FULL CYCLE CAPILLARY PRESSURE AND TRANSITION ZONE MEASUREMENTS VIA THE SEMI-DYNAMIC TECHNIQUE

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ABSTRACT

Describing capillary pressure (Pc) as a function of saturation history is important for estimating reserves, optimizing hydrocarbon recovery strategies, and for reservoir simulation. Ideally, one would like to measure Pc versus saturation with reservoir fluids and reservoir conditions so that effects of pressure, stress, temperature, interfacial tension, and rock-fluid interactions are captured by test measurements. Also, one would like to model, with one test, the saturation history that might occur during the hydrocarbon recovery process. Methods for measuring full-cycle Pc functions (primary drainage, spontaneous brine imbibition, forced brine imbibition, spontaneous oil imbibition, 2nd drainage) have been reported in the literature, but have not been widely used. The objective of this work was to evaluate the semi-dynamic capillary pressure method to gain confidence that it can deliver full-cycle Pc versus saturation functions during reservoir-condition tests.

Semi-dynamic capillary pressure tests were performed using a chalk core sample from a petroleum reservoir. X-ray methods were used to characterize saturation distribution within the core at the same time that each capillary pressure condition was imposed. Tests were relatively simple to perform, even with the core and fluids subjected to elevated temperature, pore pressure, and stress. The semi-dynamic technique yields measures of Pc versus saturation at the injection face of the core. Downstream from the injection face, saturation changes with distance from the injection face because Pc also varies with distance from the point of injection. As a result, each position along the length of the core follows a different imbibition Pc versus Sw trajectory depending upon the local minimum brine saturation achieved during primary drainage. Methods were developed to estimate local Pc from saturation measurements and correlations determined from face Pc versus saturation. A confirmation test verified the validity of the approach for estimating Pc from saturation profiles. The net result is that data from one semi-dynamic test can be used to describe a number of imbibition and 2nd drainage Pc versus saturation functions, each starting with a different primary drainage initial brine saturation condition (Swi). Such information should be valuable for estimating oil recovery from transition zones.

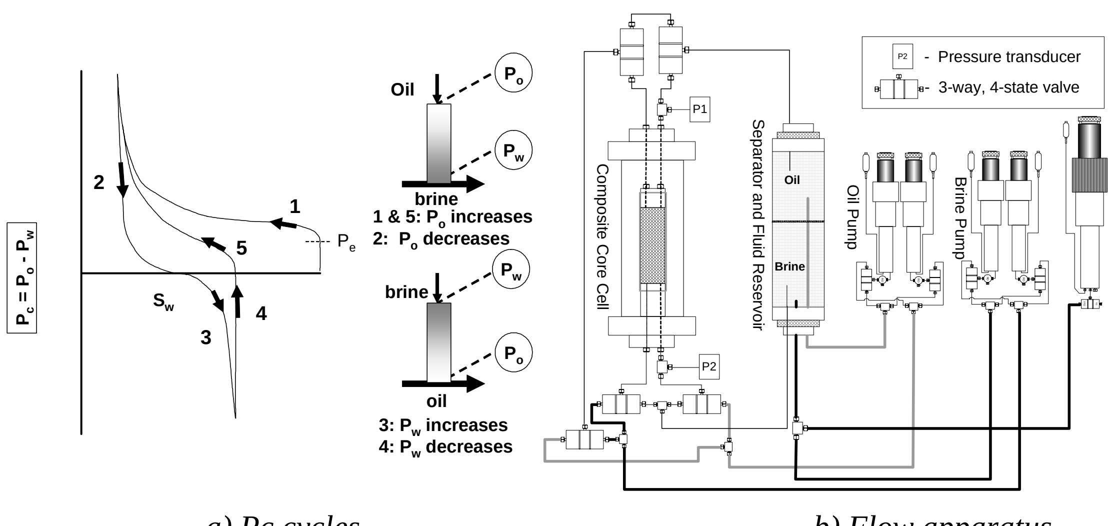
BACKGROUND

A limitation of commonly employed methods for measuring capillary pressure is that Pc versus saturation curves are typically measured with fluids and conditions that aren't the same as those of the reservoir (stress, pore pressure, composition of fluids, temperature), so lab results have to be scaled to estimate Pc versus saturation for reservoir conditions. Ramakrishnan and Cappiello (1991) describe a method for measuring Pc and other characteristics (non-wetting phase relative permeability, resistivity) as the sample, initially saturated with wetting fluid, is drained to residual wetting phase saturation by injecting a non-wetting fluid in steps of increasing injection pressure or velocity. Institut Francais du Petrole (IFP) investigators built upon the technique, describing their approach as a semi-dynamic method for measuring full-cycle two-phase capillary pressure versus saturation functions, even with reservoir conditions. They published several papers, including those by Lenormand et al (1993), Lenormand et al (1995), Lenormand and Schmitz (1997), Lombard et al (2002), and Lombard et al (2004). Lenormand et al (1997) of IFP also patented the technique. The purpose of this investigation was to evaluate advantages of the semi-dynamic Pc approach during a test in which a core was subjected to elevated temperature, pore pressure, and stress.

