THREE-PHASE UNSTEADY-STATE RELATIVE PERMEABILITY MEASUREMENTS IN CONSOLIDATED CORES USING THREE IMMISCIBLE LIQUIDS

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ABSTRACT

This paper discusses results from a series of two- and three-phase coreflooding experiments on consolidated cores using three immiscible fluids and using an unsteady-state relative permeability setup. The three-phase extension of the Buckley-Leverett theory proposed by Grader and O'Meara [1] and verified by Siddiqui et al. [2] was used for calculating three-phase relative permeabilities from the dynamic displacement data. From the results of three-phase displacement experiment, three-phase saturation trajectories are mapped and then compared against results of DDI (decreasing of water phase and oil or heavy phase and increasing of gas or light phase during a dynamic injection stage) runs found in the literature. The DID (decreasing of water phase, increasing of oil or heavy phase and decreasing of gas or light phase) runs presented in the current work are unique which map a wide range of the interior region of the ternary diagram. However, bypassing was observed during the IDD (Increasing of water phase and decreasing of oil or heavy phase and gas or light phase) runs, possibly due to fluids reaching the residual saturations before the dynamic water injection. In the petroleum industry, empirical models are often used to extrapolate three-phase relative permeabilities from two sets of two-phase relative permeability data. The experimental three-phase relative permeability data from the DDI and DID runs are compared with the model data, and it is found out that in some cases these models cannot adequately provide satisfactory matches with the experimental data.

INTRODUCTION

The existence of three-phase flow in reservoirs, especially during enhanced oil recovery processes, has led to the growing interest in obtaining reliable three-phase relative permeability data, one of the key petrophysical parameters used to characterize the hydrodynamics of multiphase fluids in porous media. It is impossible to obtain three-phase relative permeability data directly from the field or through any indirect means. The only way to obtain them is by conducting experiments. Due to the complexities of the measurements and the scarcity of reliable experimental data, mathematical models are often used to extrapolate three-phase relative permeabilities from two phase data, i.e. water-oil, and gas-oil relative permeabilities. The objective of the research presented in this paper is to further our understanding of the simultaneous three-phase flow in porous media, especially to quantify immiscible three-phase relative permeabilities by conducting a series of unsteady-state relative permeability measurements and to compare the experimental results with those generated from empirical models.

EXPERIMENTAL PROCEDURES

A special coreflooding apparatus was set up for conducting the unsteady-state coreflood experiments. A Berea core sample with porosity of 23.3% was used as the porous media. Three immiscible fluids, Brine (2% KCl by weight, 1.116 cp at 21.5 ºC), Fluorinert-40 (FC-40$^{®3M}$, 4.389 cp at 21.5ºC) and Soltrol-130 (1.48 cp at1.5 ºC) are used as the three phases in this experimental work. In this liquid system, Brine represents the water phase; FC-40 represents the heavy or DNAPL (dense non-aqueous phase liquid) phase while Soltrol represents the light or LNAPL (light non-aqueous phase liquid) phase.

Before each experiment, the core is carefully cleaned to ensure that the wettability is not altered and also to ensure the repeatability to within satisfactory limits, of brine permeability measurements. The Dean-Stark extraction method was applied to clean the core by using three solvents, toluene, methanol and FE-32$^{®3M}$. Toluene is used to dissolve Soltrol while methanol and 3M Novec fluid HFE-72DE (a hydrofluoroether solvating agent) are used to remove salt and FC-40, respectively. During each experiment, the absolute permeability was determined by flooding the core with brine at two different flow rates and Darcy's law was applied for calculations. In the unsteady-state experiments, three types of single-phase dynamic displacement measurements, i.e., IDD, DDI, DID runs were conducted. The operating conditions for the experiments are:

Confining Pressure:	3500 psia	Temperature:	21.5 ºC
Back Pressure:	500 psi	Flow rates:	10 cc/min

