CAPILLARY PRESSURE CHARACTERISTICS OF CARBONATE RESERVOIRS: RELATIONSHIP BETWEEN DRAINAGE AND IMBIBITION CURVES

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1. ABSTRACT

Carbonate reservoirs are heterogeneous and often show mixed to oil-wet characteristics. Both heterogeneity and wettability have strong impact on capillary pressure (Pc) behaviour, which is controlled by the pore size distribution, the interfacial tension and interactions between rock and fluids as well as the saturation history. Capillary pressure data are essential input in both static and dynamic modelling of heterogeneous carbonate reservoirs. Drainage capillary pressure is generally used for initialising reservoir static models and calculating hydrocarbon initially in place. Imbibition capillary pressure is used to model secondary and tertiary recovery processes. The capillary pressure data in drainage, imbibition and secondary drainage cycles can also be used to infer the wettability of the reservoir.

The objective of this paper is to present the measurement and interpretation of capillary pressure data from a Cretaceous carbonate reservoir in the Middle East and a mathematical Pc model for use in reservoir simulation. The core analysis data have been collected from different geological facies of the carbonate reservoir covering different porosity and permeability ranges. We will also discuss the core cleaning procedure and its impact on measured capillary pressure curves, and the comparison of primary drainage capillary pressure curves obtained from oil-brine and Hg-air systems, in order to verify the effectiveness of core cleaning. The results lead to improved understanding of capillary pressure characteristics in carbonates in particular the contact angle distributions and hysteresis behaviour in drainage and imbibition. We present a method to derive imbibition capillary pressure curves from drainage for carbonates taking into account the effect of wettability and pore size distributions for both uni- and bi-modal pore systems.

2. INTRODUCTION

Several experimental techniques are available to measure capillary pressure (Pc) curves, both in drainage and imbibition cycles. Mercury injection is frequently used for primary drainage Pc measurements as the technique is relatively cheap, fast and requires relatively straightforward data interpretation. The measured data need to be converted to in situ reservoir conditions by taking into account the differences in interfacial tension and contact angle. The porous-plate equilibrium method is a reliable and accurate technique for measuring Pc in drainage and imbibition under representative reservoir conditions of fluids, pressure and temperature. The main drawback of this technique is the lengthy time required to reach capillary equilibrium, which renders the technique impractical for some field applications especially for tight and heterogeneous carbonates. The multi-speed centrifuge method can be used for both drainage and imbibition Pc measurements using representative reservoir fluids. Compared with the porous-plate equilibrium technique, the centrifuge method is relatively fast, clear advantage for studying tight carbonates. However, the design of the centrifuge experiment and the interpretation of the data are not straightforward and numerical simulation of centrifuge experiments is generally required to derive capillary data for tight carbonates.

The impact of capillary forces on multiphase flow and hydrocarbon recovery has been studied extensively in the literature. However, the focus has often been on the drainage capillary pressure curves, which are used for reservoir rock classification or rock typing and the initialization of reservoir static models. Several authors have discussed the complexity of getting a consistent set of drainage capillary pressure curves from the different techniques available (Masalmeh and Jing, 2004; Sallier and Hamon, 2005; Honarpour et al., 2004). It is clear that although the experimental procedures for measuring drainage Pc curves using different techniques and conversion for different fluid pairs are established, the results are still not conclusive and often conflicting data are encountered.

This paper is also extended to the measurements of imbibition Pc curves using the centrifuge technique. The impact of imbibition capillary pressure on waterflood sweep efficiency for heterogeneous oil-wet carbonates has been demonstrated (Masalmeh et al. 2003; Masalmeh et al. 2005). The secondary drainage capillary pressure also affects secondary and tertiary recovery processes. The complete capillary pressure curves covering primary drainage, imbibition and secondary drainage cycles on a rock-type basis are required as input for modeling secondary and tertiary reservoir recovery options for heterogeneous carbonate reservoirs.

3. EXPERIMENTAL PROCEDURE AND DATA INTERPRETATION

A comprehensive SCAL program was carried out on core samples taken from this carbonate field. The permeability varies over four orders of magnitudes ranging from less than a milliDarcy to more than a Darcy. The porosity of the field ranges between 10 to over 30%, however, most of the STOIIP is located in rock types with the porosity range between 20-30%. More than 250 samples have been taken for porosity/permeability measurements and a sample set about 80 samples was selected from different permeability and porosity ranges representing key geological facies for the subsequent SCAL program. The details of the SCAL program have been described previously (Masalmeh and Jing, 2004), the program includes rock characterization and CT scanning, NMR and Hg-air Pc, and thin sections and SEM analysis. The program also includes oil/water primary drainage capillary pressure measurements, aging the samples in crude oil at connate water under reservoir temperature for four weeks to restore wettability, spontaneous imbibition measurements followed by the imbibition and secondary drainage centrifuge experiments. The characteristics of some of the samples are shown in Table 1. The capillary pressure curves have been measured using mercury injection and centrifuge methods. The mercury injection method only provides primary drainage data to mimic equivalent water-wet systems. In the centrifuge experiment, the average saturation in a core plug is recorded at a set of centrifugal speeds and then a capillary pressure vs. saturation point is calculated at each speed. The capillary pressure can be calculated from the centrifuge raw data using either analytical (e.g. Forbes, 1997) or numerical interpretation (Maas and Schulte, 1997). In this paper the experimental data have been interpreted by numerical simulation using MoReS, the Shell in-house simulator, and compared against the conventional analytical techniques.

