PORE-SCALE SIMULATION OF THE WETTABILITY INFLUENCE ON THE DISPLACEMENT OF IMMISCIBLE FLUIDS USING A LATTICE-BOLTZMANN METHOD

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Abstract

1. Introduction

Problems involving the interaction of immiscible fluids in contact with solid substrates are present both in nature and in industrial processes. In the interaction interface of immiscible fluids in contact with solid substrate surface phenomena represented macroscopic effects, such as wettability and capillarity, occurs.

In the petroleum industry the interaction of immiscible fluids in contact with solid substrates is characterized specifically in the secondary stage of the oil recovery process, where a fluid is injected into the reservoir in order to displace petroleum present in the porous formation.

According to Chavent e Jaffré (1986), the secondary stage allows the recovery of up to 40% of the oil present at the beginning of this stage, as the more recent work by Muggeridge *et al.* (2014) indicates a recovery of up to 70%. However, the fractions of oil recovered in the secondary stage are influenced by the fact that the injected fluid does not reach all the regions of the reservoir. Additionally, in the filled regions oil fraction remains retained in the porous medium by the action of the wetting and capillarity effects. The influence of these effects on the oil displacement behaviour is complex and varies according to the characteristics of the reservoir and the fluid injection process.

The displacement of immiscible fluids through porous media involves the competition of capillary and viscous forces. Consequently, the relationship between these forces directly influences the displacement state, which according to Lenormand *et al.* (1988) can be classified as viscous fingering, capillary fingering and stable displacement. In the displacement of fluids the capillary forces act locally at the fluid interface, while the viscous forces act throughout the fluid phase. The relationship between the viscous and capillary forces, and the viscous forces between the fluids, are represented by the capillary number and viscosity ratio, respectively,

$$Ca = \frac{U_{ref}\mu}{\gamma} \tag{1}$$

$$M = \frac{\mu_{fi}}{\mu_{fd}}, \tag{2}$$

where U_{ref} is the reference velocity, μ is the fluid viscosity, γ is the interfacial tension between the fluids and the subindices fi e fd represent the injected fluid and the displaced fluid, respectively (Lenormand *et al.*, 1988).

2. Formulation and Numerical Modeling of the Problem

In this work, the analysis of the interaction of immiscible fluids flowing in the porous medium is carried out through the study of the displacement of the fluid present in a porous channel by the injection of another fluid. Such a porous channel is formed by two parallel plates filled with a heterogeneous porous medium represented by the second order of the Sierpinski carpet, a fractal geometry commonly used to represent a porous media (Dullien, 1991; Jian-Hua and Bo-Ming, 2011; Bazarin *et al.*, 2017). Figure 1 illustrates the geometry of the problem. For the representation of the problem, the following hypotheses are considered:

- incompressible flow (ρ_1 e ρ_2 constant),
- isothermic flow (constant temperature),
- both fluids are considered Newtonian (ν_1 e ν_2 constant),
- gravitational force negligible,
- homogeneous wettability in the porous channel,

where ρ represents the density of the fluid, ν the kinematic viscosity of the fluid and the subscripts 1 and 2 the injected and displaced fluids, respectively.

The mass and momentum conservation equations of the problem are in agreement with Hilfer and Øren (1996) and are expressed, respectively, by

$$\nabla_x \cdot (u_\sigma) = 0, \tag{3}$$

$$\rho_\sigma \frac{\partial u_\sigma}{\partial t} + \rho_\sigma (u_\sigma \cdot \nabla_x) u_\sigma = -\nabla_x p_\sigma + \rho_\sigma \nu_\sigma \nabla_x^2 u_\sigma + \rho_\sigma g, \tag{4}$$

where σ indicates the respective fluid, u is the velocity vector, t is the time, p is the pressure, g is the external force per unit of mass and the term ∇_x^2 represents the scalar product $\nabla_x \cdot \nabla_x$.