The following procedures were followed during unsteady-state relative permeability measurement in the laboratory. First of all, the core sample was vacuum-saturated with brine and absolute permeability was measured for each run. For the Soltrol dynamic displacement (DDI) runs, drainage and imbibition stages were carried out. FC-40 (at 10 cc/min) and water (at 10 cc/min) were injected respectively to obtain the water-FC-40 two-phase relative permeability data (needed for the empirical models), followed by simultaneously injecting water and FC-40 at fixed flow rate ratio (1:2) to establish an initial two-phase (water-FC-40) saturation. The dynamic Soltrol injection (at 10 cc/min) is conducted after that stage. The FC-40 dynamic displacement (DID) runs were conducted in a similar manner. The only difference is that Soltrol and water were injected during drainage and imbibition stages, as well as for establishing the initial saturation prior to the dynamic FC-40 injection. For water dynamic displacement runs (IDD), the procedure is a bit more complicated and it involved injecting FC-40 until the core reaches the irreducible water saturation (S_{wir}) before performing the drainage and imbibition stages using FC-40 and Soltrol. During all experiments, capillary pressure was not included for relative permeability measurement.

RESULTS AND DISCUSSION

A total of eight experimental runs were conducted using the same porous medium in this work. Run 1 and 2 are for equipment familiarity and apparatus verification purpose. Runs 3 and 6 are DDI runs, Runs 4 and 7 are IDD runs and Runs 5 and 8 are DID runs.

Results from the DDI Runs. Two-phase Water-FC-40 relative permeability data were obtained from the DDI runs. The relative permeability analysis represents an irreducible water saturation (S_{wir}) of 25% and 22% and residual FC-40 saturation (S_{orw}) of 47.1% and 34% for Run 3 and Run 6, respectively. After reaching steady-state, the core was saturated with both brine and FC-40, and a final water saturation of 38.9% and FC-40 saturation of 61.1% was achieved in Run 3 from the material balance calculation. Similarly, in Run 6, a final water saturation of 41.35% and FC-40 saturation of 58.65% were calculated. During the three-phase relative permeability measurement, Soltrol is injected and upon completion the experiments, three-phase relative permeabilities are plotted as a function of their individual saturations on a semi-log plot. Figures 1 and 2 show the three-phase relative permeabilities for Runs 3 and 6, respectively.

Results from the IDD Runs. Two-phase FC-40-Soltrol relative permeability data were obtained from the IDD runs. The relative permeability analysis represents irreducible water saturation (S_{wir}) of 39% for Run 4, and 21.2% for Run 7. This saturation of water remained constant during the whole IDD experiment. Residual FC-40 saturation (S_{org}) during the Soltrol injection is calculated to be 19% for Run 4 and 27% for Run 7. At the end of FC-40 injection, residual Soltrol saturation (S_{gr}) is found to be equal to 6.3% and 15.7% for Run 4 and Run 7, respectively. After steady-state, the core was saturated by both FC-40 and Soltrol to certain saturation level. The final saturations of FC-40 and Soltrol were 24.9% and 36.1%, respectively in Run 4. In Run 7, the final saturations of FC-40 and Soltrol were 32.1% and 46.7%, respectively. During the dynamic water displacement test, neither FC-40 nor Soltrol was produced after breakthrough during water injection. It may be due to bypassing of water as water has the lowest viscosity among the three-phases.

Results from the DID Runs. The coreflooding experiments for DID gave irreducible water saturations (S_{wir}) of 48% and 26.1% for Runs 5 and 8, respectively. During the imbibition stage, Soltrol ceased to be produced after breakthrough and its saturation stayed constant at 27.5% in Run 5 and 44.7% in Run 8. After the steady-state injection of FC-40 and Soltrol simultaneously, a final water saturation of 60.17% and a Soltrol saturation of 39.83% was achieved in Run 5. In Run 8, the corresponding final saturations were 52.35% and 47.65%, respectively. Figures 3 and 4 show the three-phase relative permeabilities from Runs 5 and 8, respectively. By applying the three-phase Buckley-Leverett theory, the three-phase saturations during dynamic flood are calculated and saturation trajectories are plotted for each DID run in a ternary diagram shown in Figures 7 and 8.

Verification of Saturation Trajectory. One part of this research goes to the verification of previous work. Results from dynamic Soltrol flooding (DDI runs), i.e., Runs 3 and 6, are used to compare and verify Grader and O'Meara's [1] findings. The saturation trajectory obtained from the two DDI runs are plotted in Figures 5 and 6. Similar trend is observed in the saturation trajectories of the seven dynamic decane (light phase) injection runs from Grader and O'Meara's work as well as the gas injection runs reported by Sarem [3].