The Semi-Dynamic Pc Method

Figure 1 illustrates the semi-dynamic Pc approach for oil-brine measurements. There are 5 curves associated with full-cycle oil-brine capillary pressure versus saturation. From the convention Pc = Po – Pw (water-wet assumption), the curves are:

1. Primary or first drainage – Initial forced displacement of brine by oil, Pc > 0. Oil entry pressure (Pe) is the threshold capillary pressure that causes oil to invade the brine-saturated porous media.
2. Spontaneous brine imbibition – spontaneous imbibition of brine, with Pc ≥ 0
3. Forced brine imbibition – increase in brine saturation from brine injection, Pc < 0
4. Spontaneous oil imbibition - spontaneous imbibition of oil, Pc ≤ 0
5. 2nd drainage – second cycle displacement of brine by oil, with Pc > 0.



a) Pc cycles *b) Flow apparatus*

Figure 1. Semi-dynamic Pc method and schematic of the closed loop flow apparatus. The large pump cylinder injects or withdraws brine from the separator to maintain constant downstream pressure.

During a Pc versus saturation measurement, one fluid is injected at constant rate or constant pressure into one face of the core, while the second fluid is flushed across the opposite core face at constant rate. When steady-state is achieved, Pc at the injection face of the core is calculated as the difference in upstream and downstream pressures. A face Pc and saturation measurement represents one point on a Pc versus saturation curve. Additional points are gained by systematically changing injection rate or injection pressure, by calculating Po – Pw after pressure gradient and saturation stabilize, and by measuring saturation at the injection face. A schematic of the closed-loop approach used in this investigation is shown in Figure 1. Constant pressure injection was used for measurements of this investigation except to achieve Pc = 0 psi. For Pc = 0 psi, brine was injected across one core face at constant rate while oil was injected across the opposite core face, also at constant rate. In-situ saturations were measured by an x-ray technique described by Maloney et al (2000). Saturations measured by this method are typically accurate to within ± 0.01 saturation units (with Sw = 1.0 representing complete brine saturation).

SEMI-DYNAMIC CAPILLARY PRESSURE TEST

The method was tested using a vertically-oriented 3.81 cm diameter by 8.8 cm long chalk core plug (k_g = 1.29 mD, ϕ = 0.380), brine (2% KCl + 8% CsCl + 90% water by weight, function of CsCl is to enhance x-ray contrast) and n-Decane. Test conditions were 150 deg. F, 300 psig backpressure, and 1000 psig confining pressure. The permeability of the brine-saturated core was 0.77 mD at test conditions. Equilibration times ranged from 1 to 4 days for each Pc versus Sw measurement during the sequences described below.

Primary Drainage

Brine was flushed across the bottom face of the vertically oriented core (at elevation 0 cm). Backpressure was maintained at 300 psig such that pressure in the brine phase at the bottom face of the core was 300 psig. Oil was injected into the top face of the core (at elevation 8.8 cm) in steps, allowing time to achieve equilibrium before recording data and increasing injection pressure. Injection pressures from 301 psig to 550 psig were imposed, yielding Pc (Po – Pw) at the injection face ranging from 1 to 250 psi.

Brine Imbibition

Oil injection pressure was reduced in steps from 550 psig to 300 psig, reducing face capillary pressure from 250 psi to 0 psi. Before forced brine imbibition measurements, tubing above the core was flushed with brine. Tubing below the core was flushed with oil. The forced brine imbibition test was conducted by injecting brine in pressure steps into the upper face of the core while flushing the bottom core face with oil.

Spontaneous Oil Imbibition, Second Drainage

Spontaneous oil imbibition was tested by reducing brine injection pressure in steps, yielding measures of face Pc versus saturation with capillary pressure from -150 psi to 0 psi. Before 2nd drainage measurements, tubing above the core was flushed with oil. Tubing below the core was flushed with brine. Oil injection pressure was increased in steps to yield Pc versus saturation with face capillary pressures from 0 to 250 psi.

Results

Saturation profiles are shown in Figure 2. Data necessary for plotting Pc versus Sw includes face Pc (legend entries) and face saturation (circled data points). Full-cycle face Pc versus saturation results are shown in Figure 3. The primary drainage curve was comparable to results obtained by other means for similar samples.

