COMPARISON OF CAPILLARY PRESSURE MEASUREMENTS AT VARIOUS WETTABILITIES USING THE DIRECT MEASUREMENT OF SATURATION METHOD AND CONVENTIONAL CENTRIFUGE TECHNIQUES

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ABSTRACT

Correct measurements of the capillary pressure, as a function of wettability, are crucial to understand oil recovery mechanisms and improve upon oil recovery. Capillary pressure is one of the most important input parameters necessary for numerical simulations and extensive efforts have been dedicated to the improvement of the experimental measurements of capillary pressure.

Conventional centrifuge techniques that are used to measure capillary pressure are reliant upon averaged material balance data to calculate the in-situ fluid saturations. Heterogeneities and capillary end effects may to an unknown degree influence the saturation distributions. An analysis technique which would directly incorporate local in-situ saturations, such as provided by the Direct Measurement of Saturation method (DMS), would be a significant improvement in special core analysis technology.

The objective of this work was to use the DMS method to obtain experimental capillary pressure scanning-curves for chalk at various wettability conditions ranging from strongly-water-wet to nearly-neutral-wet. These results would then be compared with the results obtained from a conventional centrifuge technique.

The wettability of the cores was altered using a reproducible and stable aging technique. Aging core plugs to a less-water-wet state, significantly reduced the spontaneous brine imbibition rate and endpoint. The total movable oil generally increased slightly with reduced water wettability, however, this was at the cost of higher differential pressures being required. Reduced water wettability also lowered the drainage threshold pressure.

Utilizing MRI-imaging and an oil phase that solidifies at room temperature, the Pc-scanning curves were obtained at only one centrifuge rotational speed to obtain the drainage curve and one for both the positive and negative portions of the capillary pressure imbibition curve. The positive capillary pressure imbibition curve is generally not obtainable for high capillary rock such as chalk. No mathematical framework, which may be biased by the user, is necessary to refine the production data from the experiment.

The data recorded in this study were compared to capillary pressure curves obtained by conventional centrifuge techniques. The results corroborated impacts of wettability with respect to changes in the shape of the Pc-curves and values of residual oil saturations. Shift in end-point saturations for spontaneous and forced imbibition also demonstrated consistent results at the different wettability conditions investigated. Variations in wettability, hence variations in capillary pressure, were also observed within each core sample.

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INTRODUCTION

This work concentrates on improving the confidence in measuring capillary pressure scanning curves. The motivation was to improve the understanding of the recovery mechanisms in fractured chalk reservoirs and to increase the reliability of input parameters for numerical simulations of such oil reservoirs.

Hydrocarbon recovery results from a competition between capillary and viscous forces and gravity. In most chalk reservoirs, spontaneous imbibition is the dominant recovery mechanism. This dominance is due to narrow pore throats, more or less water-wet conditions, and the low permeability of this rock. Essentially all reservoirs are affected by the interplay between capillary pressure and relative permeability at various wettability conditions, however, fractured chalk reservoirs with very low matrix permeability are in particular sensitive to these interactions. The impact of these parameters for different wettability conditions, appear to be significant to the understanding of the oil recovery mechanisms in these reservoirs.

Wettability is a major factor controlling the microscopic location, flow, and distribution of fluids within a reservoir. In this study, measurements of capillary pressure in chalk core plugs at strongly-water-wet, moderately-water-wet, and nearly-neutral-wet conditions have been obtained. Selective alteration of wettability, by aging core plugs containing water, in crude oil at elevated temperature, reproducibly yielded chalk plugs at the desired wettability conditions. Capillary pressure curves were then obtained, at various wettability conditions, employing both a conventional centrifuge technique and the Direct Measurement of Saturation method. The latter technique employed in-situ saturation measurements to obtain the capillary pressure curves, and was also capable of obtaining the positive part of the capillary pressure imbibition curve which is generally not obtainable for high capillary rock such as chalk. This paper compares the results of the capillary pressure measurements obtained by these two techniques.

The methods most often used to measure wettability in core plugs are the Amott test (Ref. 1) and the USBM-method (Ref. 2). In this paper, the Amott wettability index for water and the imbibition characteristics, composed of the imbibition rate, induction time, and the imbibition endpoint values, were used to characterize the wettability of the cores. Previous work (Ref. 3,4) has reported on non-uniform wettability distributions created under unfavorable conditions during static wettability alterations. In this paper, NMR-imaging investigates whether dynamic flushing during aging provides more uniform wettability distributions and thus improved capillary pressure curves.

