Pore-scale investigation of factors influencing polymer flooding in dual-permeability porous media

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Abstract. In present work Cahn–Hilliard phase field coupled with Navier-Stokes equations were solved using finite element method to simulate polymer flooding in a dual-permeability porous medium, the effect of injection rate, oil viscosity and oil density on polymer displacement oil process was quanlitatively and quantitatively investigated. The simulated models realistically captured the micro mechanism during polymer flooding, e.g., oil film thinning and rupture, profile conformance enhancement. The result shown that with the injection rate increase, water displacement efficiency increase, however, an optimal injection rate exists for water flooding in dual-permeability porous media. under the intermediate injection rate flooding, polymer flooding could gain an incremental oil recovery up to 40.7%.

1. Introduction
Water has a higher mobility in the reservoir due to its low viscosity compared to that of oil hence by selecting the region of low resistance against the invading. It would bypass the low permeable regions, thus gives a limited incremental oil production. A remedy for this problem is addition of polymers to the injected water. The polymer network is formed causing the viscosity to increase. The high viscosity fluid preferentially flows through high permeable zone, hence increase the resistivity, allowing the flooding water to flow through low permeability zone and increase the sweep efficiency and reduced water cycling, the object of this paper is modeling polymer flooding at pore-scale and investigating the factors influenceing polymer displacement process.

Pore-scale simulation of fluid flow through porous media demands a method that can handle complex pore geometries and interfacial dynamics. Recent advances in computational facilities have enabled the use of methods (like Smoothed Particles Hydrodynamics methods (SPH) [1, 2] and Lattice Boltzmann methods (LBM) [3–5]. Aslo, direct numerical simulations based on a straightforward discretization of the Navier–Stokes (NS) equations which couple with an interface tracking methods was an preferable approach. Examples of most popular interface capturing methods are Level-Set (LS) [6], Volume of Fluid (VOF) [7–10] and phase field methods (PFM) [11]. Akhlaghi Amiri and Hamouda [12] confirmed that phase-field methods a reliable approach with a reasonable computational time to capture pore-scale fluid flow mechanisms in complex porous media.

In this paper, PFM coupled with Navier-Stokes equation was employed to simulate two-phase flow during water and polymer flooding in dual-permeability porous medium. Finite element method was
used to solve the equations with proper boundary conditions in a robust software, COMSOL multiphysics.

2. Model description

A two dimensional dual-permeability porous media was constructed which consisting of a high permeability layer on the top and low permeability layer under the bottom. In order to create non-homogeneity, permeability of both layer were controlled by different grain size. Within each layer, the grains were represented by equilateral triangular array of circles with same size. The model was initially saturated with oil, polymer solution which shows an shear thinning rheology properties was supported by constant velocity inflow from the inlet. The governing equation were supplemented by standard boundary condition (e.g., inlet, outlet, no-slip, wetted wall and symmetry). All the numerical experiments were conducted under intermediate wettability condition, the pressure was assumed to be zero at the outlet.

![Figure 1](image_url)

**Figure 1.** The geometries (a) and mesh distribution (b) of dual-permeability porous media

The effect of injection rate and oil viscosity on water and polymer flooding was investigated with velocity ($v$) of 0.001, 0.01 and 0.1 m/s, varying oil viscosity ($\mu$) of 0.005, 0.01, 0.02 Pa·s. Geometrical and fluid properties are list in Table 1.

| Geometrical and fluid properties of simulation |   |
|-----------------------------------------------|--|
| Length (mm) | Width (mm) | Pore diameter in high permeability layer (mm) | Pore diameter in low permeability layer (mm) |
| 15 | 4.6 | 0.4 | 0.5 |
| Water viscosity (Pa·s) | Oil viscosity (Pa·s) | Water density (kg/m³) | Oil density (kg/m³) |
| 0.001 | 0.01 | 1000 | 1000 |

3. Result

3.1. Water flooding

The effect of water injection rate on remaining oil distribution of water flooding was shown in Figure 2. We simulated four injection scenario, the injection rate range from low (0.005 m/s) to high (0.1 m/s). As the Figure 2a shown, because of high flow resistance in low permeability layer, water preferentially
taken path in the top high permeability layer, only a small area near inlet part of bottom low permeability was swept. The remaining oil distribution of injection rate 0.01m/s was almost the same with that of 0.005m/s, with the injection rate increase to 0.05m/s, viscous force increase, water starts to enter into the low permeability layer, thus more oil was expelled from the lower part of model, meanwhile, as the water flooding with unfavorable mobility, a fingering path formed on the bottom of low permeability layer, which lead to large area of bypass oil in the middle of model. the high injection rate(0.1m/s) water flooding result was shown in Figure 2d, it can be seen that the water flooding displacement efficiency is high with two oil blobs trapped.