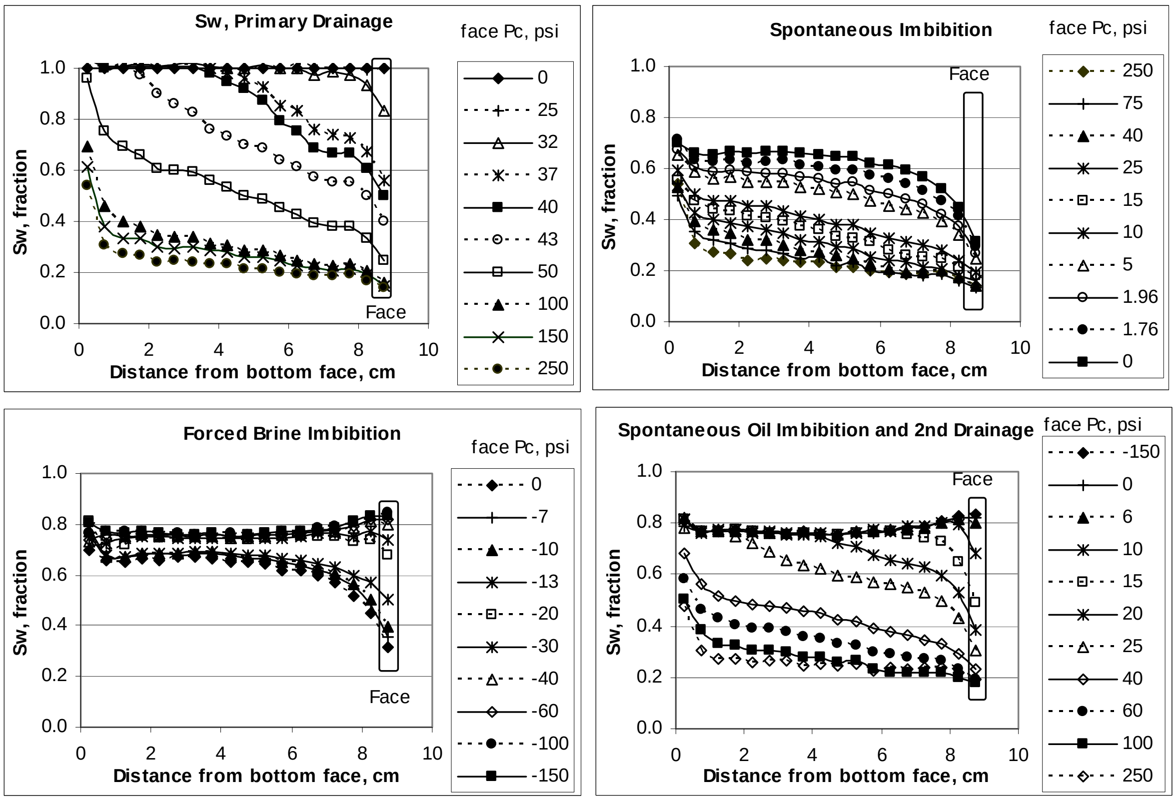


Figure 2. Saturation profiles during full-cycle semi-dynamic Pc tests.

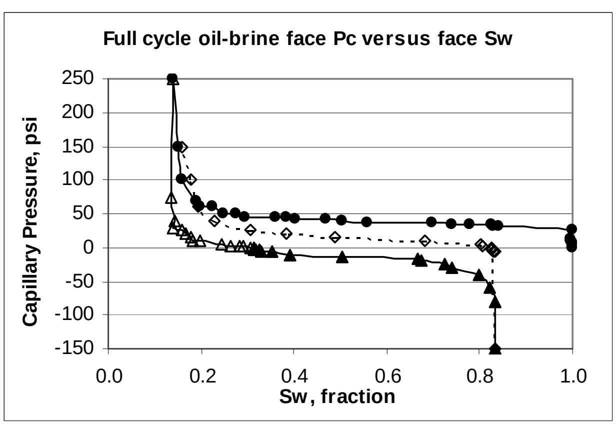


Figure 3. Full cycle oil-brine Pc results from face measurements.