Initially the problem is characterized by an inlet region filled by fluid 1, while the porous channel remains filled by fluid 2, both fluids with zero velocity field. The boundary conditions are parabolic velocity profile at the entrance and constant pressure at the channel exit; non-slip conditions are also applied to the walls and surfaces of the blocks. The boundary conditions at the interaction interface of the immiscible fluids, in order to guarantee momentum conservation, are given by:

$$u_1 = u_2 \qquad \text{and} \qquad P_1 \cdot n - P_2 \cdot n = 2\gamma\kappa n, \tag{5}$$

where n is the unit normal vector, κ is the curvature of the interface and P is the pressure tensor, given by

$$P = pI + \mu \frac{1}{2} \left(\nabla_x u + \nabla_x u^T - \frac{2}{3} (\nabla_x \cdot u) I \right). \tag{6}$$

An illustration of the boundary conditions can be seen in Figure 1.

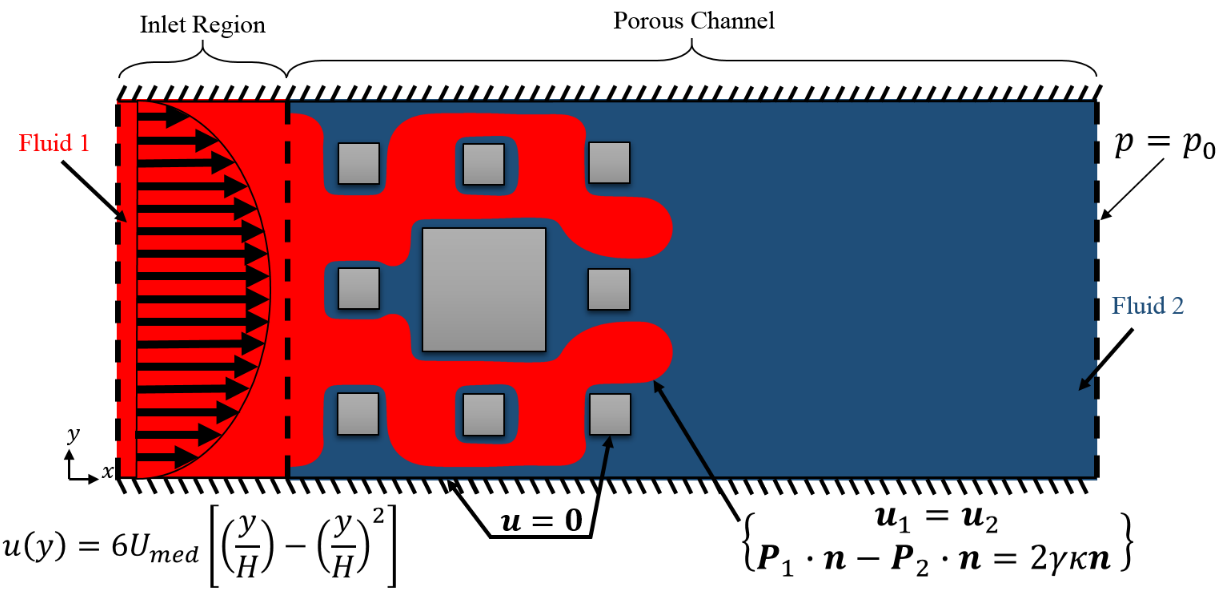

Figure 1: Geometry and boundary conditions of the fluid displacement process in porous media.

The sweep efficiency is the main analysis parameter of the present work, representing the efficiency of the displacement process of immiscible fluids, given by

$$Se = \frac{V_{fi}}{V_p} \tag{7}$$

where Se is the sweep efficiency, V_{fi} is the volume occupied by the injected fluid and V_p is the pore volume.

The numerical formulation of the problem is performed via the Lattice-Boltzmann method, which consists of a discrete form of the Boltzmann equation, in the space velocity and space-time (Abe, 1997; He and Luo, 1997). The multiphase system analysed here is represented by the pseudo-potential model developed by Shan and Chen (1993), represented by a potential interaction of the particles of each phase. The discretized form of velocity space is represented by a two-dimensional lattice of nine velocity, popularly known as D2Q9. In the space-time discretization a second-order approximation is used. In relation to the boundary conditions, the conditions proposed by Zou and He (1997) are used to represent the velocity profile and constant pressure, and for non-slip representation the bounce-back between lattices is used.

