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Pore-scale interfacial dynamics and oil–water relative permeabilities of capillary driven counter-current flow in fractured porous media

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ABSTRACT

The simulation of counter-current capillary imbibition displacement in a fractured porous medium is performed using a two-color Lattice Boltzmann Model (LBM). The kerosene–water interface development is studied at the pore-scale, and the saturation profiles are compared with core-scale experimental results by Hatiboglu and Babadagli (2008). An additional simulation is performed for a relatively larger porous system, which displays a relatively stable saturation growth. A relative permeability curve is obtained for the counter-current displacement process and it is compared with the corresponding co-current situation. The relative permeability of non-wetting (oleic) phase shows a concave nature i.e., initial increase followed by a subsequent decrease. Such a trend can be explained by the fact that the resident oil is displaced more easily in the initial water saturation stages until the peak of the relative permeability curve, after which the presence of water hinders further displacement of the trapped oil. Further, counter-current relative permeability curves are obtained for different values of equilibrium contact angles and interfacial tensions. The model can be used as a basis for further LBM counter-current simulations and to study the qualitative and quantitative nature of this physical process. Likewise, the relative permeability curves obtained can be useful data and provides qualitative insights in the simulation of waterflooding in naturally fractured reservoirs.

1. Introduction

Capillary flow in porous media is of great importance on account of its spectrum of applications in the areas of geology (Teige et al., 2006), conventional (Hatiboglu and Babadagli, 2008) and non-conventional (Liu et al., 2011) energy sources. These studies often lead to pore-scale simulations of capillary transport, which can then be extended to laboratory scale core flooding experiments (Hadia et al., 2008) and eventually to field scale simulation of oil recovery. Such simulations are deemed necessary to understand the physics of flow inside natural porous systems like subsurface reservoirs, wherein the resident phase (e.g. oil) present initially in the porous matrix is displaced by another imbibing phase (e.g. water) present in the fracture network of the reservoir due to its preferential affinity (or wettability) towards the solid porous matrix. While dealing with such displacement, the configuration and boundary conditions of the fracture-matrix system have a profound effect on the qualitative and quantitative nature of the fluid transport. A great deal of attention was paid in the mechanics and formulation of this process predominantly using experiments on core samples over the last 5 decades. Morrow and Mason (2001) provided an excellent summary of these efforts recently, particularly the effect of four different boundary conditions—all faces open, one end open, two ends open, and two ends closed, on the counter-current imbibition process.

A practically relevant situation is the imbibition and displacement of both phases through the same boundary of the porous matrix. This kind of capillary transport is often referred to as ‘counter-current displacement’. It differentiates itself from the case of ‘co-current displacement’ wherein the imbibing phase displaces the resident phase through an opposite open boundary. Fig. 1 shows the schematic representation of counter-current and co-current capillary displacement systems occurring in natural porous media.

The nature and dynamics of counter-current capillary imbibition have been described in literature through experimental observations and simulation results. One of the earliest works explaining the nature of this fluid transport was performed by Indel’man and Katz (1980). They studied the profile of advancing interface between the two phases for counter-current imbibition and related it to the inhomogeneity in the permeability of the porous system. A comparison of co-current and counter-current imbibition processes was performed by Bourbiaux and Kalaydjian (1990), where

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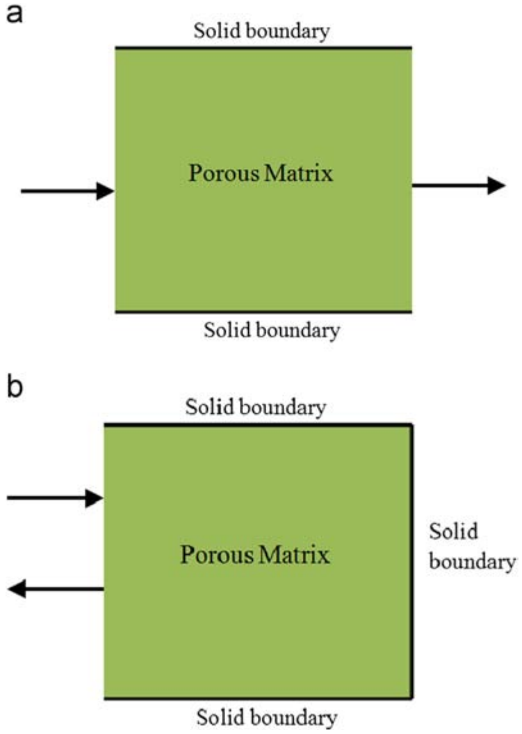

Fig. 1. (a) A schematic showing a typical co-current displacement system. The wetting phase enters the porous matrix from one boundary and displaces the resident phase from the opposing one. (b) A schematic showing a typical counter-current displacement system. The wetting and resident phases enter and exit out of the porous matrix from the same boundary, since all the other boundaries are closed.

they observed that under similar conditions, the counter-current displacement profile shows a more stable saturation growth than the predominantly co-current one. An interesting experimental study of counter-current displacement was performed by Rangel-German and Kovscek (2006), where they observed the imbibition of water in a micro-model and the simultaneous suction and expulsion of fluids through pores of different sizes.