OBJECTIVE

The objective of this work was to evaluate the capillary pressure curves, at various wettabilities, obtained by conventional centrifuge techniques and compared to the Direct Measurement of Saturation method results.

The motivation was to improve the confidence in the determination of the capillary pressure curves, in this case, for a high capillary chalk. In particular, the positive portion of the capillary imbibition curve was of interest due to the significance of the spontaneous imbibition behavior sometimes observed in water-wet chalk reservoirs. As conventional centrifuge techniques are widely used by the service companies, it is valuable to validate conventional Pc-data by a more sophisticated method of obtaining Pc-data, in particular, the entire Pc-scanning curves.

A secondary objective was to evaluate the wettability alteration technique used to obtain the different wettability conditions in chalk. In particular, the uniformity of the wettability distribution was of interest.

EXPERIMENTAL

Rock Characteristics. The Rørdal chalk used in this study was obtained from the Portland cement factory in Ålborg, Denmark. The rock formation is of Maastrichtian age and consists mainly of coccolith deposits (Ref. 5) with about 99% calcite and 1% quartz. All the core samples were drilled in the same direction from large chalk blocks to obtain analogous material and to ensure the same orientation relative to bedding planes or laminations. A total of 19 chalk core plugs were dried at 60°C for 3 days, vacuum evacuated to 10 mBar and saturated with degassed brine. Porosity was determined from bulk measurements and difference in weights before and after saturation. The cores were stored in brine for 5-10 days to reach ionic equilibrium with the rock constituents. Core permeability to brine was measured by using a biaxial core holder with a slight confinement pressure. Due to the fragile nature of the chalk material, net confining pressure was less than 10 bar (147 psi), to keep the cores in the elastic compression region. The brine permeability for the core plugs was around 4mD and the porosity ca. 45%. A summary of the core plug data is found in Table 1.

11 core plugs were selected for measurements of capillary pressure curves using a conventional centrifuge technique. The results from these measurements have been reported, Ref. 6. A summary of the experimental schedule and results are found in Table 2.

The remaining 8 core plugs were selected for capillary pressure measurements using the Direct Measurements of Saturation method. A summary of the experimental schedule and results are found in Table 3.

Fluid Characteristics. The composition of the brine was 5 wt% NaCl + 3.8 wt% $CaCl_2$. $CaCl_2$ was added to the brine to minimize dissolution of the chalk. Sodium azide, 0.01 wt%, was added to prevent bacterial growth. The density and viscosity of the brine were 1.05 g/cm^3 and 1.09 cP at 20°C, respectively. The brine was filtered through a 0.45 μm paper filter membrane. The salts used in the brine were: NaCl with a purity of 99.5%, $CaCl_2$ with a purity of 99.5%. Sodium azide had a purity of 99.5%. The materials were used as received.

A stock tank oil from a North Sea chalk reservoir was used as the crude oil. Because of possible wax problems with this crude oil, the temperature applied during aging was maintained at 90°C as long as crude oil was in the rock. Crude oil composition was measured to 0.90wt% asphaltenes, 53wt% saturated hydrocarbons, 35wt% aromatics and 12wt% nitrogen-sulphur-oxygen containing components (NSO). The acid number was measured at 0.09 and the base number at 1.79. The following procedure for preparing the crude oil was used: The barrel containing crude oil was shaken and the crude oil was tapped from the center of the barrel, and stored at 20°C in closed containers. It was then in-line filtered through a 3cm, 1½" diameter Rørdal chalk core plug, at 90ºC before it was used to oil flood the samples to initial water saturation. Physical properties of the fluids are summarized in Table 4.

Alteration of Wettability: To establish the initial water saturation, $S_{wi,}$ the plugs were alternately oil flooded from both ends. The initial water saturation used in this study was 25%PV, because the Pc-curves should be used for input to numerical simulations of block experiments performed at S_{wi} = 25%, Ref.7, 8. Oil flooding at 2 bar/cm pressure differential gave initial water saturations close to 25% for the 11 core samples selected for capillary pressure measurements using the conventional centrifuge technique. These core plugs were aged at S_{wi} in closed, crude-oil-filled containers at 90°C for different lengths of time. In Ref. 3 and 4 we reported that a non-uniform wettability distribution was recorded by NMR-imaging for some of these core plugs, when extensive aging was performed on core plugs submerged in crude oil. An improved aging technique applying continuous flooding of crude oil during aging has been shown to establish more uniform wettability distributions (Ref. 4).