4. MERCURY INJECTION VS. CENTRIFUGE CAPILLARY PRESSURE CURVES

It is common practice to use Hg-air derived Pc curves to initialise static reservoir models and calculate oil in place. This is based on the assumption that Hg-air Pc curves can be converted to oil-water drainage Pc curves using the following equation:

$$Pc_R = Pc_L \frac{\sigma_R \cos(\theta)_R}{\sigma_L \cos(\theta)_L} \qquad (1)$$

where σ is the interfacial tension (IFT) between the two fluids, θ is the contact angle, subscript L refers to laboratory (Hg-air) and R refers to reservoir (oil-water) fluids. For detailed review and discussion on relating mercury injection data to equivalent oil-water systems, see Morrow and Melrose (1991) and the references therein.

There are several factors that can affect the Hg-air and oil-water drainage Pc curves and result in discrepancies. First, the interaction of rock and fluids (e.g., the existence of swelling clays) may cause the air/brine or oil/brine Pc curve to differ from the air/Hg derived Pc curves but this is generally not applicable to carbonate. Second, since the two measurements use different fluid systems, the contact angle (i.e., wettability) and its hysteresis may show different behaviours during the Pc experiments which, if not taken into account properly, may also complicate the conversion from mercury injection to oil-brine Pc measurements. Third, while the mercury-air experiment mimics strongly water-wet conditions, the water-oil experiment is affected by wettability in case the sample was not thoroughly cleaned, (O'Meara et al., 1992; Masalmeh and Jing, 2004; Sallier and Hamon, 2005). If the sample is not properly cleaned then the contact angle in the oil-water primary drainage can be significantly larger than zero and $\cos(\theta)$ can be significantly less than 1. Finally, since the two Pc measurements (Hg-air and oil-brine) are generally not performed on the same samples, geological heterogeneity may also cause discrepancy. In general the mercury injection experiment is either performed on the end trims of the plugs used in the water-oil experiments or, as in the case of this study, the mercury injection is performed on small samples drilled next to the SCAL plugs.

We observed previously (Masalmeh and Jing, 2004) that the capillary pressure measured using centrifuge and mercury injection methods showed a close match for some samples but there was a clear discrepancy for other samples. For those samples that did not show agreement the centrifuge oil-brine capillary pressure was always lower than the Hg-air derived Pc, i.e., at the same wetting phase saturation a lower capillary pressure was obtained in the oil-water system than in the converted Hg-air system. Since 2004 more SCAL data have been obtained and a more thorough comparison has been made between Hg-air and water-oil centrifuge capillary pressure curves on about 50 samples from different porosity and permeability classes of the carbonate reservoir. Figure 1 shows a comparison between mercury injection and centrifuge water-oil Pc curves for 16 samples. The Hg-air Pc curves are converted to water-oil using $\sigma\cos(\theta)$ of 367 and 23 mN/m for Hg-air and water-oil, respectively. Note that contact angle in this study refers to an effective contact angle for the respective saturation direction (Dumore and Schols, 1974). The data confirms the observation made earlier. For the samples shown in Figure 1.1-1.8, there is a very good match between the mercury injection and centrifuge primary drainage capillary pressure curves even for dual porosity rocks. This confirms that proper design and interpretation of centrifuge experiment can capture the impact of dual porosity on capillary pressure curves, and equation (1) can be used to convert mercury injection Pc to equivalent oil water Pc in primary drainage.

However, for samples shown in Figure 1.9 -1.16, there is clear discrepancy between the mercury injection and centrifuge Pc curves. The centrifuge water-oil curves were always lower than the corresponding mercury injection curves except when approaching low saturations. As shown in the figures, in some cases the water-oil Pc curve has the same shape as the mercury injection curve while for other samples the two curves have different shapes and the difference between them increases as the wetting phase saturation decreases.

5. EFFECT OF CORE CLEANING

To investigate the cause of the difference between mercury injection and oil-brine centrifuge Pc curves, we considered the possible factors mentioned above, i.e., rock fluid interaction as a function of pore size, different fluid pairs, different samples used in the measurements or wettability effects due to ineffective cleaning.

The fact that a very good agreement between mercury injection and water-oil drainage Pc curve was obtained for the relatively high porosity samples rules out the wettability effect due to aging by the crude oil, as the aging only occurs after the oil has entered the pores. The pores that are not yet accessed by the crude oil remain water-wet hence the entry pressure for those pores will not be affected by using crude oil in the experiment, see Masalmeh (2002).

