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Pore-Level Influence of Wettability on Counter-Current Spontaneous Imbibition

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Summary

Medium wettability plays the main role during spontaneous imbibition (SI) in fractured porous media; however, one can rarely find pore-scale studies addressing wettability effects on this process. In present work Cahn–Hilliard phase field coupled with Navier-Stokes equations were solved using finite element method to simulate counter-current SI in a horizontal heterogeneous porous medium containing fracture. Capillary governed fluid displacement in media with different contact angles - θ=π/10 (extremely water-wet) up to θ=π/2 (neutral wet) - were simulated. The simulated models realistically captured micro-scale mechanisms during imbibition process in strongly water wet media, e.g., oil film thinning and rupture, fluids' contact line movement, water bridging and oil drop detachment. Water capillary fingering through matrix and oil drop expulsion from matrix grains to the fracture were evident displacement phenomena in strongly water wet media. There was a specific grain contact angle, θ=π/4, above it matrix oil recovery was negligible and below it the imbibition rate and oil recovery were significantly increased by decreasing contact angle. For instance, after 5 s, almost 20% of the matrix oil was recovered in the model with θ=π/10, while final recovery of the models with θ>π/4 was less than 10% even after more than 1 min.

Introduction

Spontaneous imbibition (SI) of wetting phase (e.g., water) from fracture into non-wetting phase (e.g., oil) saturated matrix blocks is known as the main mechanism of recovery in fractured reservoirs. Among two types of SI, known as co-current and counter-current, the last one frequently happens in fractured reservoir; however, most of the reported studies have addressed the co-current one. This work presents the results of a numerical pore-level study on the wettability effects in capillary displacements through a fractured porous medium during counter-current SI.

Lattice Boltzmann method (LBM) has been used before by Hatiboglu and Babadagli (2008) and Gunde et al. (2013) to simulate spontaneous imbibition at pore-scale, to understand the dynamics of interaction between matrix and fracture. The simulation results of Hatiboglu and Babadagli (2008) showed that pore structure controls the imbibition process in the strongly water-wet medium. Gunde et al. (2013) observed that water tends to imbibe through smaller pores and oil phase expellees from the relatively larger pores. They also concluded that relative permeability of wetting phase increases by contact angle. However, LBM demonstrated some limitations for immiscible displacements especially at high viscosity ratios.

Recently, Akhlaghi Amiri and Hamouda (2013) confirmed that phase-field method (PFM) is a reliable approach with a reasonable computational time to capture pore-scale fluid flow mechanisms in complex porous media. They simulated co-current SI for different wettability states and showed that water fingers become thinner and stabilized water saturation becomes less as the medium becomes less water wet (Akhlaghi Amiri and Hamouda, 2013). In this paper, PFM coupled with Navier-Stokes equation was employed to simulate two-phase flow during counter-current SI in a fractured porous medium. Finite element method was used to solve the equations with proper boundary conditions in a robust software, COMSOL multiphysics.

Model description:

A 2D fractured medium was constructed consisting of a nonhomogeneous porous matrix and a fracture. In the simulated porous matrix, the grains were represented by equilateral triangular array of circles with different sizes, to create non- homogeneity, and it was initially saturated with oil. The fracture, adjacent to the matrix, was initially saturated with water and its water flow was supported by low rate water inflow from an inlet. The governing equations were supplemented by standard boundary conditions (e.g., inlet, outlet, no-slip, wetted wall and symmetry). On the solid grains, wetted wall was implemented with different contact angles. Water was injected with constant velocity (u_{inj}). The pressure was assumed to be zero at the outlet.

Results

Capillary forces imbibe water into the porous matrix, however viscous forces cause water flow in the fracture and the balance between them determines microscopic distribution of fluids in pore-spaces. Through invasion of wetting phase into the porous medium, oil droplets are expelled one by one to the fracture, in good agreement with experimental observations. The stabilized distribution of water and oil (blue and red phases, respectively) in the models with different contact angles are shown in Figure 1. In neutral wet condition ($\theta=\pi/2$), oil droplet expulsion does not occur and water-oil interface just moves a little bit toward the matrix (Figure 1a). In the cases of $\theta=\pi/3$ and $\theta=\pi/4$, few oil blobs are expelled from matrix's top-right and middle, however water imbibition takes place just through small parts of porous medium, very close to the fracture (Figure 1b and c). Water imbibed zone becomes considerable as θ decreases to $\pi/6$ (Figure 1d), in which water phase forms a front with a regular shape, without any recognizable finger. When the medium is extremely water-wet, $\theta=\pi/8$ and $\pi/10$ (Figure 1e and f) water capillary fingers propagate deeply into the matrix and some oil droplets with different sizes are trapped in various parts of the porous medium. Figure 2 shows two enlarged sections of the simulated medium at two instants during described water imbibition process (with $\theta=\pi/8$). As demonstrated in Figure 2a, as water front approaches the marked grain, the film of oil phase on the grain surface narrows until it ruptures; hence water phase contacts the grain's surface. Thereafter, water–oil contact line movement takes place on the grain surface during water invasion process, until water phase surrounds the whole grain. Figure 2b shows how detachments of two oil drops (with different sizes) occur as a result of bridging of water films between adjacent grains and hence oil film thinning and rupture.