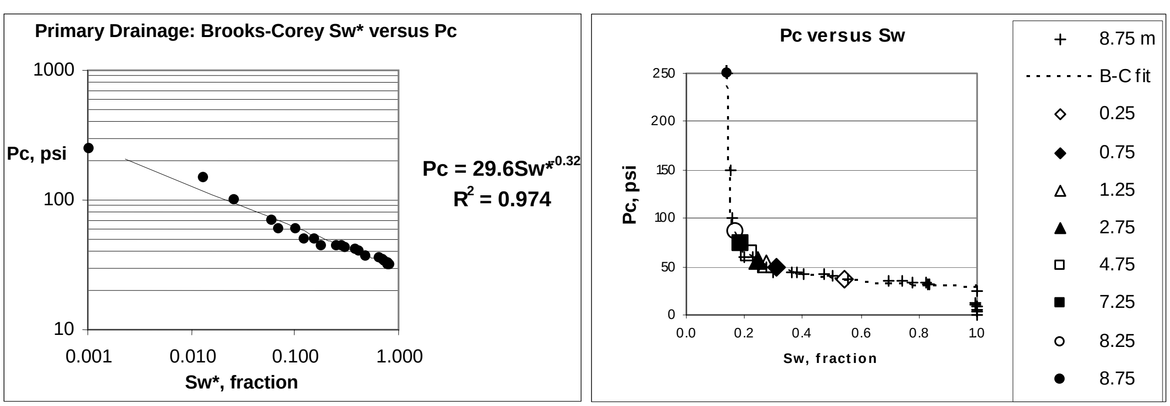
Local Pc versus Sw, Primary Drainage

If the core is homogeneous, in all places throughout the core, the same drainage Pc versus Sw relationship should apply. Thus, if drainage Pc versus Sw is described at the injection face, the same relationship can be used to estimate Pc from Sw elsewhere within the core. The Brooks-Corey equation, from Brooks and Corey (1966), is a relationship for predicting primary drainage capillary pressure from brine saturation:

$$Pc = Pe(Sw^{*})^{-1/\lambda}, \quad Sw^{*} = (Sw - Swr)/(1-Swr) \tag{1}$$

In Equation 1, Pc is capillary pressure, Pe is the entry capillary pressure or pressure necessary to cause the non-wetting phase to invade pores, λ is a pore size distribution index, and Swr is irreducible brine saturation or the saturation for which a large increase in drainage Pc has negligible effect on Sw.

With 250 psi drainage capillary pressure, the maximum Pc applied during the test, Swi at the injection face was 0.139. Setting Swr equal to 0.138 for Sw* in Equation 1 yielded a Brooks-Corey fit to the face data with correlation coefficient (R^2) closest to 1. Data for drainage Pc less than 32 psi were omitted to allow the curve fit to predict Pe. Figure 4(a) shows the Brooks-Corey fit to the primary drainage face Pc versus Sw data. The Pe of 29.6 psi from the curve-fit agrees with that observed experimentally. At the end of the drainage experiment, brine saturation magnitude varied along the length of the core in response to variation in Pc with distance from the oil injection face. Pc results corresponding to points on the saturation profile were calculated using the curve fit from Figure 4(a). Results for several distances from the bottom core face are shown in Figure 4(b).



(a) *(b)*

Figure 4. Primary Drainage. (a) Brooks-Corey fit to face Pc versus face Sw. (b) Comparison of face Pc versus face Sw (8.75 m) with Brooks-Corey fit (B-C fit). Also shown are calculated Pc versus Sw for various positions at distances (in cm) from the bottom core face at the end of the primary drainage test.

Local Pc versus Sw, Brine Imbibition

Sarwaruddin et al (2001) describe that the following function is useful in describing imbibition Pc versus Sw:

$$P_c(S_w) = \frac{C_1}{(S_w - S_{w1})^{n_1}} - \frac{C_2}{(S_{w2} - S_w)^{n_2}} \tag{2}$$

where C_1 and C_2 are positive constants, S_w is water saturation, S_{w1} is irreducible water saturation (Swr in the context of this report), and S_{w2} is water saturation at irreducible oil saturation (Swor). The authors describe that except for n_2, the bounding shape parameters (C_1, C_2, and n_1) are assumed to be the same for all other drainage-imbibition scanning loops for the rock and fluid system such that, after one has found parameters that yield a reasonable fit to the bounding imbibition curve, one can use the same parameters (C_1, C_2, and n_1) and adjustments to n_2 in describing imbibition scanning curves. The authors explain that the exponent "n_2" is used to adjust the shape of the scanning curves from that of the bounding imbibition curve. Comparing imbibition face Pc versus saturation with results of Equation 2, by trial and error, parameters that produced a satisfactory fit were:

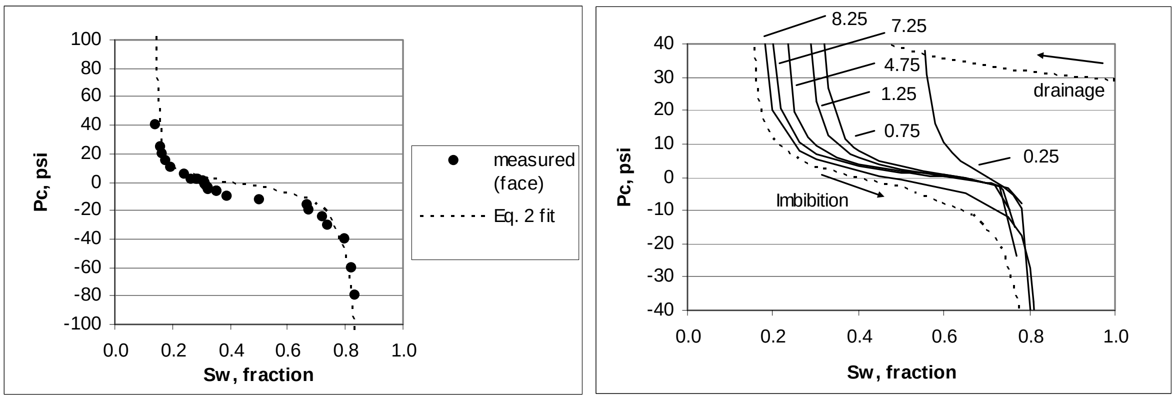
C_1=2.28	C_2=2.50
n_1=0.68	n_2=1.10
Sw_1=0.1381	Sw_2=0.86