The Pc discrepancies shown in Figure 1.9-1.16 can be explained by wettability due to in-effective cleaning. The cleaning method used at the early phase of the study (referred to as cleaning method (1) in the rest of the paper) is as follows: the plugs were cleaned by hot Soxhlet extraction using toluene followed by azeotropic mixture (84 vol% chloroform, 14.2 vol% methanol and 1.8 vol% water). Usually the toluene extraction continues for 2-3 weeks or more until the effluent becomes transparent. Then the azeotropic mixture is used for another 2-3 weeks or longer until the effluent becomes transparent again. Figure 1 shows that for some samples not all the pores have been thoroughly cleaned to achieve water-wet conditions e.g., cleaning may be less effective for smaller pores due to solvent accessibility and slowness in the diffusion process. The data also shows that ineffective cleaning has two effects on the Pc curves: it changes the shape of the curve (due to different cos(θ)) and it shifts the Pc curve to the right due to water trapping (Masalmeh, 2001 and 2002). Therefore, the difference between the water-oil capillary pressure and the mercury injection data can be used to check the efficiency of the cleaning method for the different pores. As a result of ineffective cleaning, using the water-oil primary drainage Pc to initialize the static model leads to significant difference in initial oil in place and its distribution.

The effect of cleaning on water-oil drainage Pc can be shown as follows:

1- The measured water saturation is stretched to the left to arrive at the corrected Pc curve Pc= f(S_w') using the following equation

$$S_w' = S_w - S_{wtrap}$$

$$S_{wtrap} = S_{wtrap}^{\max} * \frac{(1 - S_w)}{(S_w^{\max} - S_{wc})} \qquad (2)$$

where $S_w^{\max}$ =1 for primary drainage, $S_{wtrap}^{\max}$ is the maximum trapped water which is the difference between connate water from the Hg-air Pc and that from the centrifuge. This trapped water S_{wtrap} approaches zero if the samples are properly cleaned to reach water-wet condition before oil-brine primary drainage experiments.

2- Calculate the contact angle from the difference between the two Pc curves

$$\cos(\theta)_{w-o} = \frac{P_c^{(w-o)_{meas}}}{P_c^{(w-o)_{Hg-air}}} \qquad (3)$$

where $P_c^{(w-o)_{meas}}$ is the measured water-oil Pc curve and $P_c^{(w-o)_{Hg-air}}$ is the equivalent water-oil Pc curve calculated from the mercury injection data using equation 1. Figure 2 shows the measured capillary pressure curves compared with the corrected ones using the above procedure. For the example shown in Figure 2, $S_{wtrap}^{\max}$ =10% and a contact angle of 55 degree was calculated to match the water-oil drainage Pc with the mercury injection data. A similar procedure has been applied on all the samples which experienced a mismatch between centrifuge and mercury injection data. The derived contact angles are shown in Figure 3. The results demonstrate that comparing water-oil drainage Pc and the mercury injection data can give information about the wetting status of the plug after cleaning. In some cases a constant contact angle was observed and in other cases the contact angle increased for the small pores as they tend to be more difficult to clean. Since cleaning was found to be the reason for the mismatch between the water-oil and mercury injection data, another cleaning method was investigated which is referred to as cleaning method (2) (hot Soxhlett extraction followed by flow-through cleaning): The plugs were first cleaned using the above cleaning method (1) and then mounted in a Hassler core holder at a confining pressure of 30 bars. The plugs were alternately flooded with 100% chloroform at a backpressure of 5 bars. Approximately 3 pore volumes of chloroform was flooded and the core was left to soak overnight. The procedure was repeated again with the next chloroform flood. In total more than 15 pore volumes of chloroform were used until the effluent became colorless.

The efficiency of the new cleaning method has been investigated. Three samples that showed the most difference between water-oil and mercury injection data were selected to go through cleaning method (2) and the water-oil drainage Pc curve was measured using the centrifuge. Figure 4 compares the new water-oil Pc curve measured on one of the samples with the mercury injection data. The figure shows an excellent match which demonstrates that the new cleaning method is adequate.

6. IMBIBITION CAPILLARY PRESSURE MEASUREMENTS

Imbibition Pc curves were measured on 32 samples from this reservoir. No spontaneous imbibition of water was observed on all the samples following aging with crude oil and connate water at reservoir temperature. As discussed in the previous section some of the plugs were cleaned by method (1) and as a result the water-oil primary drainage Pc curves were affected. Since the plugs did not start from strongly water-wet conditions during primary drainage (see Figure 3), it raised a question concerning the effect of this ineffective cleaning on the imbibition Pc curves. Could the wetting state after aging be significantly affected thus resulting in a more oil-wet rock? We know from experience that aging the sample for longer time (longer than 4-6 weeks) does not result in a stronger oil-wet system for carbonate reservoirs. Therefore, starting at a weakly water-wet condition may not result in a more strongly oil-wet system if no external factors are involved other than the adsorption of organic matter from the crude.

To investigate the impact of ineffective cleaning on imbibition Pc curves, we have studied the imbibition Pc curves to see if any correlation between the negative Pc curves and the poor cleaning could be found. No such correlation was found, as higher contact angle during primary drainage did not correlate with higher contact angle during imbibition. In addition, imbibition capillary pressure curves were repeated on three samples that had gone through the further cleaning method (2). Figure 5 shows the imbibition Pc after the cleaning methods (1) and (2). The data show no difference between the two sets of imbibition Pc curves. The next section compares the measured imbibition Pc with the measured drainage Pc curves (water-oil centrifuge and mercury injection) in detail.

