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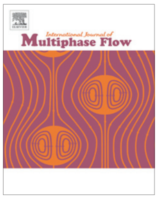

Steady-state two-phase relative permeability functions of porous media: A revisit

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ABSTRACT

Steady-state two-phase flow experiments are performed on a sand column equipped with two differential pressure transducers and six ring electrodes to measure the pressure drop across each phase, and electrical resistance across five successive column segments, respectively. The electrical resistivity index measured across various segments of the soil column is converted to water saturation by using the Archie equation. The results are analyzed by considering the water saturation and oil/water relative permeability as power functions of water and oil capillary numbers which are employed as independent variables. Results from earlier visualization studies on a glass-etched pore network are also analyzed by a similar manner to quantify the dependence of oil and water relative permeability on capillary numbers, and correlate the estimated parameters of power functions with the viscosity ratio. The new explicit relationships of relative permeabilities and water saturation with oil and water capillary numbers set the bases for a new conceptualization of the two-phase flow at reservoir-scale where the mobility of the fluids is decoupled from saturation and become non-linear functions of the local flow rates. The variation of the relative permeability exponents with the pore system dimensionality agrees qualitatively with the scaling behavior predicted by the gradient percolation approach.

Introduction

Two-phase flow of immiscible fluids in porous media has attracted the attention of many research groups during the last 30 years (Payatakes, 1982; Lenormand et al., 1983; Dias and Payatakes, 1986a,b; Lenormand et al., 1988; Blunt and King, 1991; Vizika et al., 1994; Avraam and Payatakes, 1995a,b; Aker et al., 1998; Xu et al., 1998; Knudsen and Hansen, 2002; Tsakiroglou et al., 2003; Valvatne and Blunt, 2004; Li et al., 2005; Theodoropoulou et al., 2005; Joekar-Niasar et al., 2008; Aggelopoulos and Tsakiroglou, 2008; Tallakstad et al., 2009a; Raoof and Hassanizadeh, 2012). There is a broad variety of relevant application areas such as the enhanced oil recovery (Lackner and Torsaeter, 2006), the CO_2 storage in deep saline aquifers and depleted oil reservoirs (Berg and Ott, 2012), the soil contamination and reconstitution (Gao et al., 2013), the performance of proton exchange membranes in fuel cells (Wang et al., 2010). Sophisticated experimental setups have been developed to measure the steady-state relative permeability curves of porous media (Bentsen and Manai, 1991; Ayub and Bentsen, 2001), and analyze the interfacial viscous coupling effects (Ayub and Bentsen, 2004).

The steady-state two-phase flow is established by injecting two fluids through a porous medium at fixed flow rates, and has extensively be analyzed, primarily by computer simulations at pore- and network-scale (Constantinides and Payatakes, 1996; Valavanides et al., 1998; Hashemi et al., 1999; Ramstad and Hansen, 2006; Huang and Lu, 2009; Ramstad et al., 2012; Sinha and Hansen, 2012; Yiotis et al,. 2013), and secondarily by systematic experimental approaches in model porous media (Avraam et al., 1994; Avraam and Payatakes, 1995a, 1999; Tsakiroglou et al., 2007; Gutierez et al., 2008; Tallakstad et al., 2009a, 2009b; Erpelding et al., 2013). One of the main conclusions is that the wetting fluid (water) retains its connectivity along its flow path while the non-wetting fluid (oil) may move either as a connected pathway or as a population of disconnected ganglia which undergo dynamic breakup and coalescence (Avraam and Payatakes, 1995a; Constantinides and Payatakes, 1996; Valavanides et al., 1998; Tallakstad et al., 2009a, 2009b; Yiotis et al., 2013).

Numerous models and theoretical simulators have been developed to interpret the dependence of the two- and three-phase flow coefficients of porous media on the fractional/mixed wettability

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(Bradford et al., 1997; Tsakiroglou and Fleury, 1999; Jackson et al., 2003; Gladkikh and Bryant, 2006; Kuttanikkad et al., 2011; Tsakiroglou, 2014). Under mixed-wet conditions, that characterize the majority of natural porous media (e.g. rocks, soils), both fluids may contact the solid surfaces, the steady-state two-phase flow regimes are expected to become more complicated and the steady-state oil and water relative permeability are expected to change drastically (Landry et al., 2014). Therefore, any results obtained with experiments conducted on homogeneous-wet porous media cannot be extrapolated explicitly to mixed-wet porous media. Instead, a systematic analysis of the effects of heterogeneous wettability on the steady-state two-phase flow regimes and its implications to relative permeability functions is required.

Both the two-phase flow regimes and relative permeability functions of the two fluids depend strongly on a variety of key parameters such as the capillary number, flow rate ratio, viscosity ratio, wettability, and Bond number (Avraam and Payatakes, 1995a, 1999; Gutierez et al., 2008; Tallakstad et al., 2009b). In order to interpret quantitatively such a behavior, pore-network simulators (Constantinides and Payatakes, 1996; Ramstad and Hansen, 2006; Sinha and Hansen, 2012), Lattice-Boltzman approaches (Huang and Lu, 2009; Ramstad et al., 2012; Yiotis et al., 2013), and sophisticated mesoscopic approaches (Valavanides and Payatakes, 2001) have been developed. Nevertheless, albeit the aforementioned attempts revealed the multi-correlated character of the process, when simulating the two-phase flow at field-scale, mainly on industrial scale applications, the relative permeability of wetting and non-wetting fluids are still regarded as power functions of the local saturation and their implicit dependence on other parameters, such as the local flow rates is ignored.