Figure 5 compares measured face Pc versus Sw with the trend estimated by Equation 2 using measured saturations and the parameters just mentioned. In this case, the curve fit is best near the asymptotes but not quite as good around Pc =0. Note that the face Pc versus Sw data shows a "kink" in the vicinity of Pc $\leq$ 0. This "kink" is not modeled by Eq. 5, and is likely the result of a second drainage entry pressure effect, as oil mobilized from the injection face had to drain through downstream portions of the core where brine saturation was higher. Using a different "n_2", one can force the curve to pass through the correct saturation for Pc = 0, but the asymptote at the high water saturation side of the graph then shifts toward lower saturation. The curve fit described above was considered adequate for the exploratory nature of this investigation.

Imbibition Pc versus Sw trends were calculated using Equation 2 for each position along the length of the core where saturations were measured. In using Equation 2, Swi and Swor for a scan position (or position at some distance from the bottom core face where saturation was measured) were used as S_{w1} and S_{w2}. The same C_1, C_2 and n_1 values that were used to fit the face Pc versus Sw data were used for all scan positions. The parameter n_2 was adjusted to cause the Pc curve for a scan position to pass through the measured saturation when Pc was 0 psi. Results for selected scan positions are shown in Figure 5(b). A noteworthy observation is that oil recovery during spontaneous brine imbibition was influenced *by the preceding maximum drainage Pc and accompanying Swi*. One might describe this as the influence of trapping, as described by the interesting and pertinent results of Masalmeh (2001).

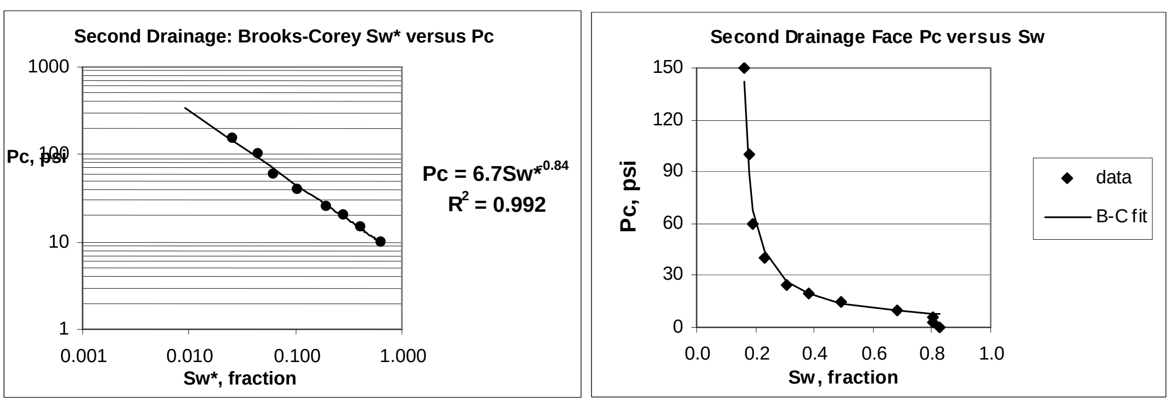
Local Pc versus Sw, Spontaneous Oil Imbibition and Second Drainage

There was little spontaneous oil imbibition or redistribution of fluids within the core in changing from forced brine imbibition to second drainage until Pc approached 10 psi (see Figure 2). The Brooks-Corey equation was used to fit the second drainage face Pc versus Sw data, again using the same Swr determined during primary drainage in calculating Sw* (Equation 1). Figure 6(a) is a plot of face Pc versus face Sw*. Data points at high brine saturation were omitted from the plot to facilitate determination of Pe. From a power fit to the data, λ was found to be 1.19. Pe was 6.7 psi. Pc estimates were then calculated using equation 1 to compare with test measurements. As shown by Figure 6(b), the fit appears reasonable.