7. WATER-OIL IMBIBITION VS. PRIMARY DRAINAGE TO VERIFY CLEANING

As no spontaneous imbibition was observed, the water displacing oil process during imbibition followed the same pore-filling sequence as in the primary drainage experiment, i.e., non-wetting phase enters the largest pores first. Therefore, based on a conceptual pore-space model for the oil-wetting system, imbibition and drainage should be a mirror image of each other if the $\sigma\cos(\theta)$ and trapping are accounted for. The drainage Pc can be calculated from the measured imbibition Pc as follows:

1- Shift the water saturation to start from Sw=0

$$S_w^{imb} = S_w - S_{wc}$$

2- For the primary drainage the experiment starts at Sw=1, the water saturation of the derived drainage Pc is then given as

$$S_w^{dra} = 1 - S_w^{imb} = 1 - S_w + S_{wc}$$

3- During imbibition oil trapping takes place and the amount of this trapping is a function of the initial oil saturation. Therefore to span the whole saturation range the trapped oil at each saturation point should be accounted for (i.e., subtracted from the drainage water saturation). Moreover, in case the imbibition Pc measurement started from a water saturation that is higher than the connate water due to trapping, then this difference between connate water and water saturation at the end of drainage water-oil experiment should also be taken into account. The water saturation of the drainage is then given as follows:

$$S_w^{dra} = 1 - S_w + S_{wc} + S_{wtrap}(S_w) - S_{otrap}(S_o) \qquad (4)$$

where the trapped volumes S_{otrap} and S_{wtrap} are either derived experimentally or from correlations. In this study we used a linear correlation:

$$S_{wtrap}(S_w) = S_{wtrap}^{\max} * \frac{1 - S_w - S_{or}}{1 - S_{wc} - S_{or}} \qquad (5)$$

$$S_{otrap}(S_o) = S_{otrap}^{\max} * \frac{S_w - S_{wc}}{1 - S_{wc} - S_{or}} \qquad (6)$$

$$S_{wtrap}^{\max} = S_{wi} - S_{wc}$$

where S_{wi} is the initial water saturation at the end of the primary centrifuge experiment and $S_{otrap}^{\max}$ is the maximum S_{or} measured at the end of imbibition.

4- The drainage Pc is then given by

$$P_c^{dra}(S_w) = P_c^{imb}(1 - S_w + S_{wc} + S_{wtrap}(S_w) - S_{otrap}(S_o)) * \frac{\cos(\theta_{dra})}{\cos(\theta_{imb})} \qquad (7)$$

To test the impact of cleaning on imbibition Pc curve we started with the sample that showed the largest difference between Hg-air and water-oil drainage Pc (Figure 6). For this sample a water advancing contact angle of 110 and a primary drainage contact angle of 0 was used. Using a range of low drainage contact angles from 20 to 30 had very little effect on the calculated imbibition contact angles. As shown in the figure, the calculated Pc curve matches the measured Hg-air drainage Pc curve. This indicates that the ineffective core cleaning did not affect the imbibition capillary pressure curves. Note that for this sample the water-oil drainage Pc curve affected by insufficient cleaning cannot be obtained from converting the imbibition curve for this sample as it has a different shape compared to the Hg-air drainage curve.

The same procedure described above was repeated on all the samples and the results of the calculated and measured drainage Pc curves are shown in Figure 7 for four different samples. For all uni-modal plugs, the calculated and measured drainage Pc matched very well with a consistent contact angle range of 108-111 for most of the samples as shown in Table 1. For the dual porosity system, the imbibition Pc curve could not be converted to the drainage Pc curve using a constant contact angle. All the dual porosity samples showed a consistent behavior where the large pores had higher contact angles than the small pores, see Table 1. This indicates that the large pore system became more oil-wet than the small pore system for the samples with bi-modal pore size distribution. Further research is needed to fully understand the underlying reason for the observed contact angle distribution in carbonates.

8. DERIVING IMBIBITION P_C FROM PRIMARY DRAINAGE P_C

The procedure described above can also be used to calculate the imbibition Pc curve from the measured drainage Pc curve for all cases where water does not spontaneously imbibe. The procedure is similar to that discussed in Masalmeh (2001) where the imbibition Pc curve is given as follows:

$$P_c^{imb}(S_w) = P_c^{dra}(1 - S_w + S_{wc} + S_{wtrap} - S_{otrap}) * \frac{\cos(\theta_{imb})}{\cos(\theta_{dra})} \quad (8)$$

where S_{wtrap} represents either trapped water during drainage or the difference between the connate water and the average water saturation where the imbibition experiments starts and both can be zero. Both S_{wtrap} and S_{otrap} should be calculated using similar procedure described in previous section. Figure 8 shows the calculated and measured imbibition Pc curves. In order to calculate the imbibition Pc curves it is necessary to have an estimate on the contact angle hysteresis and oil trapping in imbibition which can be obtained from a limited number of measurements on core materials taken from the same reservoir.

