EF model are given as

\[
u_{ik}^{eq} = \sum_{k} \frac{\rho_{k} u_{ik}}{\sum_{k} \rho_{k}} (8)
\]

\[
u = \sum_{k} \rho_{k} u_{ik}/\sum_{k} \rho_{k} (9)
\]

**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](image)

Fig. 1 The skeleton diagram, red grains are water-wet and blue grains are CO2-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>
<thead>
<tr>
<th>density ratio</th>
<th>viscosity ratio</th>
<th>( g_{kk} ) for water-wet</th>
<th>( g_{ads,k} ) for CO2-wet</th>
<th>inlet velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>1:30(CO2/H2O)</td>
<td>0.32</td>
<td>0.05</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

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Effect of Wettability Heterogeneity on the Flow Path. Fig. 2 has shown the various stages during the CO₂ flooding processes of the three models. As shown in Fig. 2, the displacement in the homogeneous wet model is relatively even from the inlet to the outlet. By contrast, the flow patterns in two heterogeneous models are quite different from that in the homogeneous model, especially when CO₂ reaches the CO₂-wet region. In the stripe model, when CO₂ reaches the stripe, CO₂ preferentially flows along the stripe instead of towards the outlet, due to the lower CO₂ phase pressure in the stripe. All of the injected CO₂ reaches the stripe through 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 CO₂ phase pressure, an overwhelming majority of CO₂ is sucked into the lens region, which restrains the flow of CO₂ in the surrounding regions of the CO₂-wet region. Meantime, it can be observed that all of the CO₂ flowing out from the outlet comes from the lens, which can severely affect the CO₂ 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 CO₂, and the totally different flow patterns between the two heterogeneous models indicate that the distribution of heterogeneity also has a very significant impact on the flow path.

Effect of Wettability Heterogeneity on the Ultimate Saturation. The variation curves of ultimate CO₂ 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 because the CO₂ cross-bedding in the stripe region causes a considerable part of water not to be displaced and the CO₂ saturation 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 dramatically influenced, thus the wettability heterogeneity should be taken into consideration in researches of the CO$_2$/brine system.

Summary

Two kinds of typical heterogeneous models have been implemented to 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 determining the CO$_2$ saturation, and should be taken into consideration in researches of the CO$_2$/brine system.

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References