(a) *(b)*

Figure 5. Imbibition Pc results: (a) Comparison of face data with Equation 2 fit; (b) Local imbibition Pc calculated from Eq. 2 versus saturation for various distances from the bottom core face. Graph (b) also shows bounding curves from face drainage and imbibition Pc versus saturation.



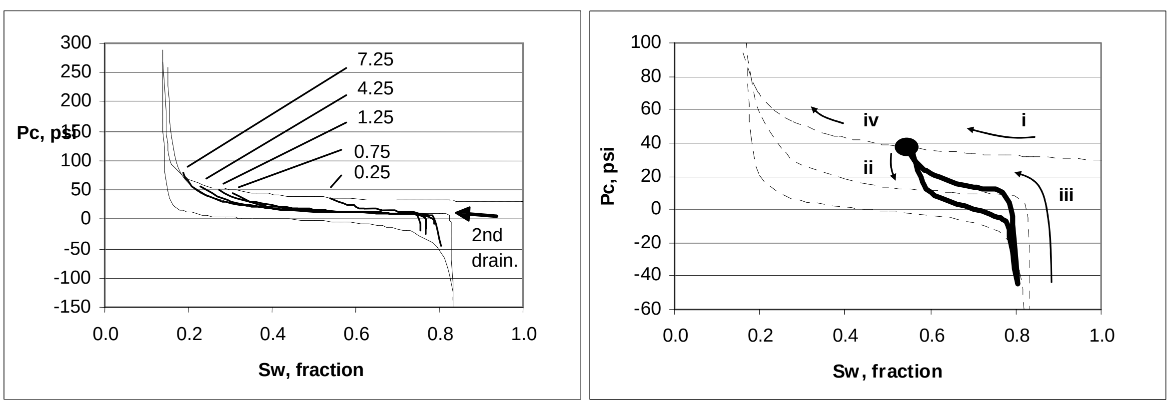
(a) *(b)*

Figure 6. Second drainage. (a) Brooks-Corey fit to face Pc versus Sw. (b) Comparison of face Pc versus saturation test data and estimates from the Brooks-Corey fit.

Pc versus Sw trends were estimated from measured saturations. One perception, also described by Killough (1976), is that scanning loops, under the response of similar capillary pressure in secondary drainage, will return to the same Swi that previously existed during primary drainage. Thereafter, if Pc is increased beyond that imposed during primary drainage, the secondary drainage curve will follow the bounding primary drainage curve. The following were assumed in estimating 2nd drainage Pc from in-situ saturation data:

- Spontaneous oil imbibition is represented by a line connecting (Pc, Swor) and (Pc=0 psi, Sw = measured spontaneous oil imbibition end-point) since little if any spontaneous oil imbibition occurred.
- For Sw ≥ Swi (the lowest Sw attained previously during primary drainage), use Equation 1 and the same Brooks-Corey Pe and exponent ($-1/\lambda$) found by fitting 2nd drainage face Pc versus Sw in calculating Pc from Sw. Adjust Swr that is used in calculating Sw* for a particular position within the core to cause the 2nd drainage curve to intersect the primary drainage curve at the original (Pc, Swi) point of departure from the primary drainage curve.
- For Sw < Swi, calculate Pc using the same Brooks-Corey parameters that were used to fit the primary drainage face Pc versus Sw data, (i.e. the trend with Swi ≈ Swr).

Figure 7(a) shows estimated second drainage Pc versus Sw functions for selected positions within the core. Figure 7(b) shows a Pc scanning loop estimated for the position along the length of the core that is 0.25 cm from the bottom core face. The scanning curve includes: (i) primary drainage to Swi (black dot), (ii) spontaneous and forced brine imbibition, (iii) spontaneous oil imbibition and 2nd drainage to the original Swi, and (iv) trajectory for additional second drainage to saturation lower than that previously achieved during primary drainage. The figure was constructed by combining results for position 0.25 from Figures 4(b), 5(b) and 7(a). For reference, the bounding curves, or full cycle curves from face Pc versus face Sw measurements are also shown.



(a) *(b)*

Figure 7. Second drainage. (a) Pc curves estimated for core positions at various distances from the bottom core face. (b) Pc scanning loop for the position 0.25 cm from the bottom core face compared to the bounding Pc curves.

TEST 2, CONFIRMATION TEST

A second full-cycle test was conducted to follow the same Pc history as that shown in Figure 7(b). The core was cleaned and saturated with brine. Pore pressure, confining pressure, and temperature were increased to match conditions of the first test (300 psig, 1000 psig, 150 deg. F). The permeability of the core to brine at test conditions was nearly the same as before; 0.72 mD compared to the 0.77 mD result at the start of the first test.