9. CAPILLARY PRESSURE MODEL: DRAINAGE AND IMBIBITION P_C CURVES

Figure 9 shows drainage and imbibition Pc curves measured on 30 samples (see Table 1 for samples characteristics). The data are measured on samples from different permeability and porosity classes and different rock textures. It is beyond the scope of this paper to discuss static/dynamic rock typing combining SCAL data with thin sections and SEM. Here we will only present analytical equations that can be used to match Pc curves measured on all the samples used in this study.

The measured drainage (Pcd) and imbibition (Pci) capillary pressure curves can be fitted using the following mathematical formulae given by equations (9-10).

$$P_c^{dra} = \frac{c_{wd}}{\left[\frac{S_w - S_{wc}}{1 - S_{wc}}\right]^{a_{wd}}} + \frac{c_{od}}{\left[\frac{1 - S_w - S_{or}}{1 - S_{or}}\right]^{a_{od}}} + b_d\,(S_{w\_cutoff}^{dra} - S_w) \qquad (9)$$

$$P_c^{imb} = \frac{c_{wi}}{\left[\frac{S_w - S_{wc}}{1 - S_{wc}}\right]^{a_{wi}}} + \frac{c_{oi}}{\left[\frac{1 - S_w - S_{or}}{1 - S_{or}}\right]^{a_{oi}}} + b_i\,(S_{w\_cutoff}^{imb} - S_w) \qquad (10)$$

where b_d is zero for water saturation higher than $S_{w\_cutoff}^{dra}$ and b_i is zero for water saturation less than $S_{w\_cutoff}^{imb}$ and c_{wd}, c_{od}, a_{wd}, a_{od}, b_d, c_{wi}, c_{oi}, a_{wi}, a_{oi} and b_i are fitting parameters used to fit experimental data. The formulae are an extension of the power-law form first introduced by Brooks and Corey (1966) (first term) and then extended by Skjaeveland et al. (1998) (second term) for mixed-wet reservoir rocks. We introduce the third term in the equations to describe different shapes of capillary pressure curves (e.g., for bi-modal pore size distributions) as the first two terms alone could not match the experimental data particularly for samples of dual porosity or samples of a wide range of pore size distributions. This capillary pressure function offers flexibility for generating a wide range of curves of different shapes and it honors experimental data e.g., in the asymptotic values relating to the threshold capillary pressure, and the connate water saturation at a significant distance above free-water level. In addition the same Swc and Sor can be used in both the capillary pressure function and the relative permeability function, ensuring consistency. Figure 10 shows both measured and model generated Pc curves for three samples of different pore size distribution. The Pc curves shown in Figure 10a can be generated assigning zero value for b_d and b_i, however, the curves shown in Figure 10b-c can only be generated with the third term included. This is found to be the case for all heterogeneous bi-modal samples and for samples of wide pore size distributions.

10. CONCLUSIONS

1. The primary drainage Pc curves measured using two different methods (mercury injection vs. centrifuge oil-brine) have been compared for the same plugs from different porosity and permeability ranges. Close agreement between the Pc curves has been observed if the core samples are thoroughly cleaned.

2. Water-oil primary drainage Pc curves can be significantly affected by ineffective core cleaning which, if not properly recognized and reconciled against Hg-air Pc curves, can have severe impact on STOIIP calculations especially for the low permeability reservoirs.

3. Comparing the primary drainage Pc curves from water-oil centrifuge and Hg-air is used to check the effectiveness of the cleaning methods which gives a quantitative evaluation of which part of the pore system was cleaned and which part was not, as reflected in the calculated contact angle distributions.

4. Despite the significant impact of cleaning on primary drainage water-oil Pc curves, it seems to have little or no impact on imbibition Pc curves if no external factors other than crude oil contributed to wettability alteration.

5. We propose a procedure to relate imbibition capillary pressure with primary drainage for both uni-modal and bi-modal pore size distribution taking into account the effect of wettability in carbonates. Based on limited SCAL experiments, it's possible to generate the contact angle distributions for imbibition and oil trapping behavior, and convert the primary drainage Pc curves to imbibition Pc curves taking into account the effect of wettability.

6. We present a new capillary pressure model for both drainage and imbibition cycles to capture the complexity of the carbonate pore structure for different wetting systems. This model can be calibrated by SCAL measurements and allows easy implementation in reservoir simulations.

