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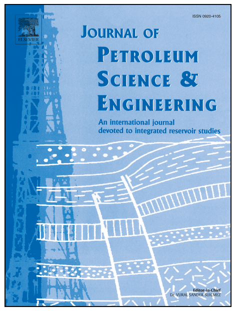

Relative permeabilities hysteresis for oil/water, gas/water and gas/oil systems in mixed-wet rocks

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Abstract

Accurate determination of relative permeability (k_r) curves and their hysteresis is needed for reliable prediction of the performance of oil and gas reservoirs. A few options (e.g., Carlson, Killough and Jargon models) are available in commercial reservoir simulators to account for hysteresis in k_r curves under two-phase flow. Two-phase k_r curves are also needed for estimating k_r hysteresis under three-phase flow during water-alternating-gas (WAG) injection. Although, most oil reservoirs are mixed-wet, the existing hysteresis predictive approaches have been developed based on water-wet conditions. Experimentally measured data are needed to assess the performance of these methodologies under more realistic reservoir conditions e.g. low gas-oil IFT and mixed-wet systems.

This paper includes two parts. In the first part we review the most valuable works in the literature regarding the effect of hysteresis on two-phase relative permeabilities in different wettability conditions. As will be highlighted most of these data are generated on water-wet or slightly water-wet condition which are most likely not representative of the oil reservoirs. Even the generated two-phase relative permeabilities on mixed-wet and oil-wet conditions are not fully developed for the full hysteresis cycle and/or not for the all three possible systems (oil/water, gas/oil and gas/water) in one place. It is recently recommended by some of the valuable theoretical works in the literature that to enhance the predictions of three-phase hysteresis models, hysteresis for all possible two-phase systems shall be considered in the provided equations. As a result in the second part of this paper, we summarize comprehensive set of experimentally measured relative permeabilities for the two-phase systems of oil/water, gas/water and gas/oil. This set of data can be used with new three-phase hysteresis models such as that presented by Hustad and Browning (2010) to enhance the prediction of the WAG processes in non-water-wet systems.

Experiments were performed in 65mD sandstone with mixed-wettability.

For the gas/water system, the first set of fluid displacements began by water injection (imbibition: I) in the core saturated with gas and immobile water. This was followed by a period of gas injection (Drainage: D) which was followed by alternating periods of water and gas injections (IDIDI). In the second series, the core was initially 100% saturated with water and the experiment started with gas injection (D) followed by successive imbibition and drainage periods (DIDIDI). Similar sets of displacement experiments were performed for oil/water and gas/oil systems. The gas/oil system in our experiments represents extra low-IFT (near-miscible) system with an IFT value of 0.04 $mN.m^{-1}$. The measured pressure drop and fluid production data obtained during the experiments were then history matched to estimate k_r values for each imbibition and drainage period for each pair of fluids.

In the oil/water system (DIDID injection sequence), k_{rw} shows cycle hysteresis which is in contrast to the common observations made in water-wet systems in which k_{rw} does not show hysteresis. In addition to k_{rw}, k_{ro} also shows significant hysteresis for the 1st imbibition period compared to the 1st drainage period but after the 1st imbibition period the k_{ro} hysteresis was not significant. In the gas/water system (IDIDI), both k_{rg} and k_{rw} decreased as the alternation between imbibition and drainage continued. The results show significant differences in the k_r hysteretic behaviour in gas/water and oil/water systems. We demonstrate that the approach used in some of the three-phase simulations reported in literature, where the oil/water k_r curves are