DEPENDENCE OF THE STEADY-STATE RELATIVE PERMEABILITY FUNCTIONS OF POROUS MEDIA ON FLOW RATES: A REVISIT

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SUMMARY

The experimentally measured water and oil relative permeability curves of 2-D and 3-D water-wet model porous media are interpreted in terms of multi-parameter functions of water saturation and oil and water capillary number. Depending on the porous medium type and prevailing flow parameters, the oil and water relative permeability may be strong, moderate or weak functions of capillary numbers.

INTRODUCTION

Significant errors may arise in the interpretation of field-scale tests in oil reservoirs when representing the oil and water relative permeability curves as unique functions of water saturation. In addition to the transient techniques [1], steady-state flow tests are also employed to determine the water k_{rw}, and oil k_{ro} relative permeability curves of porous media [2-4]. A systematic parametric analysis of the experiments of the simultaneous flow of oil and water through glass-etched pore networks of well-characterized topology and geometry [2-4], allowed the identification of several two-phase flow regimes dominating over different ranges of pertinent parameters (e.g. capillary number Ca_w, viscosity ratio κ, and contact angle θ_e): small-ganglion dynamics (SGD); large-ganglion dynamics (LGD); drop-traffic flow (DTF); connected pathway flow (CPF) [2-4]. The goal of the present work is to quantify the dependence of k_{rw}, k_{ro} on flow rates for both 2-D and 3-D porous media. Assuming that k_{rw} and k_{ro} correlate to water and oil capillary number by power laws, datasets of two-phase flow tests on 2-D model porous media [2] are fitted with multi-parameter modified versions of Corey models. In addition, preliminary steady-state brine / oil flow tests are performed in a 3-D sandpack by using a multi-point resistivity meter to measure water saturation, and the results are fitted with multi-parameter modified versions of Corey models.

METHODS AND MATERIALS

Relative permeability curves of 2-D porous media. Datasets of two-phase flow tests performed on planar glass-etched (2-D) pore networks [2] were fitted with the following modified versions of Corey models:

$$k_{rw} = k_{rw}^{0} S_w^{m_w} \tag{1}$$

$$k_{ro} = k_{ro}^{0} (1 - S_w^{m_o}) \tag{2}$$

$$k_{rw}^{0} = a_w Ca_w^{b_w} Ca_o^{b_o} \tag{3}$$

$$k_{ro}^{0} = a_o Ca_w^{e_w} Ca_o^{e_o} \tag{4}$$

where the capillary numbers are defined by

$$Ca_w = \mu_w q_w / (A\gamma_{ow}) \tag{5a}$$

$$Ca_o = \mu_o q_w / (A\gamma_{ow}) \tag{5b}$$

μ_i=viscosity of phase i (i=w,o), q_i=flow rate of phase i (i=w,o)), γ_{ow}=interfacial tension, A=cross-sectional area of porous medium.

Relative permeability curves of 3-D porous media. Preliminary experiments of the simultaneous flow of oil and water were performed on a long horizontal PVC column (D=5cm, L=30cm) packed with a well-sorted sand (k=25 D, φ=0.42) and equipped with ring electrodes used to monitor the electrical conductance along the column [5]. The pressure drop across each phase was measured with the aid of pressure transducers connected to the inlet tubes. First, the sand column was evacuated and filled with brine (aqueous solution of NaCl at concentration C_{NaCl} = 20 g/L). Then, oil (mixture consisting of 61% n-C_{10} and 39% n-C_{12}) and brine with a viscosity ratio, $\kappa=\mu_o/\mu_w=1.0$, were co-injected in the sandpack at flow rates 5 ml/min and 0.1 ml/min, respectively, by using two high performance liquid chromatography (HPLC) pumps. Steady-state conditions were established when the time-averaged values of oil and water injection pressures and electrical conductance were stabilized. Then, the oil flow rate was reduced to 0.5 ml/min and once steady-state was re-established, the oil flow rate was kept constant and the water flow rate varied stepwise from 0.1 to 3.0 ml/min in successive bumps. At each step, the steady-state relative permeability across each phase was calculated by using Darcy law and time-averaged pressure drop. At the end of each step, the effluent was weighted, the total water saturation was estimated and used to calibrate the resistivity index of the sandpack with water saturation by estimating the saturation exponent, n, of Archie equation [5]

$$I_R = aS_w^{-n} \tag{6}$$

In this manner, the water saturation in five successive segments of the column was calculated from measured resistivity index by using Eq.(6). In order to quantify the dependence of k_{rw}, k_{ro} on S_w, Ca_w, Ca_o, the measured relative permeability curves were also fitted with modified Corey models.

RESULTS AND DISCUSSION

Experiments in 2-D porous media. Water flows mainly as a continuous phase, and its relative permeability is sensitive to water capillary number but almost insensitive to oil capillary number (Table 1). The oil relative permeability depends on both capillary numbers (Table 1) since the oil flow is dominated by connected pathways and ganglia dynamics (e.g. motion, entrapment, coalescence, fissioning) [2].

Table 1. Parameter values of modified Corey models for the 2-D model porous medium [2]

Param	m_w	m_o	b_w	e_w	b_o	e_o	a_w	a_o
κ=3.35	2.11	2.45	0.29	0.4	0.02	0.24	14.8	4.4×10^3
κ=1.45	1.72	3.59	0.43	0.46	-0.03	0.10	30.3	0.9×10^3

Experiments in 3-D porous media. Volume averaging indicates that the exponents relating the k_{rw} and k_{ro} with local saturation are almost identical to those correlating $<k_{rw}>_{ij}$, $<k_{ro}>_{ij}$ with average water saturation. With the aid of Darcy law and conditions

$$\Delta P_{w,t} = \sum_{i=1}^{4}\sum_{j=2}^{5}\Delta P_{w,ij} \quad \Delta P_{o,t} = \sum_{i=1}^{4}\sum_{j=2}^{5}\Delta P_{o,ij} \tag{7}$$

the column-averaged $<k_{rw}>$, $<k_{ro}>$ can be expressed as functions of the segment-averaged saturations. At the prevailing conditions ($\kappa=1.0$, $Ca_o=9\times10^{-8}$, $Ca_w=10^{-8}$-10^{-6}) $<S_w>$ changes over a narrow range, $<k_{ro}>$ is a weak function of $<S_w>$ and almost independent on Ca_w, whereas the very rapid increase of $<k_{rw}>$ with $<S_w>$ can be interpreted by accounting for its dependence on Ca_w according to a modified Corey model (Fig.1).

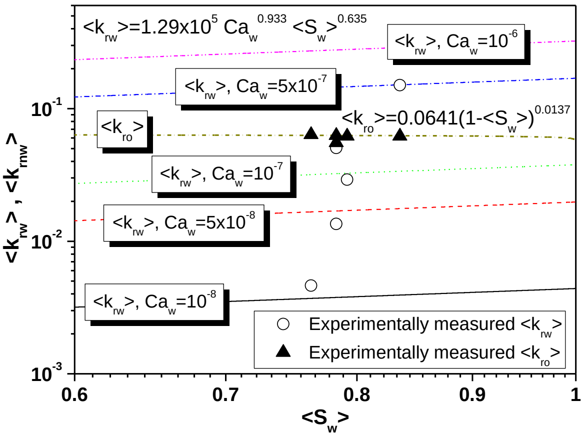

Figure 1. Experimentally measured vs estimated relative permeability curves of 3-D sandpack

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