Test 2, Primary Drainage

Oil injection pressure was increased in steps. Pe was observed to be between 28 and 30 psi, in good agreement with the 29.6 psi result from the first test. Drainage capillary pressure at the core face was increased in steps to 38 psi. With 38 psi face capillary pressure, Sw at the core face was 0.55. This brine saturation was very close to the Sw of 0.54 attained with estimated Pc of 37.7 psi during the first test. Saturation profiles are shown in Figure 8(a). Note that with face Pc of 38 psi during primary drainage, the oil saturation front did not extend to the bottom core face.

Test 2, Spontaneous and Forced Brine Imbibition

Oil injection pressure was reduced in steps while the downstream core face was flushed with brine. Figure 8(b) shows saturation profiles recorded during spontaneous and forced brine imbibition. From Figure 8(b), one can see that the lower 1/3rd of the core was still completely saturated with brine when spontaneous imbibition was satisfied. According to the protocol of Figure 1, to initiate forced brine imbibition, one would inject oil across the lower face of the core while injecting brine into the top core face in steps of increasing pressure. In this case, however, since the oil phase was discontinuous, injecting oil across the bottom core face would not yield desired results. Instead, brine was injected into the lower core face (same face that was previously flushed with brine) while oil was flushed across the top face of the core (where oil was previously injected). Saturation profiles were obtained for water injection conditions yielding 5 psi and 20 psi pressure difference between the bottom and top core faces. By this means, Sw was increased by forced brine imbibition although Pc for those conditions was uncertain.

Test 2, 2nd Drainage

Second drainage cycle measurements were recorded by injecting oil into the top face of the core with steps of increasing pressure while brine was flushed across the bottom face of the core. Saturation profiles measured during 2nd drainage are shown on Figure 8(c).

Test 2, Face Pc Versus Saturation Results

Figure 8(d) shows measured face Pc versus Sw results from this test compared to the estimated scanning loop of Figure 7(b). The data sets are in good agreement. The bounding drainage curve from Figure 4(b) is also shown on Figure 8(d). Note that for this confirmation test, during 2nd drainage, when Sw was driven lower than the original Swi attained during primary drainage, the Pc versus Sw curve followed the bounding primary drainage curve.