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Table 1: Characteristics of samples used in the study

sample id	depth (ft)	phi %	K_air (md)	Kw (md)	K_brine/K_air	Contact Angle	
						small pore system*	Large pore system **
s17	8593.40	31.6	400	348	0.87		
s18a	8593.80	30.5	50.0	36.9	0.74	101	122
s18b	8593.90	28.9	23.5	15.2	0.65	107	122
s19b	8594.90	30.5	45.7	37.4	0.82	98	120
s19d	8595.30	29.2	28.0	25.3	0.90	108	
s24b	8599.50	26.3	14.0	12.2	0.87	100	118
s41	8617.10	24.2	22.6	19.9	0.88	102	120
s42	8617.80	24.9	17.2	13.6	0.79	98	120
s44a	8619.50	27.3	14.0	13.5	0.96	111	
s46b	8622.20	30.2	73.0	53.0	0.73	103	120
s46c	8622.35	31.0	59.4	52.7	0.89	102	126
s47	8622.85	31.1	103	78.1	0.76	104	120
s51	8626.90	29.8	1010	834	0.83		
s55b	8631.15	28.4	128	106	0.83		
s60	8635.77	30.6	18.0	14.7	0.82	110	
s61	8636.65	30.4	14.0	10.4	0.74	111	
s82	8658.30	28.0	7.3	4.7	0.65	107	
s83	8659.35	28.1	6.9	5.6	0.81	108	
s85b	8660.93	29.7	8.2	7.6	0.93	108	
s85d	8661.43	28.3	5.5	3.5	0.64	108	
s86a	8661.70	29.0	6.6	4.2	0.64	108	
s89a	8664.50	22.8	9.4	5.9	0.63	104	
s89c	8665.25	22.9	8.6	7.9	0.92	101	
s90b	8665.85	20.8	11.1	9.3	0.84	110	
s90c	8666.10	20.1	1.7	1.4	0.82	113	
s91a	8666.90	16.4	0.6	0.5	0.79	111	
s91b	8667.35	21.6	2.0	1.9	0.95	113	
s94a	8669.60	26.1	3.7	2.5	0.68	115	
s94c	8670.00	24.1	4.9	3.5	0.73	110	
s95	8670.50	28.0	4.7	3.6	0.77	120	
s126	8702.15	29.1	5.5	3.4	0.61	111	
s134	8709.80	30.2	4.6	2.6	0.57	110	

* for uni-modal pore systems or the smaller pore population in the bi-modal systems.
** for dual porosity systems