Core plug preparations for Magnetic Resonance Imaging and the DMS method: In the present study, the improved aging technique was used for the 8 core plugs selected for the capillary pressure measurements by the DMS method. All aging was performed with duplicate sets of plugs to determine the experimental repeatability. Core weights were measured both before and after aging to determine whether any water had evaporated.

The core plugs to be used at strongly-water-wet conditions, core plugs PH-9 and PH-10 from the experimental set# 1 (see Table 3), were oil flooded at elevated temperature using octadecane. No aging was conducted on the cores PH-9 and PH-10.

Oil floods of the core plugs to be used at less-water-wet conditions, core plugs PH-3 and PH-7 from set# 1 and the entire set# 2, were drained using the stock tank crude oil at 90°C in a heated pressure vessel. By using different lengths of time of flushing (36 hours and 72 hours) during the aging process, different wettability conditions were obtained. The wettability was indicated by the Amott-Harvey Index to water (I_w): strongly-water-wet (I_w=1.0), moderately-water-wet (I_w=0.6) and nearly-neutral-wet (I_w=0.3). During the aging process while applying continuous oil flow at 90^0C (194F), the oil flow rate was held constant at a throughput of 2PV/day with a confining pressure at 5 bars (73.5psi). Fig. 1 shows the experimental set-up for the continuous oilflood during aging. After the aging, the cores were flushed with 5PV decahydronaphthalene (decalin) (flow rate: 80 ml/h) and 5PV decane (flow rate: 100 ml/h) at 90^0C, before they were slowly cooled to room temperature. Decalin was used as a buffer between the crude oil and the decane, when crude oil was exchanged with decane, to avoid precipitation of asphaltenes which may occur if the reservoir crude oil was first contacted by the refined oil. Decane has been shown not to alter wettability in chalk (Ref. 9). Decalin had an isotopic purity of >98 % and the decane had an isotopic purity of >95 %. Both hydrocarbons were used as received. The physical properties of the oils are summarized in Table 4.

After aging, oil recovery by spontaneous imbibition at room temperature and then followed by a waterflood, was used to produce the Amott water index for the core plugs included in experimental set# 2. The plugs containing brine and decane were cooled to room temperature for at least 12 hours and then placed in graduated imbibition cells. Produced oil as a function of time was measured volumetrically. Before each measurement, the imbibition cell was gently shaken to displace the oil drops adhered to the cell and core surface. When the cores stopped producing oil they were water flooded at high rates (34 cc/hr) to drive them to a viscous endpoint.

The Amott test was also carried out for the core plugs in experimental set#1, but this test was performed after the centrifugation. After centrifugation, the core plugs in experimental set#1 were oil flooded with decane, to replace the octadecane, at elevated temperature to Swi=25% and the Amott index to water was produced at room temperature.

A consistent change in wettability towards a less-water-wet state was observed for all core plugs with increased aging time. For the 36 hours aging process, the Amott-Harvey index to water, I_w, was observed to approximate the range 0.7-0.8, and for 72 hours aging, I_w was approximately 0.5-0.6. Table 3 shows the I_w for the three cores aged for 72 hours and the corresponding data for the three cores aged for 36 hours.

MRI tomography was used as the high spatial resolution imaging technique required for the DMS method. After establishing the desired wettability, decane was replaced by octadecane at 45°C at S_{wi}. The cores were then cooled to room temperature. Octadecane solidifies at 27°C, hence the oil phase could now be considered immobile.

The cores were subjected to NMR (Nuclear Magnetic Resonance) spectroscopy, to check the efficiency of the octadecane-decane displacements. Plotting response vs. T_2 of the NMR analysis made it possible to calculate the saturation of each phase. Results for a typical core plug is shown in Fig. 2.

The core plugs were imaged by MRI to obtain the initial water saturation distribution, before centrifuging for DMS. A free water level around the lower part of the cores was established with octadecane above. The cores were then spun in a centrifuge at 3300 RPM for 1 week. The free water level, determining the position of zero capillary pressure, was essentially constant because of a large volume of water in contact with the plug. By increasing the temperature after the centrifuge reached the desired rotational speed the oil phase became mobile with both spontaneous and forced imbibition starting upon exceeding the 27°C melting point of octadecane. Spontaneous imbibition occurred in the area above the free water level, forced imbibition in the part of the core below the free water level.