3. Results and Discussion

This section is dedicated to the analysis of the influence of the static contact angle (θ_c) in the process of displacement of immiscible fluids in a porous medium represented by the second order of the Sierpinski carpet for $M = 1$ and $Ca = 10^{-2}$. According to the range of the static contact angle, Figure 2 shows the results obtained at the constant sweep efficiency point (Se) $t = 6.0 \times 10^4$.

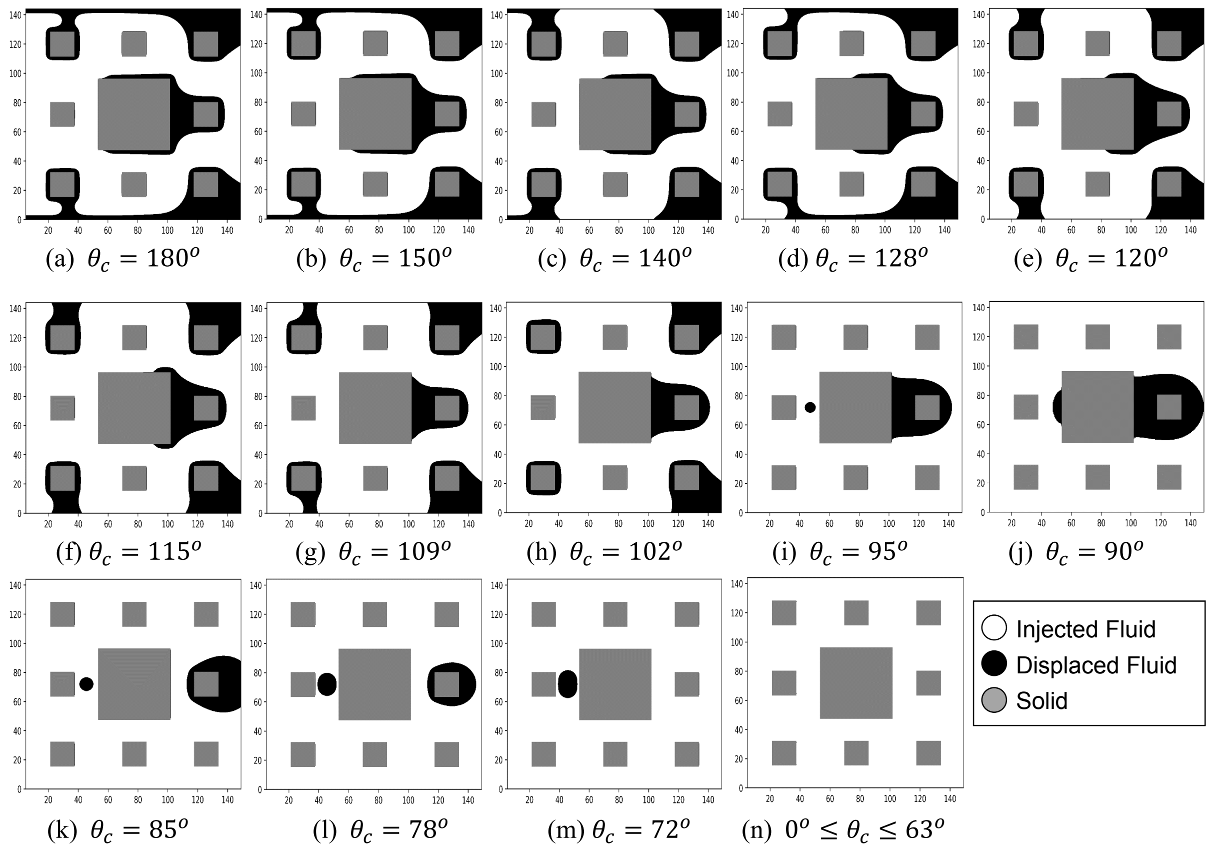

Figure 2: Representation of the displacement process for variation of $0^o \leq \theta_c \leq 180^o$ in the constant sweep efficiency.

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