MULTIPHASE FLOW IN FRACTURES

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ABSTRACT

Fractures or cracks affect the movement of fluids in petroleum reservoirs. Fracture orientations reflect the histories of stresses acting upon reservoirs. In moderate to deep reservoirs, many fractures are vertically oriented with horizontal widths.

To describe fluid flow effects in vertical fractures, oil and brine permeability and relative permeability functions were measured in vertically oriented, smooth-walled plastic fracture cells. While the cells did not mimic all features of fractured rock, they were simple to use and instrumental in isolating effects of fracture widths on oil-brine relative permeability functions. Experiments were performed with both wide (787 μm) and narrow (51 μm) fractures. Fracture widths and saturation distributions during flow tests were measured using an X-ray scanner.

From fracture cell measurements, single phase permeabilities agreed well with permeabilities predicted from the literature. In the wide fracture, oil and brine relative permeability versus saturation functions were greatly influenced by the densities of the fluids as well as flow directions. In the narrow fracture, relative permeabilities were found to be simple functions of fluid saturations and agreed well with results from the literature.

BACKGROUND

The investigation of fracture permeabilities and relative permeabilities is worthwhile given that production from many reservoirs is influenced by the presence of natural fracture systems. As stated by Hensel,1 "Fractures, either naturally occurring or induced, are the life blood of many reservoirs because of their influence on well deliverability." So how wide are these fractures? Hensel described fracture widths ranging from about 10 μm to over 6,000 μm. He stated that widths of 50 μm seem reasonable while 6,000 μm extension fractures "existing at overburden stress conditions appear unlikely or may have been created during the coring/core retrieval process." Romm[2] stated that most fractures are in the range from 10 μm to 40 μm. Raven et al.[3] inferred fracture widths to be in the range from 100 μm to 200 μm from pumping tests. To put fracture widths in perspective, consider that a sheet of typing paper is about 100 μm thick.

In reporting work from Buckingham described in Croft,[4] Amyx et. al.[5] express the pressure drop through a slot of fine clearance and unit volume as a function of the flow velocity divided by the fracture width squared. When the velocity is expressed in terms of flow rate divided by cross sectional area, the pressure drop is proportional to the rate divided by the fracture width cubed, yielding the familiar cubic law for fluid flow in fractures.[6] An analogy to Darcy's law yields an expression for fracture permeability in terms of the width of the fracture squared.[5]

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When two or more fluids flow through a porous medium, fluid transmission qualities are often expressed as relative permeabilities. Relative permeabilities are effective permeabilities for a particular set of saturation conditions normalized with respect to a base permeability, such as the permeability of the porous medium to brine when completely saturated with brine. Relative permeabilities tend to be strongly related to phase saturations. They are critical to mathematical modelling of multiphase flow in porous media.[7] Laboratory measurements of fracture permeabilities and relative permeabilities are difficult. Some of the greatest degrees of difficulty lie in measuring fracture widths, pressure drops through fractures, and fluid saturation distributions. Other complications include wettability and surface roughness effects. Very few fracture relative permeability measurements have been performed. Romm[2] performed relative permeability measurements using parallel plate fractures with surfaces of mixed wettability. Romm's results indicate that fracture relative permeabilities for each phase are equal to their respective phase saturations. This condition that relative permeabilities are equal to phase saturations for flow within fractures is used as a simplifying assumption in many simulations,[7,8,9,10,11] although some investigators indicate that this assumption might not be accurate.[10,12,13,14] From their own test results, Pieters and Graves[14] concluded that fracture relative permeabilities are not linear functions of saturations. Fourar et al.[13] reported that their experimental data showed that fracture relative permeabilities are not linearly dependent on saturations, but instead vary with different fluid injection velocities. In simulating a linear displacement in a fractured core plug reported by Kazemi and Merrill,15 Kazemi et. al.[16] described that a mismatch between simulation and experimental results might indicate that fracture relative permeabilities are not equal to the respective phase saturations as used in the simulation.