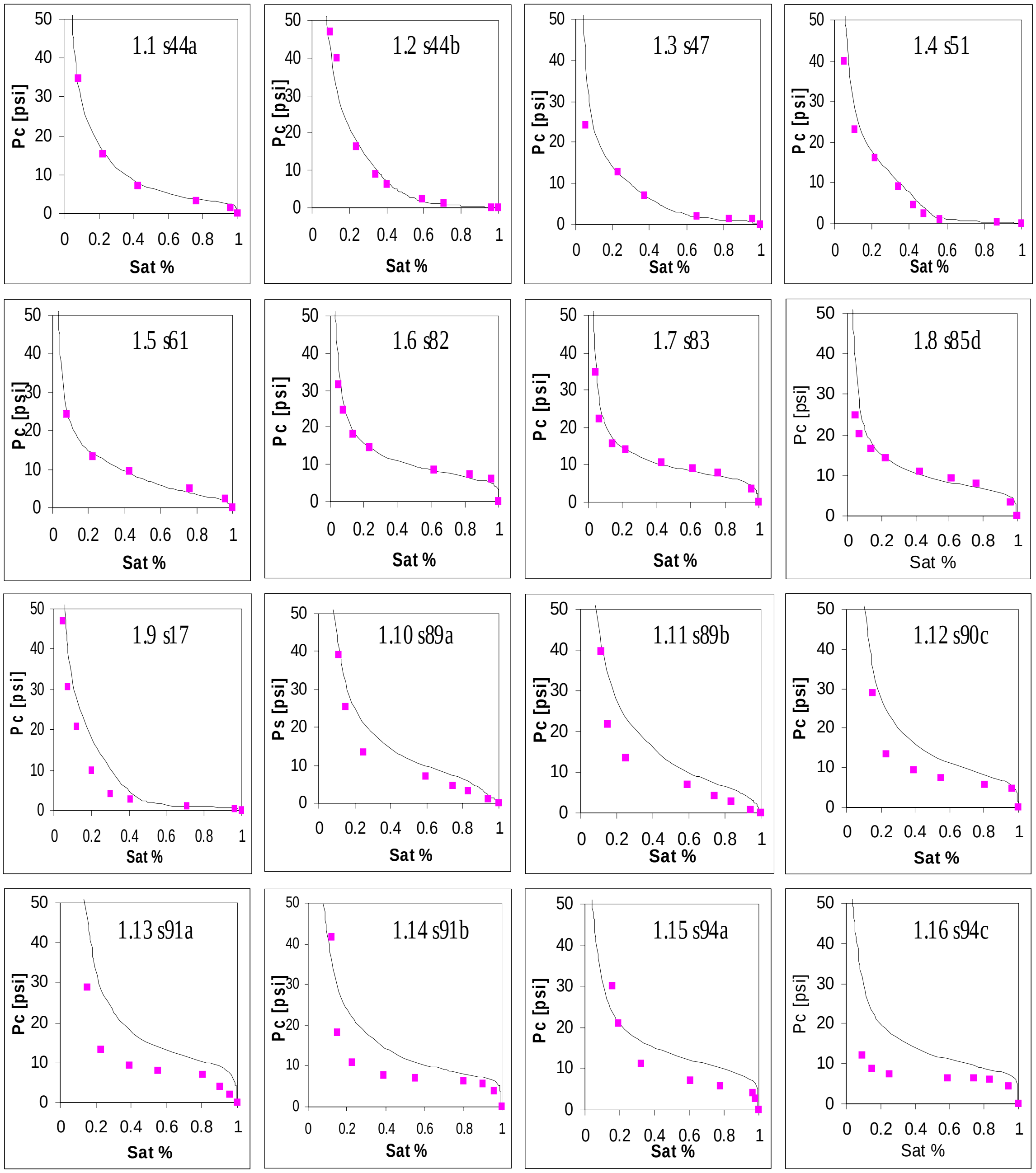

Figure 1: Comparing centrifuge oil-water Pc (symbols) to Hg-air Pc (lines) curves for 16 samples, a close match is shown in Figure 1.1-1.8 while significant difference is found in Figures 1.9-1.16.

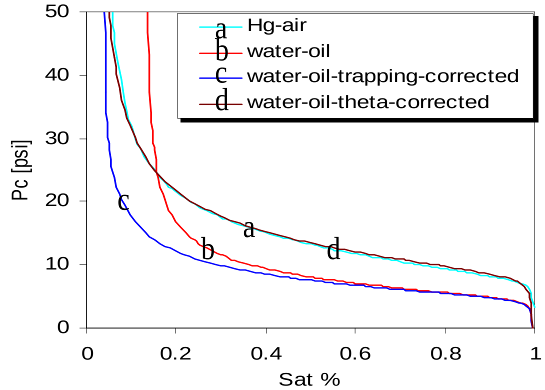

Figure 2: Impact of cleaning on water-oil drainage Pc curve, s94a.

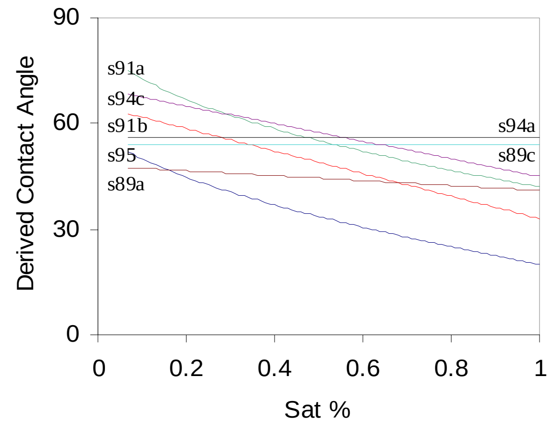

Figure 3: Derived contact angle to correct for impact of cleaning on water-oil drainage Pc curves for 7 samples.

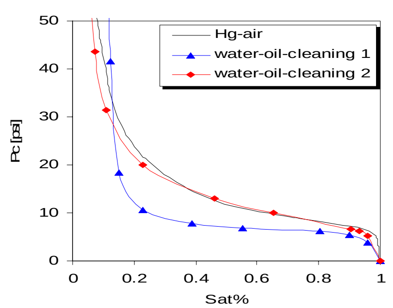

Figure 4: Drainage Pc curve measured on sample s91b following two different cleaning methods.

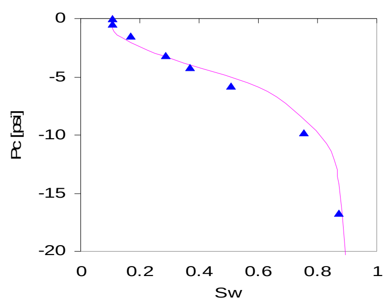

Figure 5: Imbibition water-oil Pc measured on sample s91b to check impact of cleaning on imbibition data (symbols = imbibition after clean (1); line = imbibition after clean (2).

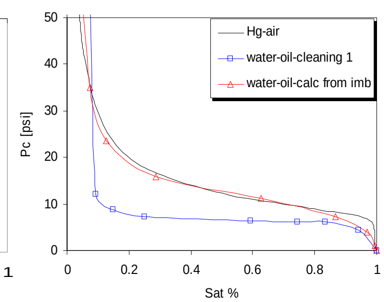

Figure 6: Calculate drainage Pc from imbibition Pc curve. Close match with Hg-air drainage Pc further demonstrates that cleaning did not affect imbibition data.

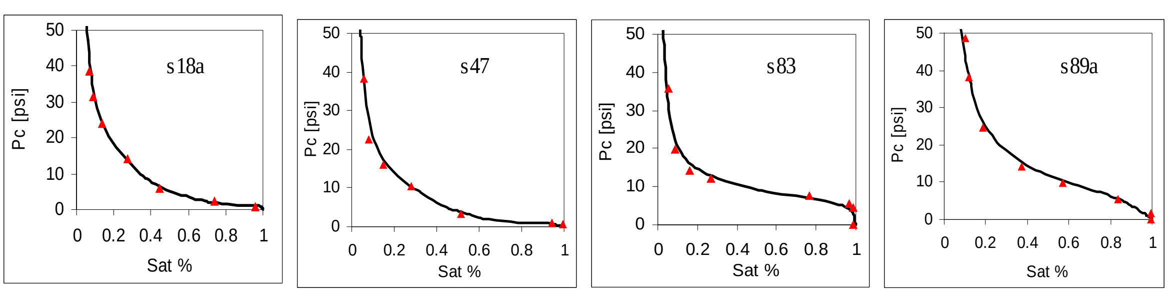

Figure 7: Comparison of measured (solid line) and calculated drainage Pc curves (symbols) .