The scope of the present work is to re-examine the rate-dependent oil/water relative permeabilities for steady-state co-current two-phase flow in porous media, and produce explicit correlations of fluid relative permeability and saturation with the oil and water capillary numbers. Steady-state two-phase flow experiments are performed on a sand column equipped with two differential pressure transducers and six ring electrodes to measure the pressure drop across each phase, and electrical resistance across five successive column segments, respectively. The oil to water viscosity ratio is kept equal to one in order to focus exclusively on the effect of capillary numbers on relative permeabilities. The electrical resistance is converted to water saturation based on a calibrated Archie-type equation. The results are analyzed by considering the water saturation and oil/water relative permeability as power functions of water and oil capillary numbers. Results from earlier experimental studies on 2-D porous media (Avraam and Payatakes, 1995a) are also analyzed in a similar manner so that the sensitivity of the relative permeabilities to capillary numbers is quantified for 2-D porous media.

Methods and materials

Experimental procedure

Steady-state experiments of the simultaneous flow of oil and water were performed on a long horizontal PVC column ($D = 5$ cm, $L = 30$ cm) packed with a well-sorted sand ($k = 25$ D, $\varphi = 0.42$) and equipped with ring electrodes and a multi-point conductivity meter used to monitor the electrical conductance along the column (Fig. 1, Aggelopoulos and Tsakiroglou, 2008). All measuring devices were connected to a data acquisition card equipped in the host computer. The apparatus was placed inside a thermostatic incubator so that the temperature was kept constant and equal to 25 °C to avoid any disturbances of electrical conductance. Two metallic plates placed in the inlet and outlet of the column acted as end current electrodes whereas six (6) intermediate rings placed at equal distances along the column were used as voltage electrodes. To improve the electrical contact of the soil with the end electrodes, ensure the uniform distribution of the flow across the column inlet/outlet, and avoid the entrainment of soil grains, two stainless steel screens were inserted between the end electrodes and the soil. The multi-point conductivity meter allowed the simultaneous measurement of the electrical resistance across various segments of the column with respect to a reference electrode. More details concerning the determination of the electrical resistance over the successive segments of the column from measurements of the corresponding voltages are reported elsewhere (Aggelopoulos and Tsakiroglou, 2008). The pressure drop across each phase was measured with the aid of pressure transducers connected to the inlet tubes (Fig. 1). First, the sand column was evacuated and filled with brine (aqueous solution of NaCl at concentration $C_{NaCl} = 20$ g/L). Then, oil (mixture composed of 61% n-C_{10} and 39% n-C_{12}) was injected at a high flow rate ($q_o = 5$ ml/min) until attaining an irreducible wetting phase saturation. Afterwards, oil and brine (viscosity ratio, $\kappa = \mu_o/\mu_w = 1.0$), were co-injected at flow rates 5 ml/min and 0.5 ml/min, respectively, by using two high performance liquid chromatography (HPLC) pumps (Fig. 1). The viscosity ratio was kept equal to one to exclude its effect on relative permeabilities and saturation and isolate it from that of the capillary numbers. Steady-state conditions were established when the time-averaged oil and water injection pressures along with the time-averaged electrical conductance were stabilized. Then, the oil flow rate was kept constant and the water flow rate varied stepwise from 0.5 to 5.0 ml/min in successive bumps. At each step, the column-averaged steady-state relative permeability of oil $\langle k_{ro} \rangle$ and water $\langle k_{rw} \rangle$ phase were calculated by using the Darcy law and the measured time-averaged pressure drop across the oil and water phases, respectively

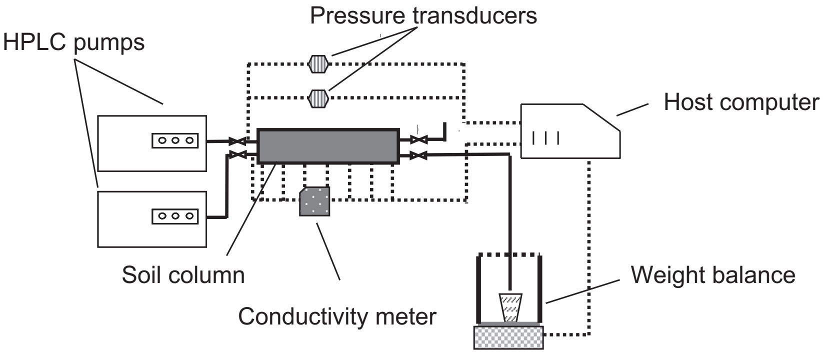

Fig. 1. Experimental setup of steady-state two-phase flow tests in soil columns.