This paper describes results from an investigation of oil and brine permeabilities and relative permeabilities in simple, smooth walled fracture models with vertical flow. Particular emphasis was placed on looking at effects of fluid densities on vertical multiphase flow in fractures.

FRACTURE FLOW MEASUREMENTS

Figure 1 provides schematics of two fracture cells that were used for this investigation, as well as the X-ray device that was used to measure fracture saturations. The cells were fabricated of rigid, transparent plastic. The fracture width in the 'wide' cell could be varied mechanically. The width of the narrow cell was fixed at 50.8 μm. Further descriptions of the cells are available elsewhere.[17,18] Tests with these cells were performed with fracture lengths oriented vertically as depicted in figure 1. Front views of the cells are shown in parts b and c of figure 1. The fracture width dimension is perpendicular to the page. Saturation distributions within the cells were measured using a 2-D linear X-ray scanner.[19]

Test fluids used were brine and oil. High viscosity fluids were used to provide measurable pressure drops for liquid flow rates between 10 and 400 ml/hour. The brine was a mixture of water, glycerin, and sodium bromide. Glycerin was used to increase the viscosity of the aqueous mixture. Sodium bromide was added to the brine so that brine and oil saturations could be measured using X-ray techniques. For tests using the wide fracture cell, the viscosity of the brine was 49.4 cP. The oil was prepared using a mixture of mineral oil and Soltrol 100 (an isoparaffinic oil product of Phillips Petroleum Company).

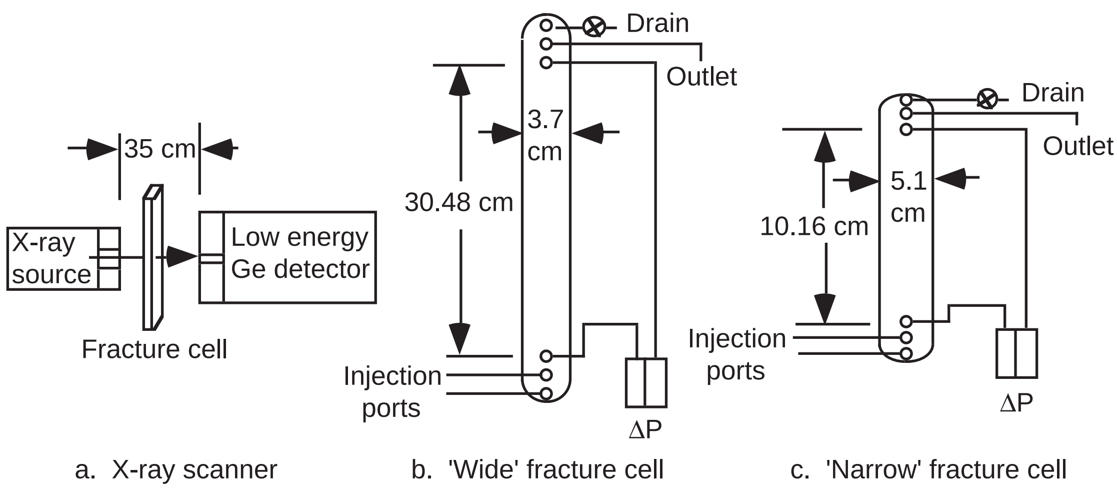


Figure 1. Schematics of the X-ray scanner (for saturation measurements) and fracture cells.

For tests on the wide fracture, the oil viscosity was 58.5 cP. Densities of the oil and brine fluids were 0.861 g/cm^3 and 1.362 g/cm^3 respectively. Brine and oil samples prepared for tests using the narrow fracture cell had viscosities of 24.2 cP and 61.3 cP respectively. ISCO pulsation-less syringe pumps were used to inject fluids into the cells. A draft-range differential pressure transmitter with brine-filled pressure lines was used for pressure drop measurements.

