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Productivity index enhancement by wettability alteration in two-phase compressible flows

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ABSTRACT

Water blocking due to the capillary end effect near the wellbore vicinity creates significant formation damage and decreases well productivity for oil and gas. The alteration of the rock wettability by a chemical well treatment is an effective way to reduce water blockage and enhance oil and gas production. Presently, several surfactants and nanofluids are used in the industry for contact angle alteration. After the treatment, the porous medium in the well vicinity (or along the core) has stepwise contact angle. The previous paper (Naik et al., 2015) develops analytical models for incompressible steady-state two-phase linear and axi-symmetric flows, accounting for the piecewise constant contact angle and contact-angle-dependent capillary pressure and relative permeability. The current paper adds the effect of compressibility, which is particularly important for high rate gas wells and wells in unconventional and tight-sand reservoirs. The obtained semi-analytical model has been validated by comparison with a set of laboratory coreflood tests. The modelling reveals a complex interplay between the competing effects of compressibility, viscous and capillary forces, yielding non-monotonic dependencies of well productivity on the wettability and the optimal contact angle. The model closely matches the productivity index data for two production wells from a field case before and after wettability treatment using surfactant.

1. Introduction

The reservoir rock wettability determines the phase distribution near the wellbore during commingled gas-water and oil-water production. Particularly, the capillary end effect in water-wet rocks creates water film/layer near the wellbore with residual saturation of gas or oil. This layer enhances the hydraulic resistance for gas or oil flow and is called water-blocking (Barenblatt et al., 1990; Bedrikovetsky, 1993). Water blocking in gas and oil wells is a widespread source of formation damage, resulting in low productivity index (Mahadevan and Sharma, 2005). The effect is loudly pronounced in low-permeability fields, especially in tight-sand and unconventional reservoirs (Bazin et al., 2010; Bahrami et al., 2011; Morsy et al., 2014).

In hydrophobic rocks, the effluent water saturation is equal to the connate water saturation, and water blocking does not occur. Therefore, alteration of wettability from hydrophilic to hydrophobic may increase the well productivity index. Significant efforts have been made to develop the technologies to alter wettability near the wellbore (Parekh and Sharma, 2004; Kumar et al., 2008; Sheydaeemehr et al., 2014). Treatment of wells by surfactants and nanoparticles that change the rock wettability near the wellbore remove the wetting water barrier and increase well productivity (Weiss et al., 2006; Li and Liu, 2008; Butler et al., 2009; Al-Yami et al., 2013). Numerous types of surfactants have been applied to wettability alteration (Adibhatla et al., 2006), which includes fluoro-surfactants (Bang et al., 2009; Torres et al., 2010), amine surfactants (Bryant et al., 2006), and anionic surfactants (Kathel and Mohanty, 2013). Nanoparticles ranging from Al_2O_3 (Giraldo et al., 2013), SiO_2 (Ju and Fan, 2009, 2013; Roustaei et al., 2012; Li and Torsaeter, 2015), TiO_2 (Esmaeilzadeh et al., 2015) and ZrO_2 (Karimi et al., 2012) have also been applied for wettability alteration. Polymers and amine salts have also been tested for this purpose (Restrepo et al., 2012; Liu et al., 2015). Presently, chemical wettability-altering well-stimulation methods are widely spread in gas and oil production.

Fig. 1a shows the schematic of gas and water flow towards the fractured well; here β is the dimensionless treatment depth. It is assumed that the reservoir is fully water-wet. Fig. 1b presents saturation profiles near to the fracture face. The upper curve corresponds to the case where the altered contact angle, θ_1, is lower than 90°, and the altered contact angle for the lower curve exceeds 90°. Contact angle alteration yields a decrease in the water saturation near to the fracture face and an increase in the gas relative permeability. The same effects

