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Analysis of counter-current imbibition with gravity in weakly water-wet systems

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Abstract

Counter-current imbibition in one dimension is analyzed, in which a wetting phase (water) displaces a non-wetting phase against gravity. An approximate analytical approach is used to derive an expression for the saturation profile in the case where the mobility of the displaced phase at the inlet is finite. This approach is applicable to waterflooding in hydrocarbon reservoirs, flow in geothermal systems, or the displacement of non-aqueous phase liquid (NAPL) or air by water. Solutions are developed for both gravity-dominated and capillary-dominated cases. In the capillary-dominated limit the predicted recoveries compare very well with experimental data from the literature, over all time scales. The use of this expression for field-scale dual-porosity modeling of flow in fractured systems is briefly discussed.

Keywords: Dimensionless time; Dual-porosity; Fractured reservoirs; Imbibition

1. Introduction

Counter-current imbibition is a process whereby a wetting phase spontaneously imbibes into a porous medium, displacing the non-wetting phase. This process is an important recovery mechanism during waterflooding in fractured oil reservoirs, as water in the fractures quickly surrounds lower permeability matrix from which oil is displaced by imbibition if the system is water-wet. Similar processes are observed in geothermal systems and aquifers polluted by non-aqueous phase liquids (NAPLs), or in the unsaturated zone, where air can act as the displaced phase.

This process has received extensive experimental, theoretical and numerical study in the literature (Zimmerman et al., 1990; Reis and Cil, 1993; Chen et al., 1995; Zhang et al., 1996; Pooladi-Darvish and Firoozabadi, 2000; Civan and Rasmussen, 2002; Zhou et al., 2002; Kashchiev and Firoozabadi, 2003; Li and Horne, 2004). Experimentally, counter-current imbibition can be studied by recording non-wetting phase recovery from a core surrounded by wetting phase. A review of these experiments has been given by Morrow and Mason (2001). The recovery of non-wetting

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phase can be fit by a simple exponential function of time (Aronofsky et al., 1958).

Tavassoli et al. (2005) used the approach of Zimmerman and Bodvarsson (1989,1991) to study counter-current imbibition in a strongly water-wet system with a non-negligible non-wetting phase viscosity. We define a strongly water-wet system as one where the residual oil saturation is reached by spontaneous imbibition. This means that the oil is immobile at the inlet and there can be no further recovery by forced water injection — the water wettability index is 1 (Dullien, 1992). However, the oil has to escape as water enters the system. This implies that the saturation gradient must be infinite at the inlet. However, most systems are not strongly water-wet and the oil saturation reached after imbibition is not residual (Tavassoli et al., 2005), meaning that the oil phase is continuous at the inlet. We call such systems weakly water-wet; they allow significant recovery by spontaneous imbibition, but also allow some displacement by forced water injection (the wettability index is greater than 0, but less than 1).

Barenblatt et al. (1990) studied this problem using the integral method, and found an exponential recovery at late times. In the present paper this approach is extended to study imbibition in the presence of buoyancy forces, and the predictions of the model are compared with experimental results. The systems considered here are weakly water-wet, meaning that the displaced phase has a finite mobility at the inlet. The modified dimensionless time derived in the capillary-dominated limit is similar to that proposed by Zhou et al. (2002), and confirmed experimentally in diatomite.

The derivation of semi-analytic expressions for recovery is important for large-scale simulation of flow in fractured systems. One use of the recovery functions found in the present work will be to serve as transfer functions for dual-porosity modeling of fractured media. This allows the accurate and efficient modeling of field-scale flow based on a semi-analytic, rather than purely empirical, treatment of the basic displacement processes.

2. Problem formulation

Fig. 1 shows a schematic of the problem under consideration: wetting phase imbibes upwards in a one-dimensional porous medium of height L, with a zero capillary pressure at the bottom and no flow at the top. Conservation of water volume in one dimension with no overall flow can be expressed as follows (Dullien, 1992):

$$\phi \frac{\partial S_w}{\partial t} + \frac{\partial}{\partial x}\left[\frac{\lambda_w \lambda_o}{\lambda_t} K \left(\frac{\partial P_c}{\partial S_w}\frac{\partial S_w}{\partial x} - \Delta\rho g\right)\right] = 0, \tag{1}$$

where the x-axis is vertically upwards, ϕ is the porosity, K is the absolute permeability, S_w is the water saturation, P_c is the capillary pressure, $\lambda = k_r/\mu$ is the mobility, k_r is the relative permeability, $\Delta\rho$ is the density

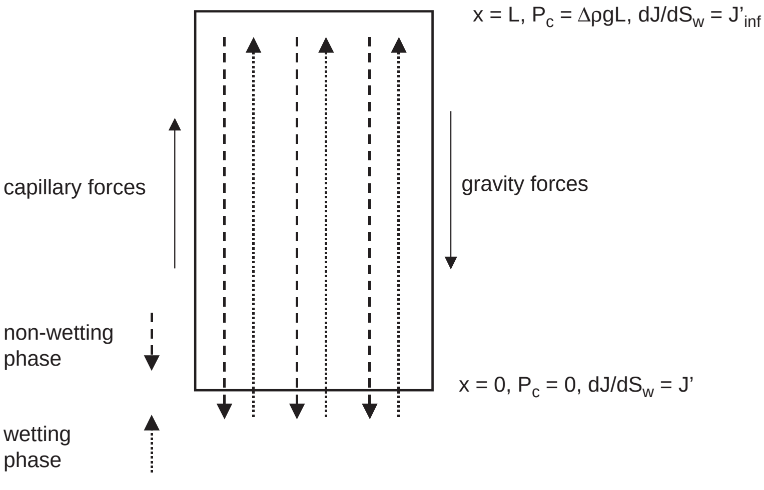

Fig. 1. Schematic diagram of one-dimensional imbibition against gravity.