Verification of Three-phase Relative Permeabilities. Three-phase relative permeability data obtained from the DDI runs are compared with the DDI experiments conducted by Siddiqui et al. [2]. It can be found that the relative permeability of a particular phase increases as a function of the saturation of that phase within the saturation range in the experiment and the trend for each phase is similar between the same types of dynamic experiments.

Comparison of Experimental Three-phase Relative Permeability Results with Empirical Models. With the water-FC-40 and Soltrol-FC-40 two-phase relative permeability data available from DDI and IDD runs, three-phase relative permeability values are calculated using four different empirical models: Stone's I and II, Baker's and Hustad and Hansen's and compared with those experimental results from dynamic Soltrol flood and FC-40 flood [4]. Detailed comparisons are shown in Figures 9 through 12. For Run 3, Stone's model I matches better than the other models, especially at higher FC-40 saturations (from around 50% to 55%). Within the saturation range of 37% to 43%, the Hustad and Hansen model gives a better match. For Run 6, the data match very well with both of the Stone's models. For Run 5, all the models under-predict the relative permeability of FC-40 during dynamic FC-40 flood. In Run 8, Stone's Model I gives a better match within the saturation range of 20% to 45% while Stone's Model II and Baker's model provide a better match at higher FC-40 saturations.

CONCLUSIONS

1. A novel coreflood apparatus has been constructed and the laboratory data successfully generated three-phase relative permeabilities by applying the extension of Buckley-Leverett three-phase theory.
2. Same behaviors as literature data are seen in saturation paths from DDI runs.
3. The DID experimental data, usually rare in three-phase relative permeability tests, contributed to mapping more of the interior region of the ternary diagram.
4. Bypassing was observed in the case of the IDD runs. After breakthrough, no FC-40 nor Soltrol were observed. This may be due to the specific immiscible liquid system used in current research in which water has the lowest viscosity. The reason behind this bypassing phenomenon needs further investigation.
5. Empirical models that are generally used for three-phase flow are not always reliable for predicting three-phase relative permeabilities, especially when complicated hysteresis effects exist.

ACKNOWLEDGEMENTS

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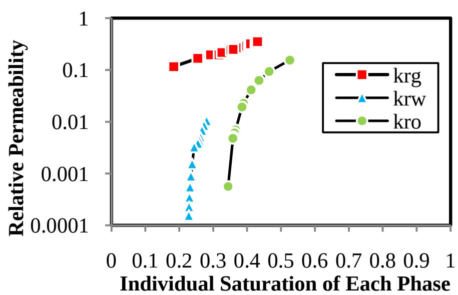

Figure 1: Three-phase relative permeability of each phase during Soltrol injection for Run 3.

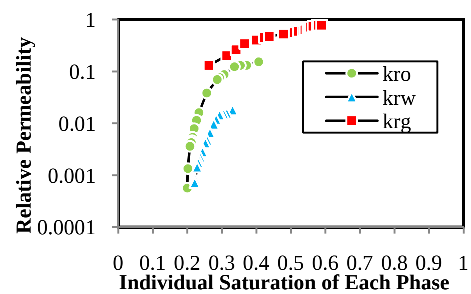

Figure 2: Three-phase relative permeability of each phase during Soltrol injection for Run 6.

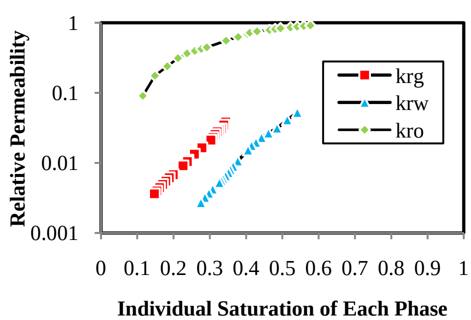

Figure 3: Three-phase relative permeability of each phase during Soltrol injection for Run 5.

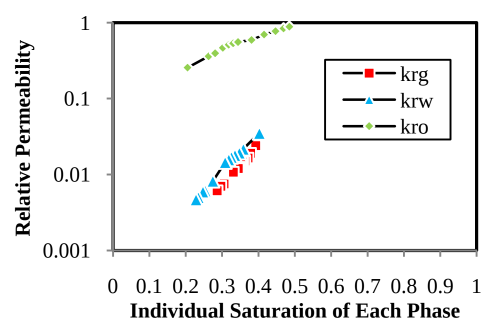

Figure 4: Three-phase relative permeability of each phase during Soltrol injection for Run 8.