In parallel with experimental efforts, analytical and numerical techniques are also applied to understand the capillary displacement in fractured porous media. Silin and Patzek (2004) studied the time scale for counter-current imbibition in regards to storage of liquid waste in rocks and thereby obtained analytical solutions in terms of the volume of displaced fluids. Further, a pore-scale numerical simulation was performed by Behbahani and Blunt (2005) using pore-scale network modeling. In their simulations they obtained a semi-empirical relation relating the recovery of imbibition with time for different wettabilities and viscosity ratios. Similarly, the co- and counter-current spontaneous imbibition was illustrated by Unsal et al. (2007). A semi-analytical solution for co- and counter-current imbibition was also proposed by Schmid et al. (2011).

The existing literature suggests that the counter-current displacement process takes place in a heterogeneous porous medium because of differential suction of wetting phase through the different pore sizes. This phenomenon has been observed in experiments using micro-models (Rangel-German and Kovscek, 2006). However, an in-depth understanding of the pore-scale capillary imbibition process under counter-current case is still missing. Moreover, the characterization of this displacement process in terms of relative permeability curves is yet to be presented. It is to be noted that certain numerical techniques can provide detail understanding of capillary flow in porous media; one such technique is the Lattice Boltzmann Method (LBM) (Kang et al., 2002; Pan et al., 2004; Hatiboglu and Babadagli, 2008).

LBM has emerged as a preferred numerical technique for multi-phase fluid flows in porous media in recent times due to its relative simplicity of application in systems with geometrically complex boundaries. Originally developed from the meso-scale method of Lattice Gas Automata (LGA) (Wolf-Gladrow, 2000), it has undergone several improvements to incorporate the fluid dynamics of a multi-phase capillary transport process (Rothman, 1988; Shan and Chen, 1993; Latva-Kokko and Rothman, 2005a, 2005b). Recent studies applied this tool to analyze pore-scale displacement processes and investigate their qualitative (Hatiboglu and Babadagli, 2008) and quantitative nature (Ramstad et al., 2010), through the calculation of relative permeabilities of the phases undergoing capillary transport. Hatiboglu and Babadagli (2008) applied this numerical technique to counter-current capillary imbibition in a sand pack model and compared the results with experimental observations. However, a pore-scale description of the counter-current imbibition process is yet to be elucidated by this numerical technique. One needs to be cognizant of the fact that this technique is for weakly compressible flows, which creates limitations in the mass conservation of the system.

This paper applies the LBM to perform simulations of counter-current imbibition in a fractured porous medium and compares the obtained saturation profiles with experimental results from literature (Hatiboglu and Babadagli, 2008). The two-color model with the interface diffusion parameter (Latva-Kokko and Rothman, 2005a) is used, along with the wettability method proposed by Latva-Kokko and Rothman (2005a). The pore-scale interfacial profiles are studied in order to understand the basic physics of the counter-current capillary displacement process. The simulation is performed on two porous matrices of different sizes in order to study variability of counter-current and co-current displacement processes. A two-phase relative permeability curve is obtained to quantify the displacement process. The relative permeability curves are then plotted for different values of contact angles and interfacial tensions and their respective variation is analyzed. This study can provide a basis for further simulations of counter-current flows by LBM and understanding the physical processes involved in such displacement mechanism.

2. Lattice Boltzmann model (LBM)

The LBM used for the subsequent simulations is briefly described in this section.

2.1. LBM governing equations

The LBM uses two primary equations for a weakly compressible fluid particle system, in order to advance the simulation through a certain number of time steps. The solution obtained at each time step is considered to reflect the actual position and momentum of fluid particles in the physical system. These equations are applied at each lattice node and are given as (Mohamad, 2007)

$$f_i(r,t_l) = f_i(r+c_i,t_l+dt_l) \tag{1}$$

$$f_i(r,t_l+dt_l) = f_i(r,t_l) + \Omega + F \tag{2}$$

Eqs. (1) and (2) are referred to as streaming and collision respectively, and can be obtained from a discretized form of the Boltzmann transport equation (Mohamad, 2007). They represent the motion of fluid particles, including the transport from one lattice node to the next and their momentum redistribution due