X-ray absorption techniques were used to measure fluid saturations and fracture widths within cells during flow tests. Saturations were determined by scanning the cells according to a closely spaced grid of horizontal and vertical measurement points. The X-ray tube was operated at 25 kV for these measurements.

Single-Phase Measurements

Single-phase flow tests were performed first to verify that the cells provided permeability results that were consistent with descriptions from the literature. Brine permeability measurements were recorded using the wide cell for widths ranging from 0.0787 cm to 0.1073 cm, and for the narrow cell with a 50.8 μm fracture width. Permeabilities to oil under conditions of complete oil saturation were also measured for the wide cell with a width of 0.0787 cm and for the narrow cell with a width of 50.8 μm.

Fracture permeabilities were calculated using Darcy's equation. These were compared with a commonly referenced[5,6] fracture permeability equation,

$$k = wf^2/12, \qquad (1)$$

where k is permeability in cm^2 and wf is fracture width in cm. For permeabilities in darcys, Equation 1 becomes

$$k = 84.4 \times 10^5\, wf^2. \qquad (2)$$

Figure 2 shows that measured brine and oil permeabilities compared favorably with permeabilities calculated by Equation 2, with closest agreement from oil permeability measurements. Pugh et al.[20] presented correlations among specific or absolute air, oil, and brine permeabilities for hundreds of reservoir rock samples. They found that oil permeabilities were slightly lower than air permeabilities in the range from 0.1 to 10,000 mD, whereas brine permeabilities were about half as great as air permeabilities over the same range. Because many rock samples are preferentially wetted by brine, this suggests that the specific permeability of a porous media to the wetting phase is somewhat lower than its permeability to a non-wetting phase fluid. The plastic in the wide fracture cell has a slightly greater affinity for oil than brine, as shown by the shapes of beads of oil and brine when placed on the plastic. Considering oil as the wetting phase, it is reasonable to expect specific permeabilities to oil measured within the cell to be slightly lower than those of brine. If the fracture permeability correlation of Equation 2 was originally developed using a fluid that wetted the surfaces of the experimental fixture, then one would suspect the correlation to be most appropriate for wetting-phase fluids.

In summary, single phase fracture cell measurements provided results that agreed well with permeabilities predicted using equations from the literature.

