Simulating effects of the permeability anisotropy on the formation of viscous fingers during waterflood operations

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A B S T R A C T

The capture of interfacial instabilities during water injection simulations in oil reservoirs is a challenging topic, which requires elaborate techniques, generally able to describe heterogeneities of reservoirs and phenomena associated with the flow of immiscible fluids. This article deals with simulations of viscous fingers in two-phase flows (water–oil) through heterogeneous and anisotropic porous media, where both heterogeneity and anisotropy are modeled by the three-parameter Kozeny–Carman generalized equation, which was included in a classical model commonly used to simulate immiscible flows during waterflood operations. As main result, this paper presents a sophisticated numerical simulator, which allowed us to perform predictions of high quality, proving to be a suitable tool to describe physical aspects associated with flows in petroleum reservoirs. In fact, our simulations show that the permeability anisotropy can influence the formation and development of immiscible viscous fingering. For example, when water is injected through three different configurations, five-spot, line-drive and inverted five-spot, the results of this study indicate that this anisotropy may impose a significant degree of stabilization to the viscous fingering phenomenon, benefitting oil recoveries under water flooding processes.

1. Introduction

Viscous fingers are products of an interfacial instability phenomenon that occurs in porous media, when a high viscosity fluid is displaced by another fluid that has low viscosity. When the fluids are immiscible, this phenomenon is referred to as the immiscible viscous fingering. As a relevant example, we have the formation of viscous fingering in oil reservoirs during waterflood operations, where part of the invading water (bypassing the oil) prematurely addresses the extraction wells (Chouke et al., 1959; Rachford, 1964; Peters and Flock, 1981).

Theoretical and experimental studies have been conducted in order to understand the formation and evolution of immiscible viscous fingering, see Jerauld et al. (1984), Riaz and Techelepi (2006), and Yadali Jamaloei et al. (2011), for example.

In oil reservoirs, viscous fingers are triggered primarily by natural geologic heterogeneities, such as the heterogeneities of the permeability field. In numerical simulations, often viscous fingers are triggered using synthetic permeability fields, generated randomly from a log-normal distribution with a specified variance (Christie, 1989).

Recently, Henderson et al. (2015) have been successful in using the so-called three-parameter Kozeny–Carman generalized (TPKCG) equation to trigger viscous fingers in the simulation of two-phase displacements through heterogeneous porous media. The TPKCG equation is a mathematical model that was developed to allow the use of a Kozeny–Carman type equation to a broad class of porous media with fractal nature, generalizing various models previously reported in the literature, which commonly are employed to describe specific porous materials, including oil reservoirs with fractal heterogeneities (Henderson et al., 2010).

Here we investigate the influence of permeability anisotropy on the formation of immiscible viscous fingering, where both heterogeneity and anisotropy are modeled by the TPKCG equation. We consider two-dimensional porous media with rectangular formats, and to observe the effects of well locations on the geometric structure of immiscible fingers, we study three water injection patterns: five-spot, line-drive and inverted five-spot.

As a practical result, this work led us to a sophisticated numerical simulator for two-phase flows in porous media, which proved to be a suitable tool to describe physical aspects associated with the formation...
and development of immiscible viscous fingers in heterogeneous and anisotropic porous media.

The remainder of this paper is organized as follows. In Section 2, we describe the TPKCG equation. Section 3 is devoted to the presentation of the model for immiscible fluids flow in heterogeneous and anisotropic porous media. In Section 4, we report the results. In Section 5, we present some discussions. The conclusions are summarized in Section 6.

2. The generalized Kozeny-Carman equation

The permeability ($k$) is one of the most important properties of a porous material, which characterizes the ease with which a fluid may be made to flow through the medium.

Henderson et al. (2010) proposed the TPKCG equation, which was used in the modeling of permeability fields. The description of a porous material using the TPKCG equation necessarily considers the existence of a functional relationship of the form

$$k = f(\phi),$$

where $f$ is the porosity of the material (the fraction of the bulk volume of the porous medium occupied by voids). In Eq. (1), $f$ summarizes the mathematical model, such that $f(\phi)=0$ if $\phi=0$.

Throughout this section, let $M_b$ be the called specific surface of porous medium, i.e., the interstitial surface area of the pores per unit of bulk volume of a representative sample of the solid matrix, and let $f$ designate the tortuosity, which describes the ratio of flow-path length to sample-path length.

The TPKCG equation models fractal structures, which are characterized by the existence of fundamental properties between the specific surface ($M_b$) and the portion of the bulk volume occupied by solid matrix ($1-\phi$), and between the tortuosity ($\tau$) and the porosity ($\phi$). This model assumes that Henderson et al., 2010:

(1) The reciprocal of the specific surface admits the fractal scale law

$$\frac{1}{M_b} = C_{1Mb}(1-\phi)^{-D_{1Mb}},$$

where $C_{1Mb}$ and $D_{1Mb}$ are, respectively, the fractal coefficient and the fractal exponent of $1/M_b$.

(2) The tortuosity is described by the fractal scale law

$$\tau = C_{\tau} \phi^{-D_{\tau}},$$

where $C_{\tau}$ and $D_{\tau}$ are the fractal coefficient and fractal exponent of $\tau$, respectively.

(3) The porous medium can be modeled as a bundle of $n$ capillary tubes non-necessarily of circular cross-sections, where the flow in this bundle of hydraulic tubes is described by an extension of Hagen–Poiseuille law

$$\hat{q} = n f R_h^4 \frac{\Delta P}{\mu L_h},$$

In Eq. (4) $\hat{q}$ is the fluid flow rate in volume per unit time, $\mu$ is the viscosity of the fluid, $\Delta P$ is the applied pressure difference across the length of the tubes, $R_h$ and $L_h$ denote, respectively, the hydraulic radius and length of the mean hydraulic tube, and $f$ is a shape factor of volume of the tubes.

(4) The hydraulic radius obeys the relation

$$R_h = \frac{\phi}{M_b}.$$

As stated by Henderson et al., 2010, such conditions lead to the TPKCG equation, which can be written in the following short form

$$k = \epsilon^c \left[ \phi^{(\zeta+\eta)} \right]^{-1/(1-\phi)^\zeta}.$$

In Eq. (6), the three fractal parameters $\xi$, $\zeta$ and $\eta$ depend on the fractal coefficients and fractal exponents described in Eqs. (2) and (3). The parameters $\xi$, $\zeta$ and $\eta$ are dimensionless quantities, while the parameter $\xi$ has length dimension.
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