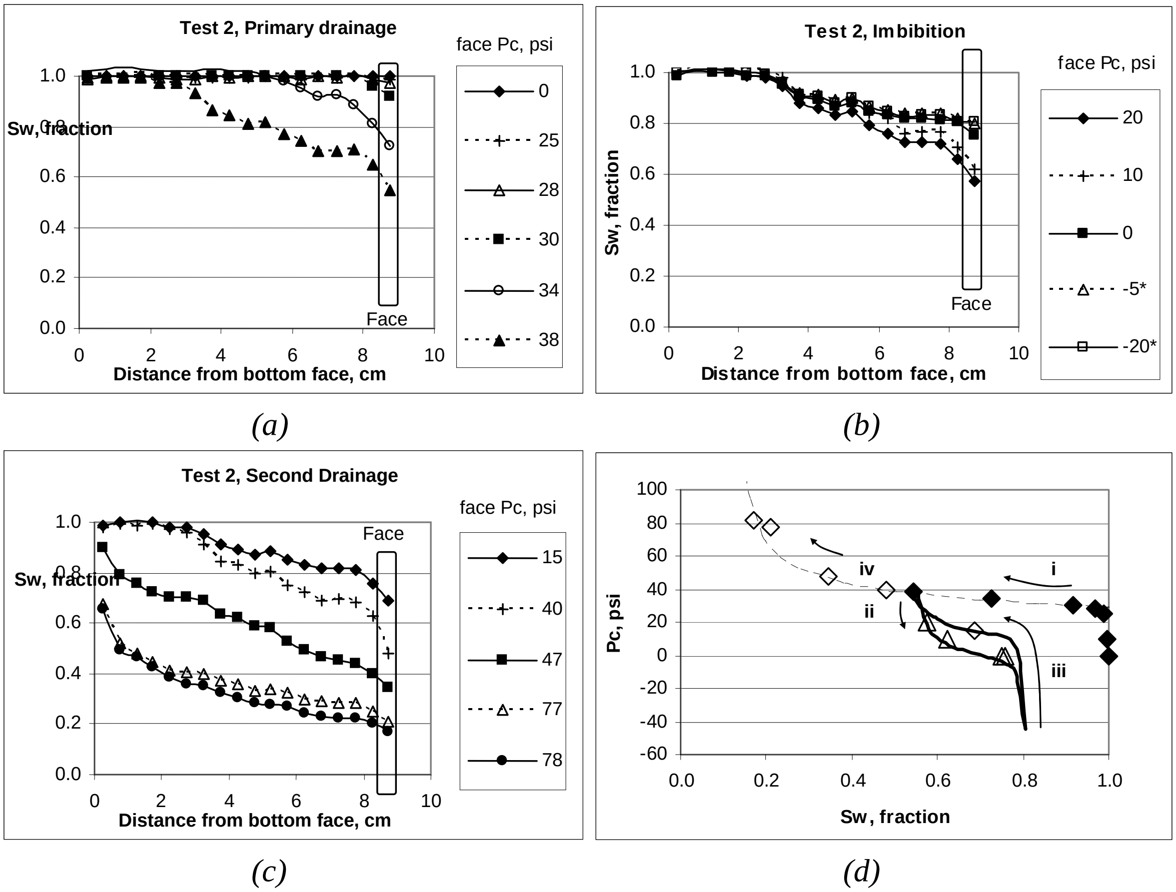


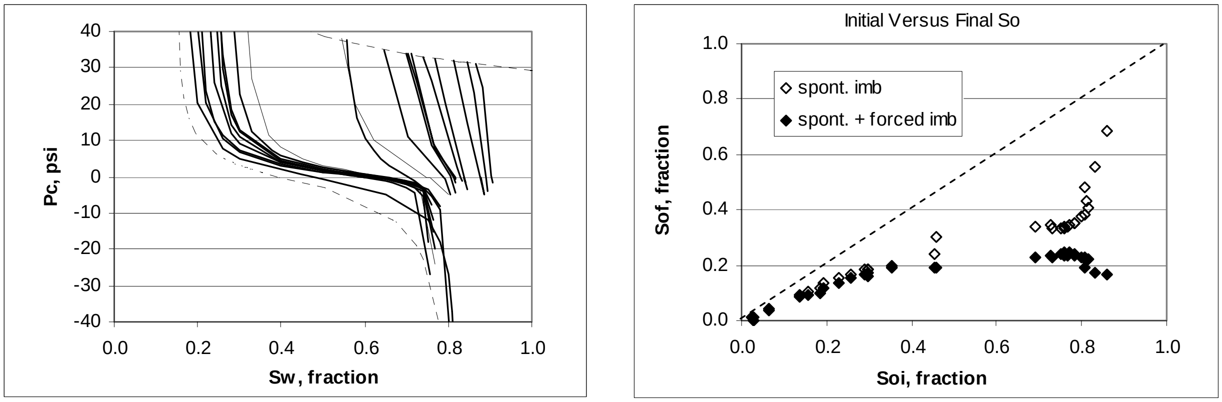
Figure 8. Test 2 saturation profiles (a-c), and (d) face Pc versus Sw data.

SUMMARY OF IMBIBITION RESULTS FROM BOTH TESTS

Saturation profile data from test 2 were used to estimate local imbibition Pc versus Sw curves using methods previously described. Results from both tests are shown in Figure 9(a). In Figure 9(b), final oil saturation is compared to initial oil saturation using local saturation data from both tests. The dashed reference line marks where Sof equals Soi.

DISCUSSION

Tests of this nature, and especially results such as those from Figure 9, may provide useful information about potential transition zone recovery, given that Swi will vary within a reservoir with height above the free-water level. Results of Figure 9(b) showing differences in trapping are interesting and bear further consideration. Optimum time to wait before changing Pc is something that could be explored in more depth. Another portion of the test that warrants further consideration is how best to interpret face Pc versus Sw during the early portion of the forced brine imbibition test, when oil displaced from the vicinity of the injection face must be produced through rock that is of higher brine saturation. The semi-dynamic method is patented by IFP. Permission to use the method would be required from IFP before it is put into commercial use.



(a) *(b)*

Figure 9. Imbibition results. (a) Pc versus Sw, (b) final versus initial oil saturation.

CONCLUSIONS

The following are some conclusions from this work:

1. The semi-dynamic Pc technique appears to be suitable for measuring full-cycle Pc versus saturation functions (primary drainage, spontaneous brine imbibition, forced brine imbibition, spontaneous oil imbibition, 2nd drainage).
2. Semi-dynamic measurements can be performed at reservoir temperature and pressure conditions using reservoir fluids, capturing effects of fluid interfacial tensions and wettability directly - without the need to scale laboratory results to reservoir conditions.
3. The entry pressure, or capillary pressure necessary to cause the non-wetting phase to invade the sample during primary drainage, was found to be related to pore phenomena rather than just a discontinuity at the core face.
4. When the core is homogeneous, parameters defined through curve fitting Pc versus saturation data for the injection face can be used to estimate Pc versus Sw functions elsewhere within the rock. In this manner, from one test, one can characterize Pc versus saturation and scanning loops for a broad range of saturation conditions that may be encountered in an oil reservoir within and above the transition zone.
5. One Pc curve beginning at Swr may be inadequate for describing Pc versus Sw where Swi is greater than Swr. Instead, many imbibition curves starting with different Swi may be needed to give a better picture of potential recovery. It is possible to gain such descriptions using an approach similar to that described in this report.

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