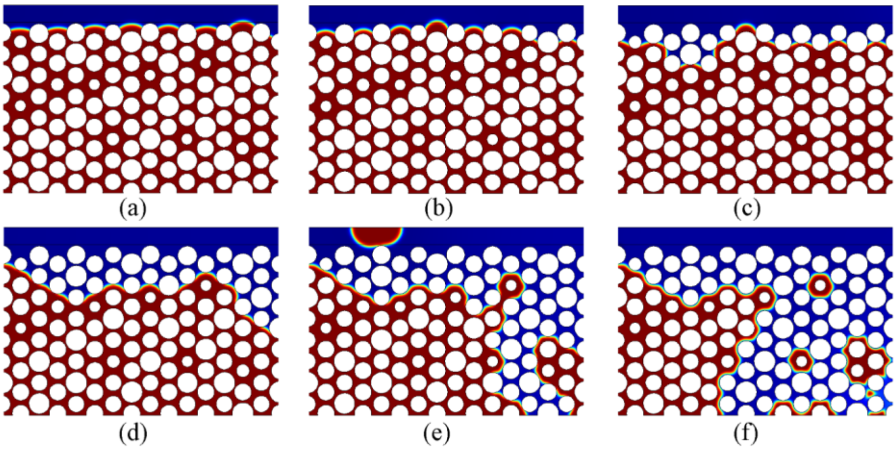

Figure 1. *Snapshots of stabilized fluid distributions for the simulated model with different grain contact angles of. (a) θ= π/2, (b) θ= π/3, (c) θ= π/4, (d) θ= π/6, (e) θ= π/8, and (f) θ= π/10.*

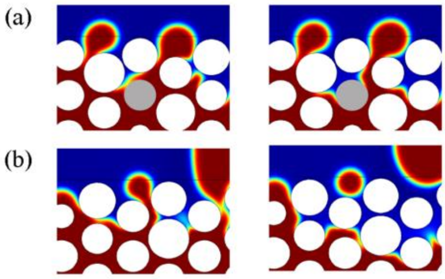

Figure 2. *Two enlarged sections of the simulated model with θ=π/8 at two successive instants during imbibition process.*

Conclusions

The aim of the present work was to assess the effect of medium wettability on the water-oil displacement during matrix-fracture interaction in the process known as counter-current spontaneous imbibition (SI). Different pore-scale mechanisms such as oil film thinning and rupture, fluids' contact line movement, water bridging and oil drop detachment were captured in strongly water wet condition (i.e., θ=π/8). It was found that fluid distributions are strongly dependent on the matrix wettability and there is a specific grain contact angle, θ=π/4, above it matrix oil recovery reduces drastically. In addition, the obtained results showed that phase field method is able to capture successfully pore level mechanisms in counter current SI.

References

Mirzaei-Paiaman, A., Masihi, M., Standnes, D.C., [2011]. An analytic solution for the frontal flow period in 1D counter-current spontaneous imbibition into fractured porous media including gravity and wettability effects. Transp. Porous Media 89, 49-62.

Hatiboglu, C.U., Babadagli, T., [2008] Pore-scale studies of spontaneous imbibition into oil-saturated porous media. Phys. Rev. E 77, 066311.

Gunde, A., Babadagli, T., Roy, S.S., Mitra, S.K., [2013] Pore-scale interfacial dynamics and oil–water relative permeabilities of capillary driven counter-current flow in fractured porous media. J. Pet. Sci. Eng. 103, 106-114.

Akhlaghi Amiri, H.A., Hamouda A.A., [2013] Evaluation of level set and phase field methods in modeling two phase flow with viscosity contrast through dual-permeability porous medium. Int. J. Multiphase Flow 52, 22-34.

Akhlaghi Amiri, H., Hamouda, A., [2014] Pore-scale modeling of non-isothermal two phase flow in 2D porous media: Influences of viscosity, capillarity, wettability and heterogeneity. Int. J. Multiphase Flow 61, 14-27.