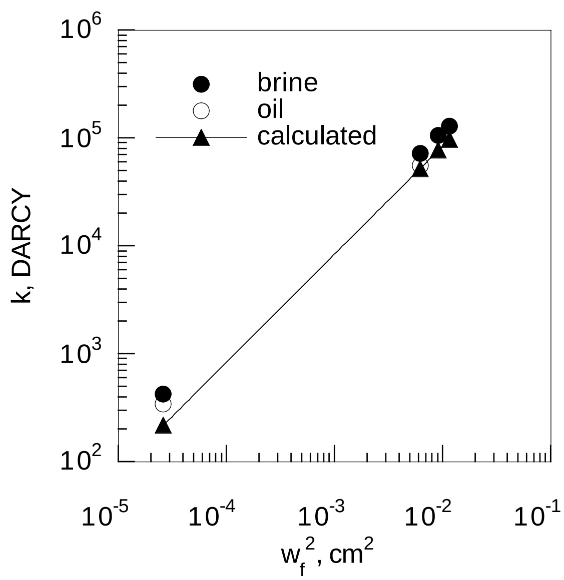
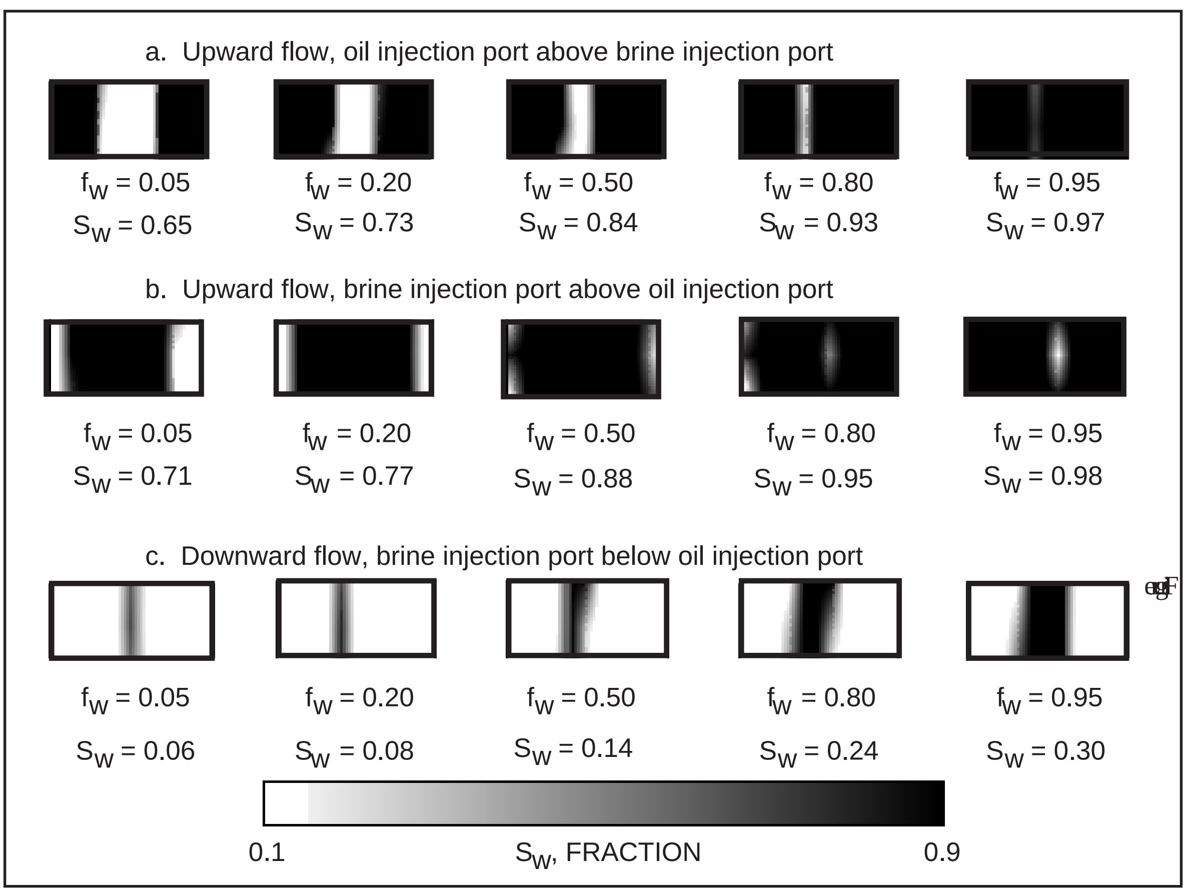


Figure 2. Measured versus calculated (from eq. 2) fracture permeabilities vs. fracture width squared.

Wide Fracture Multiphase Flow Measurements

A steady-state oil-brine relative permeability test was conducted using the wide fracture flow cell and a fracture width of 0.0787 cm. Brine and oil permeabilities when the cell was completely saturated with each fluid were 72,600 darcys and 55,700 darcys respectively. After completing single-phase oil permeability measurements, both oil and brine were injected into the cell. Oil and brine flow rates and pressure drops were recorded as both fluids were injected upward through the cell. Brine was injected through the first or lowest injection port, while oil was injected into the second, higher port (see figure 1). The total injection rate (brine plus oil) was kept at 200 ml/hr for each set of measurements. This corresponds to a total injection velocity of about 165 m/day. Fluids were produced from the top of the cell. Measurements were recorded for brine fractional flows (fraction of brine injected in the total flow stream, fw) of 0.05, 0.20, 0.50, 0.80, 0.95, and 1.00. For each fractional flow condition, sufficient time was allowed for the pressure drop and saturation conditions to stabilize before recording test data. Fluid saturations were measured by X-ray scanning the flow region within the cell at 220 positions according to a grid with 20 rows spaced 1.5 cm apart and 11 columns spaced 0.3 cm apart. The 2D X-ray scanner was used for these measurements. Saturations between pressure taps were averaged for comparisons with relative permeabilities. Figure 3a shows saturation profiles for a 1.5 cm vertical region within the fracture cell for several of the fractional flows. As shown, oil flowed within a narrow stream surrounded by brine.