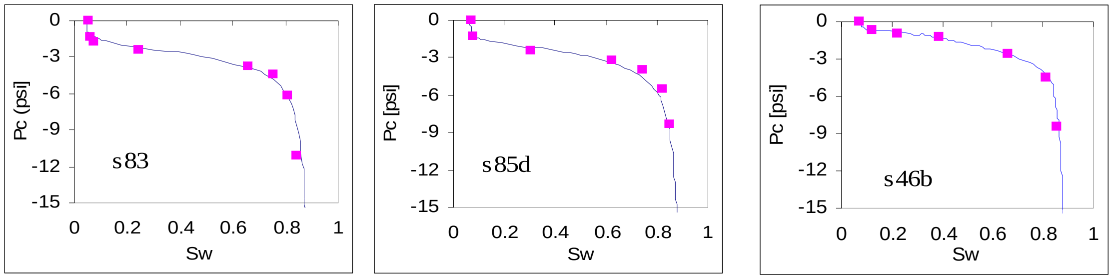

Figure 8: Comparison of measured (symbols line) and calculated (solid lines)

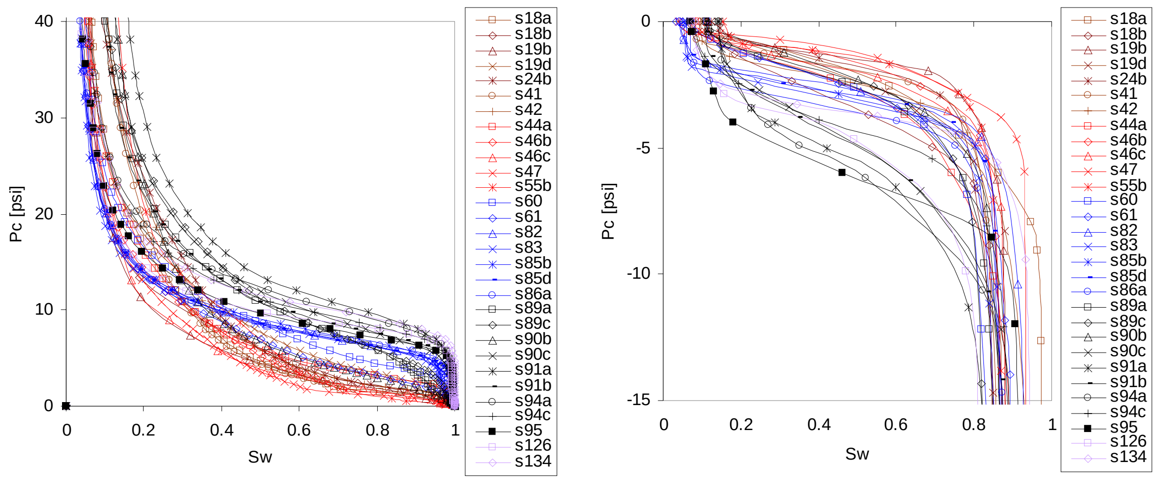

Figure 9: a) Drainage Pc curves and b) imbibition Pc curves measured on 30 samples.

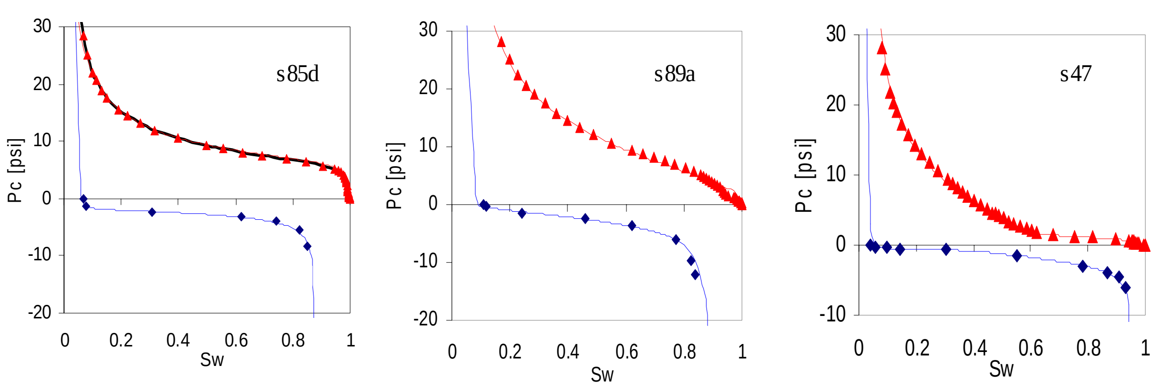

Figure 10: Model (lines) and measured (symbols) Pc bounding curves of a) low permeabilitye sample of uniform pore size distribution, b) low permeability sample of wide range of pore size distribution and c) high permeability sample of dual porosity system.