Journal of Petroleum Science and Engineering 153 (2017) 178–186

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

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

Nélio Henderson[a,c,*], Luciana Pena[b,c]

[a] Instituto Politécnico, Universidade do Estado do Rio de Janeiro, 28625-570 Nova Friburgo, RJ, Brazil
[b] Instituto de Matemática e Estatística, Universidade Federal Fluminense, 24020-14 Niterói, Rio de Janeiro, Brazil
[c] Thermodynamics and Optimization Group (TOG), Brazil

ARTICLE INFO

Keywords:
Viscous fingering in porous media
Three-parameter Kozeny–Carman equation
Modeling of heterogeneous reservoirs
Simulations of water flooding processes
Studies of permeability anisotropy effects

ABSTRACT

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) trough 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, benefiting 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

* Corresponding author at: Instituto Politécnico, Universidade do Estado do Rio de Janeiro, 28625-570 Nova Friburgo, RJ, Brazil.
E-mail address: nelio@iprj.uerj.br (N. Henderson).

http://dx.doi.org/10.1016/j.petrol.2017.03.047
Received 13 February 2016; Received in revised form 8 October 2016; Accepted 26 March 2017
Available online 27 March 2017
0920-4105/

Nomenclature

C_τ	fractal coefficient of τ (unitless)
C_{1/M_b}	fractal coefficient of $1/Mb$ (m)
D_{1/M_b}	fractal exponent of 1/Mb (unitless)
D_τ	fractal exponent of τ (unitless)
f	arbitrary function
f_v	shape factor of volume (unitless)
f_w	fractional flow of the water phase (unitless)
k	permeability (m^2)
$\bar{\bar{k}}$	permeability tensor (m^2)
k_x	permeability in x-direction (m^2)
k_y	permeability in y-direction (m^2)
k_{r0}	relative permeability of the oil phase (unitless)
k_{r_w}	relative permeability of the water phase (unitless)
L_h	length of the mean hydraulic tube (m)
M	mobility ratio (unitless)
M_b	specific surface in area per unit of bulk (1/m)
P_c	capillary pressure (Pa)
$P_{c_{max}}$	maximum capillary pressure (Pa)
P_o	pressure of the oil phase (Pa)
P_w	pressure of the water phase (Pa)
q	total source (or sink) term (1/s)
q_w	water source (or sink) term (1/s)
$\hat{q}$	flow rate (m^3/s)
Q	total flow rate (m^2/s)
Q_w	flow rate of water phase (m^2/s)
R_h	hydraulic radius (m)
S_w	water saturation (unitless)
$S_w^{(0)}$	initial water saturation (unitless)
t	time (s)
u	total velocity (m/s)
u_w	velocity of the water phase (m/s)
ϵ	real number (unitless)
ζ	parameter of TPKCG equation (unitless)
ζ_x	parameter of TPKCG equation in x-direction (unitless)
ζ_y	parameter of TPKCG equation in y-direction (unitless)
η	parameter of TPKCG equation (unitless)
η_x	parameter of TPKCG equation in x-direction (unitless)
η_y	parameter of TPKCG equation in y-direction (unitless)
λ	total mobility (1/Pa s)
λ_o	mobility of the oil phase (1/Pa s)
λ_w	mobility of the water phase (1/Pa s)
μ	viscosity (Pa s)
μ_o	viscosity of the oil phase (Pa s)
μ_w	viscosity of the water phase (Pa s)
ν	unit vector normal to $\partial\Omega$
ξ	parameter of TPKCG equation (m)
ξ_x	parameter of TPKCG equation in x-direction (m)
ξ_y	parameter of TPKCG equation in y-direction (m)
τ	tortuosity (unitless)
ϕ	porosity (unitless)
ΔP	pressure difference (Pa)
Ω	two-dimensional domain
$\partial\Omega$	boundary of Ω

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

$$k = f(\phi), \tag{1}$$

where ϕ 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 τ 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 (τ) and the porosity (ϕ). This model assumes that (Henderson et al., 2010):

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

$$\frac{1}{M_b} = C_{1/M_b}(1-\phi)^{-D_{1/M_b}}, \tag{2}$$

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

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

$$\tau = C_\tau \phi^{-D_\tau}, \tag{3}$$

where C_τ and D_τ are the fractal coefficient and fractal exponent of τ, 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

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

In Eq. (4) $\hat{q}$ is the fluid flow rate in volume per unit time, μ is the viscosity of the fluid, ΔP 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_v is a shape factor of volume of the tubes.

(4) The hydraulic radius obeys the relation

$$R_h = \frac{\phi}{M_b}. \tag{5}$$

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

$$k = \xi^2\left[\frac{\phi^{(\zeta+3)}}{(1-\phi)^{2\eta}}\right], \tag{6}$$

In Eq. (6), the three fractal parameters ξ, ζ and η depend on the fractal coefficients and fractal exponents described in Eqs. (2) and (3). The parameters ζ and η are dimensionless quantities, while the parameter ξ has length dimension.