3. Front view of two-phase oil-brine saturation profiles within a 0.0787 cm fracture. Regions shown are for 1.5 cm tall sections located between pressure taps. Also shown are brine fractional flows and bulk brine saturations measured between pressure taps.

When brine injection first began with the 0.05 fractional flow condition, brine slowly crept up the outer edges of the cell while oil flowed in a straight line path from its injection port to the production port. Oil and brine flow streams remained segregated for each fractional flow condition. The thin stream of oil appeared to be bounded on all sides by brine for the 0.95 fractional brine flow condition. Average saturations for each fractional flow condition are also shown on Figure 3. Note that high brine saturations existed even with low brine fractional flows.

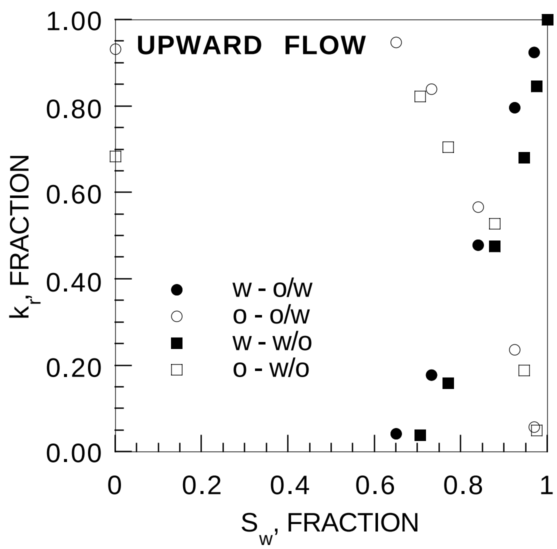
Permeabilities were calculated by Darcy's law using fluid injection rates and pressure drops corrected for head effects. With the pressure taps filled with brine, pressure drops were corrected for pressure heads using:

$$\Delta P_{corrected} = \Delta P_{measured} - \Delta P_{head} \tag{3}$$

$$\Delta P_{head} = (1-S_w)(p_o - p_w)gh, \tag{4}$$

where S_w is the average brine saturation fraction between pressure taps, p_o and p_w are oil and brine densities, g is the gravitational constant, and h is the distance between the two pressure taps.

In a second relative permeability test using the wide fracture model, oil and water were injected into the bottom of the cell again but with the water injected from a port above the oil port. Saturation distributions are shown in figure 3b. In this case, for the most part, brine flowed within the central region of the cell while oil flowed around the brine. Within the plastic fracture cell, with vertical upward flow, the fluid injected into the cell from the highest injection port tends to occupy the center portion of the cell. Figure 4 **shows comparisons of** oil and brine relative permeability results for upward flow within the fracture model. Two cases are shown, corresponding to the two measurement sets previously described. The first case is that where oil flows within the center portion of the cell and is surrounded by flowing water (o/w). The second case is that where water occupies the center portion of the cell and is surrounded by oil (w/o). Relative permeability vs. saturation results were similar for both cases. As shown by the figure, relative permeabilities did not vary linearly with saturation, in contrast to Romm's[2] results, which showed a linear relationship between relative permeability and saturation.