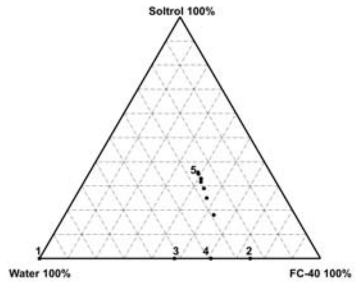

Figure 5: Saturation trajectory for DDI Run 3.

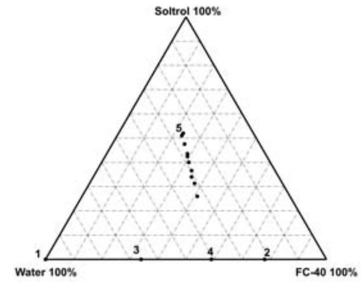

Figure 6: Saturation trajectory for DDI Run 6.

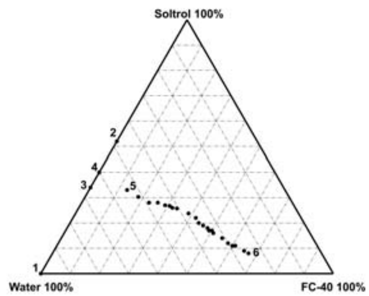

Figure 7: Saturation trajectory for DID Run 5.

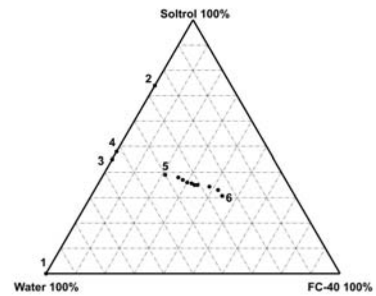

Figure 8: Saturation trajectory for DID Run 8.

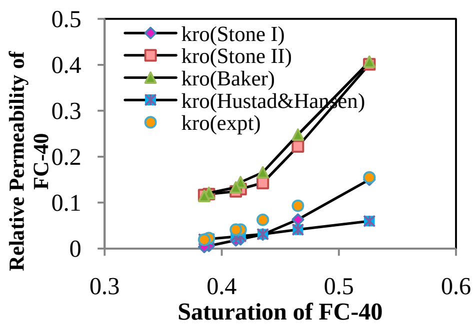

Figure 9: Comparison of FC-40 relative permeability for Run 3.

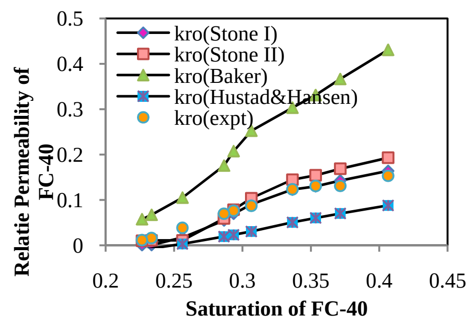

Figure 10: Comparison of FC-40 relative permeability for Run 6.

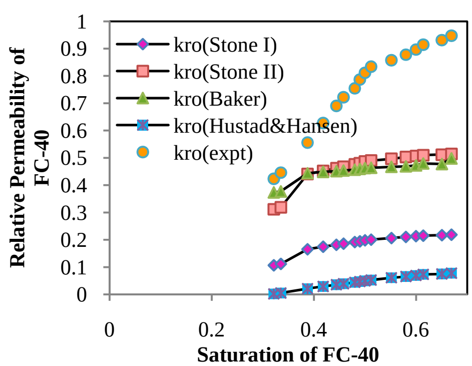

Figure 11: Comparison of FC-40 relative permeability for Run 5.

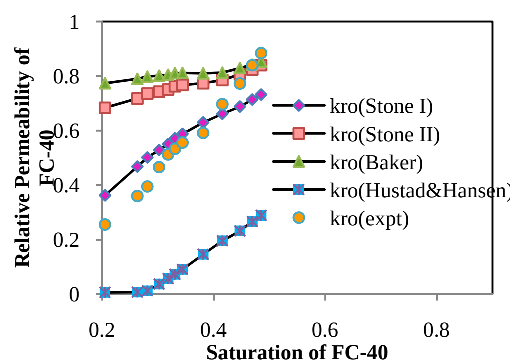

Figure 12: Comparison of FC-40 relative permeability for Run 8.