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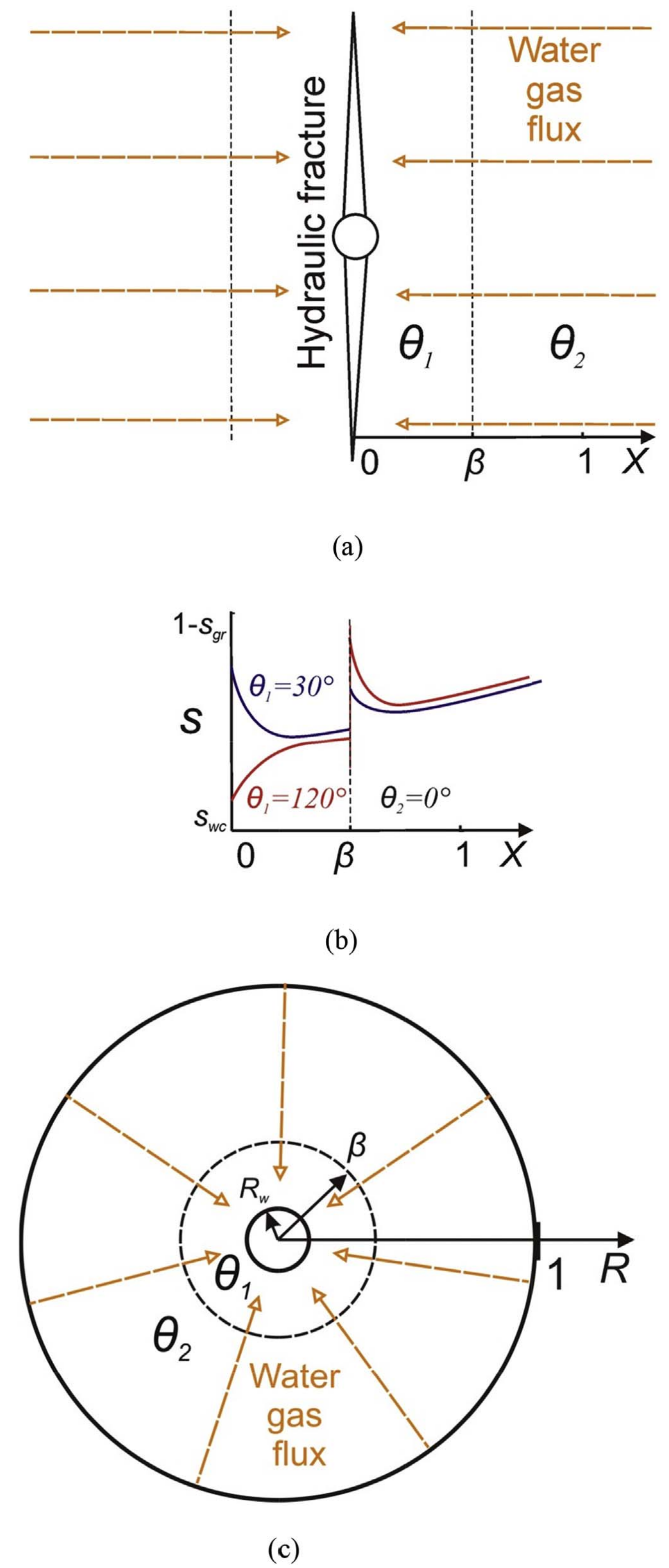

Fig. 1. Schematic figure for commingled gas-water production in the reservoir with piecewise-constant contact angle: a) water-gas flow towards fracture; b) saturation profiles near the fracture face; c) inflow of gas and water towards well.

occur near the vertical and horizontal wellbores (Fig. 1c).

Decision-making on a chemical well treatment and its planning and design rely on the results of laboratory-based mathematical modelling. Particularly, the choice of chemicals and injected volume will depend on the initial and altered contact angles, relative permeability, capillary pressure and rock heterogeneity, which are reflected in the mathematical models. Analytical models for inflow performance with laboratory-based empirical functions provide a reliable tool for planning and design of various well stimulation techniques (Economides and Nolte, 2000).

Mathematical models for chemical treatment contain piecewise-constant contact-angle as a function of the spatial coordinate. Chaouche et al. (1993) investigated steady-state two-phase incompressible flow in rocks with piecewise constant permeability. The condition at the permeability discontinuity is the continuity of capillary pressure. It allows matching steady-state flow in rocks with constant permeability into solutions for the overall core with piecewise constant permeability. Yortsos and Chang (1990) studied steady state two-phase incompressible immiscible flow for the case of multiple abrupt permeability changes along the flow path and observed that saturation response is sensitive to parameters such as rate and heterogeneity length scale. The particular case of two-phase incompressible flow with immobile oil phase has been investigated by Van Lingen et al. (1996) in order to estimate trapped oil in heterogeneous rocks, i.e. for upscaling the residual oil saturation.

Van Duijn et al. (1995) studied transient two-phase flows of incompressible liquids in porous media with discontinuous permeability. Matching the unsteady-state solutions in rock segments with piecewise constant permeability was also performed by the capillary-pressure continuity condition on the permeability discontinuity.

Two competitive factors define the well behaviour during chemical treatment. On the one hand, the contact angle increase will yield the decrease, or even removal, of the wetting water barrier, resulting in the increase of well productivity. On the other hand, increase in the contact angle displaces oil or gas into smaller pores, causing a decrease in the oil or gas production (Berman and Mirotchnik, 2005). This yields a non-monotonic well-productivity dependence on contact angle and capillary pressure. These effects are obtained from steady-state solutions for two-phase incompressible flow with piecewise-constant wettability (Naik et al., 2015).

However, gas-compressibility effects are significant in inflow-performance modelling and well productivity estimation (Economides et al., 2012). Compressibility along with the effects of wetting film removal and gas displacement in small pores would result in more complex gas well behaviour due to chemical treatment. Yet, analytical solutions for compressible flow in rocks with discontinuous wettability are not available in the literature.

In the current paper, the previous work is extended by accounting for fluid compressibility during commingled water-gas production. Steady-state profiles for compressible flow in rocks with piecewise-constant wettability have been investigated for linear and axi-symmetric flows. Asymptotic value for inlet saturation in long cores is defined by a relationship derived and is determined graphically. A non-monotonic dependency of gas-well index on the contact angle has been discovered, indicating the existence of an optimal contact angle for the maximum well productivity.

The structure of this paper is as follows. Section 2 derives the solution for steady-state compressible flow in linear and axi-symmetric geometry. Section 3 validates the model by comparison with laboratory coreflood data. Section 4 analyses the interplay between compressibility and wettability-alteration effects and presents typical dependency of well index of the well-treatment parameters. Section 5 interprets two field cases of well treatment using the analytical model. Discussion in Section 6 and conclusions in Section 7 finalise the paper.

2. Mathematical modelling of steady-state two-phase immiscible flows

In this section, we describe the steady-state two-phase immiscible flow of water and gas accounting for gas compressibility. Linear and axi-symmetric flows are considered. The porous media with piecewise-