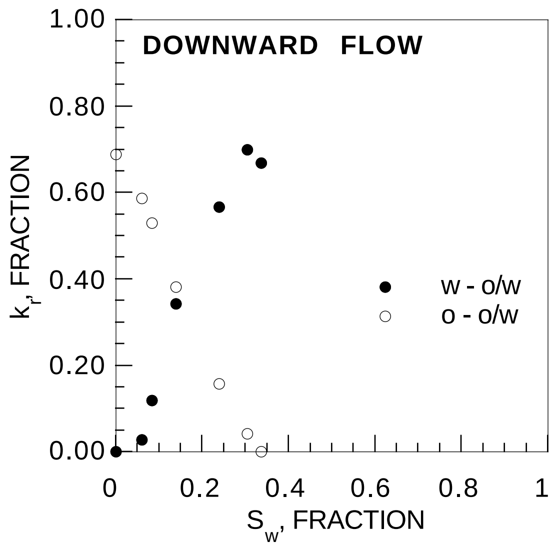


Figure 4. Relative permeabilities for vertical upward flow. Caption description: o/w indicates that oil was injected from a port above the water injection port; w/o indicates the opposite. The fracture width was 0.0787 cm.

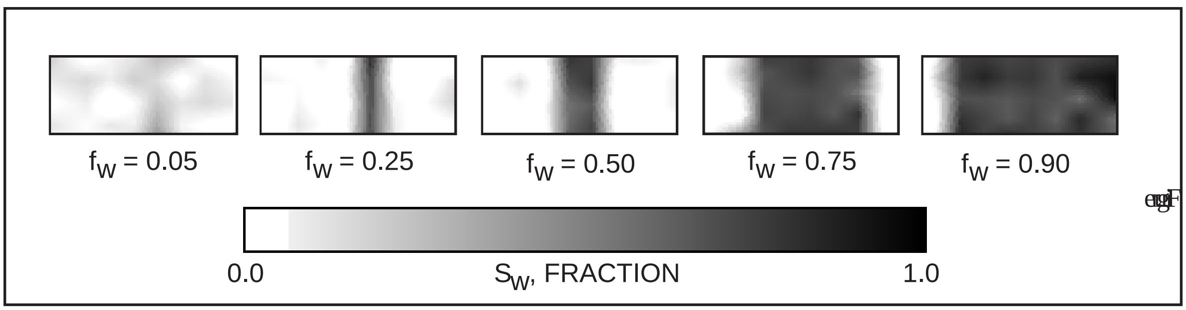
Figure 5. Fracture relative permeabilities for vertical downward flow. Oil was injected from a port above the brine injection port. The fracture width was 0.0787 cm.

What happens when the fluids flow downward through a crack rather than upward? Another test was performed in which oil and brine were injected into the top rather than the bottom of the fracture cell. For this test, the positive pressure tap to the ΔP transmitter was connected to the cell’s upper pressure tap port, while the negative pressure tap was connected to the cell’s bottom pressure port. The pressure head correction was the negative of that described in eq. 4. Fluids were produced from the bottom of the cell. Oil was injected into the uppermost injection port while brine was injected into a lower port. For this configuration, brine flowed downward through the center of the cell, surrounded by oil. Saturation distributions for several brine fractional flows are shown in figure 3c. Brine flowed through a narrow channel in the center of the cell. Saturation distributions looked completely opposite from those of vertical upward flow. The manner in which brine, surrounded by oil, flowed downward through the cell was very similar to the manner in which oil, surrounded by brine, flowed upward through the cell during a previous test. Relative permeability vs. brine saturation results are shown in figure 5. These results show that relative permeability characteristics of wide fractures are greatly influenced by differences in densities of the flowing fluids and flow direction. Simple correlations between saturation and fractional flow do not describe the vertical flow phenomena.

Narrow Fracture Multiphase Flow Measurements

Steady-state oil-water relative permeability tests were also performed using the narrow fracture model of figure 1c. The fracture width was fixed at 50.8 µm. Consistency of the fracture gap width dimension was verified by X-ray scans. The permeabilities of the cell under conditions of complete saturation were 425 darcys for brine and 347 darcys for oil. Two-phase steady-state oil-brine relative permeability measurements were recorded for various water fractional flow conditions during a brine displacing oil saturation cycle. The total injection rate (oil plus brine) was maintained at 30 mL/hr for each set of measurements. This rate corresponds to a flow velocity of about 280 m/day. Fluid saturation distributions within the cell were measured using X-ray techniques. During this test, flow was upward. Water was injected from a port above the oil injection port.