Figure 2. Snapshots of stabilized fluid distributions for the simulated model with different water injection rate at $\mu =0.01\text{Pa}\cdot\text{s}$. (a) $v= 0.005\text{m/s}$ (b) $v= 0.01\text{m/s}$ (c) $v= 0.05\text{m/s}$ (d) $v= 0.1\text{m/s}$

The comparison of production curve under different injection rate of water flooding was shown in Figure 3. it can be seen that with the injection rate increase, water flooding displacement efficiency increase, however, when injection rate increased to 0.05m/s, the increasing tendency gradually slow. An optimal water injection rate exist for dual-permeability porous media.

Figure 3. comparison of production curve (a) and recovery factor (b) under different injection rate of water flooding

3.2. Polymer flooding
In order to investigated the effect of injection rate and oil viscosity on polymer flooding displacement, a shear thinning polymer solution which fitted with an power law model was used with consistence index of 17.25 and power index of 0.754. The stabilized distribution of water and oil (blue and red phases, respectively) in the models with different injection rate and oil viscosity are shown in Figure 4. It can be seen from Figure 4a-4c that with low rate(0.001m/s) polymer injection, the high permeability layer was completely swept at oil viscosity of 5mPa·s, with the oil viscosity increase, the width of water flow path gradually decrease. In the intermediate injection rate case(0.01m/s), remaining oil distribution almost same with oil viscosity lower than 10mPa·s, remaining oil was distributed at the low permeability
layer near outlet, as the oil viscosity increase to 0.02 Pa·s, polymer solution fingering path formed, very close to the Figure 2c. As high injection rate polymer flooding result shown in Figure 4g-4i, polymer displacement efficiency was significantly improved compared to low and intermediate injection rate polymer flooding, after flooding process stable, only a small amount of trapped oil blobs remain in the model for different oil viscosity.

Take intermediate injection rate (0.01 m/s) water flooding as base case to make a comparison to that of polymer flooding, it can be seen from Figure 4e and Figure 2b, as the polymer solution injected, the viscosity of displacing fluid increase, which causing high resistivity zone in front of the high permeability layer. Hence the water is diverted to the low permeability zone.

Figure 4. Snapshots of stabilized fluid distributions for the simulated model with different injection rate and oil viscosity. (a) $v=0.001\, \text{m}/\text{s}, \mu=0.005\, \text{Pa} \cdot \text{s}$ (b) $v=0.001\, \text{m}/\text{s}, \mu=0.01\, \text{Pa} \cdot \text{s}$, (c) $v=0.001\, \text{m}/\text{s}, \mu=0.02\, \text{Pa} \cdot \text{s}$ (d) $v=0.01\, \text{m}/\text{s}, \mu=0.005\, \text{Pa} \cdot \text{s}$ (e) $v=0.01\, \text{m}/\text{s}, \mu=0.01\, \text{Pa} \cdot \text{s}$, (f) $v=0.01\, \text{m}/\text{s}, \mu=0.02\, \text{Pa} \cdot \text{s}$ (g) $v=0.1\, \text{m}/\text{s}, \mu=0.005\, \text{Pa} \cdot \text{s}$ (h) $v=0.1\, \text{m}/\text{s}, \mu=0.01\, \text{Pa} \cdot \text{s}$, (i) $v=0.1\, \text{m}/\text{s}, \mu=0.02\, \text{Pa} \cdot \text{s}$

Figure 5. Comparison of recovery factor curve under different parameter combination
4. Conclusions
The purpose of this work was to assess the effect of injection rate, oil viscosity on pore-scale polymer flooding displacement efficiency. According to the simulation result, water bridging and oil drop detachment were captured under high injection rate polymer flooding. And with the injection rate increase, both the displacement efficiency of water and polymer flooding increase, and high injection rate polymer flooding can narrow the flooding performance with varying oil viscosity.

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