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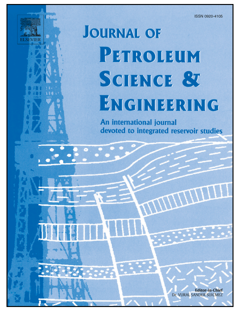

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Pål Ø. Andersen, Dag C. Standnes, Svein M. Skjæveland

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Waterflooding Oil-Saturated Core Samples - Analytical Solutions for Steady-State Capillary End Effects and Correction of Residual Saturation

Pål Ø. Andersen[a,b,*], Dag C. Standnes[a], Svein M. Skjæveland[a,b]

[a]*Department of Petroleum Technology, University of Stavanger, Kristine Bonnevies vei 22, 4036 Stavanger, Norway*
[b]*The National IOR Center of Norway*

Abstract

Capillary end effects can play an important role when interpreting or designing a core flood experiment. The outlet of the core is characterized by a zero capillary pressure which can trap wetting phase in a region near the outlet of the core, potentially leading to a wrongful estimation of parameters such as residual saturation and relative permeability. We consider the steady state obtained in a core flooding experiment: one fluid (assumed water) is continuously injected and produced, while a second fluid (assumed oil), displaced during a transient production phase, is completely immobilized during the considered steady state due to entrapment. An analytical model is derived giving an explicit formulation of the saturation and pressure distributions, the average saturation and the pressure drop at this steady state. The model is general enough to consider different wetting states as given macroscopically by a capillary pressure curve that can vanish at a selected saturation and function shapes and magnitudes that can be adjusted. To our knowledge previous works have been limited to implicit relations between the mentioned parameters and also been restricted to strongly wetted media, which underlines one part of the novelty in this work. A second novel result from this work is that it is possible to derive meaningful capillary numbers that incorporate saturation function parameters. The model predicts a position L_E (measured from the outlet) where the end effects become negligible. At the critical value 1 of our dimensionless number N (which also includes saturation function parameters) the end effects exactly reach the inlet position. The model shows different behavior according to whether $N > 1$ (strong advective forces) or if $N < 1$ (strong capillary forces). In the first case, both scaled pressure drop (relative to the pressure drop without end effects) and average saturation change proportionally to the inverse of N (and accordingly, the inverse of injection rate). In this regime the curves can be scaled uniquely and we can specify physically meaningful capillary numbers incorporating all saturation function parameters. The pressure drop and average saturation behave differently with the saturation function parameters and thus scale with different dimensionless numbers. For $N < 1$ the average saturation and pressure drop do not scale easily according to one capillary number, but the model can easily and intuitively explain variations in the behavior resulting from changes in these parameters. We show that it is possible, based on a simple three-rate water flooding test to estimate the water relative permeability curve and the negative capillary pressure curve. A third novel result is that we for the first time provide a theoretical derivation of the intercept method proposed by Gupta and Maloney (2016) from the fundamental equations of multi-phase flow in porous media and extend the amount of information that is obtained from this procedure. The pressure drop trends considered in unscaled variables is equivalent to their model, stating that at high rates the pressure drop will be linear with rate. Unlike the pressure drop, the saturation will however vary linearly with the inverse of rate. The slopes provide further

*Corresponding author
Email addresses: pal.andersen@uis.no (Pål Ø. Andersen), dag.c.standnes@uis.no (Dag C. Standnes), svein.m.skjeveland@uis.no (Svein M. Skjæveland)