Figure 6 shows saturation profiles for a 1.5 cm vertical region within the fracture cell for several of the fractional flows. Brine mostly flowed through the middle of the cell. The width of the brine channel increased with increasing brine fractional flow. Relative permeability results are shown in figure 7. The oil relative permeability when the fracture was completely saturated with oil was 0.82 instead of 1.00. This is because permeabilities were normalized with respect to kw at S_W = 1.00, and the specific permeability of the cell to oil was only 82% of the specific permeability of the cell to brine. For this narrow fracture, relative permeabilities can be fairly well approximated by simple functions of saturations in manner similar to that described by Romm.[2]



6. Oil-brine saturation profiles within a 51 μm fracture. Regions shown are for 1.5 cm tall sections located between pressure taps. Also shown are brine fractional flows. Flow was upward.

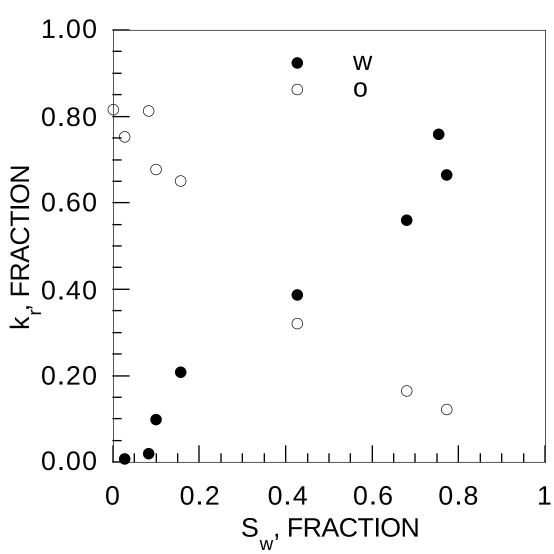


Figure 7. Oil-brine steady-state relative permeability results for a 51 μm fracture gap width.

DISCUSSION

As shown in this paper, differences in densities for the two flowing phases and flow directions have pronounced effects on multiphase flow within wide vertical fractures. For vertical two-phase flow through a 787 μm fracture, relative permeabilities were not equal to phase saturations. The primary forces acting during these experiments were gravitational (Fg), viscous (Fv), and capillary (Fc). Effects related to differences in fluid densities appear to become less significant when:

1. Flow rates are such that Fv >> Fg (assuming Fc is negligible).
2. Narrow fracture widths and flow rates yield Fv + Fc >> Fg.

Relative permeability results for the 51 μm fracture indicate that effects related to differences in fluid densities were minimal for the flow rates used. However, even for narrow fractures, it is probable that density differences affect relative permeability versus saturation trends with low fluid flow rates.

CONCLUSIONS

The following are concluded from this work:

1. Oil and brine permeability functions measured in wide (787 μm to 1070 μm) and narrow (51 μm) smooth-walled fractures agreed well with permeabilities predicted from correlations in the literature.

2. For a wide (787 μm) fracture, oil and brine relative permeability versus saturation functions were significantly influenced by the densities of the flowing liquid phases as well as directions of fluid flow. Relative permeabilities were not equal to phase saturations. Simple correlations between saturations and fractional flows do not describe vertical flow phenomena.

3. For a 51 μm fracture, oil and brine relative permeabilities varied almost linearly with saturations for the flow rates imposed. However, even for narrow fractures, it is probable that fluid density differences affect relative permeability versus saturation trends when gravity forces are significant compared to viscous and capillary forces.

4. The shapes of relative permeability versus saturation curves appear to be sensitive to fluid flow rates, fluid densities, and direction of fluid flow.

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