After 1 week of centrifuging, the core plugs included in the experimental set# 1 were cooled to room temperature while spinning, allowing the oil phase to solidify and thus become immobile. The core plugs were then imaged in the core holders in the MRI. The centrifuge experiment was continued by repeating the procedure until capillary equilibrium was reached. This took up to 5 weeks for the lower wettability plugs. The recorded data provided the in-situ saturation information necessary to generate both the positive and negative part of the capillary pressure imbibition curve. A similar procedure was carried out for the core plugs included in the experimental set# 2.

The plugs were then centrifuged under brine using an angle head to drive them to residual oil saturation. The core plugs were then spun to measure the secondary capillary pressure drainage curve using the DMS method.

The core plugs PH-2 and PH-4 were then centrifuged under octadecane using an angle head to drive them to initial water saturation. Spontaneous imbibition tests at elevated temperature with octadecane as the oil phase were then carried out to provide wettability information.

Calibration procedures after centrifugation: To obtain the S_w = 100% calibration profiles, the cores were flooded with deionized water to remove the salt before being dried under vacuum. The cores were then 100% saturated with brine before MRI-imaging to be able to normalize the MRI image intensities from the prior images. A calibration curve was obtained by draining and imbibing the plug under air and using gravimetric means to measure average brine saturation and whole plug MRI profiles to obtain relative MRI intensities for the various brine saturations. Thus absolute values for water saturations were obtained and the saturations for the capillary pressure curves were calculated. The corresponding pressure field for Pc was determined from the standard centrifuge equation.

RESULTS AND DISCUSSION

Wettability Alteration: All core plugs were subject to the Amott wettability test, before or after centrifuging for DMS to obtain information on the wettability conditions. The wettability alteration method was different for the core plugs used in the two different capillary pressure measurement methods and thus it is imperative to compare the imbibition behavior. Fig. 3 shows the spontaneous imbibition characteristics for all core plugs used in the capillary pressure measurements using a conventional centrifuge technique. Fig. 4 shows the spontaneous imbibition characteristics for the core plugs used in the first experimental set of core plugs used for capillary pressure measurements by the DMS method. Fig. 5 shows the corresponding data for the second set of core plugs included when applying the DMS method.

The comparison of the spontaneous imbibition characteristics for strongly-water-wet samples is shown in Fig. 6. With respect to endpoint saturation, all four samples were quite similar. However, there was a difference in the early stage of the imbibition, within the first 10 min., where there was a higher imbibition rate for the two samples PH-9 and PH-10. This is possible due to the different plug geometry, as CPA-1.5 and CPA-1.6 both were 2" diam. plugs, while PH-9 and PH-10 were 1.5" diam. plugs. The first observations of the produced volumes of oil, during a very fast production within the first 10 min., were very sensitive to recording time due to oil droplet formation and adherence of oil blobs to the chalk surface causing periodical production of oil blobs. Both sets of plugs produced 30%PV oil within the first 20 min. The imbibition tests for PH-9 and PH-10 were performed after the centrifugations and the results do not indicate any change in wettability due to the contact with decane and octadecane.

The results on measurements of $I_{w,}$ after the alteration of wettability by aging submerged in crude oil, for core plugs centrifuged by the conventional method are listed in Table 2. In Table 3, the wettabilities for the core plugs aged with continuous oil flooding during aging and used with the DMS method are listed.

Spontaneous imbibition characteristics for the moderately-water-wet plugs are plotted in Fig. 7 and Fig. 8, reflecting the wettability indices of I_w=0.7 and I_w=0.5, respectively. Endpoint saturations are consistent, except for plugs CP-7 and CP-8 in Fig. 8. These two plugs had slightly lower initial water saturations and yielded lower endpoint water saturation after imbibition. This is coherent with results found in Ref. 10,11. The behavior during the spontaneous imbibition is similar at each given wettability, independent of aging method. However, we observed a slightly shorter induction time for the samples aged by flushing. For core plugs PH-2 and PH-4, the wettability was measured both before and after DMS for Pc. In the before test, decane was the oil phase, and in the after tests octadecane at elevated temperature was the oil phase. Similar wettability indices to water were obtained. This indicates that there has not been any change of wettability during the DMS method under octadecane at elevated temperature. Ocatdecane was found to be compatible as an oil phase and a satisfactory reproducibility was present in these tests.

The wettability tests demonstrated an overall indication that the wettability conditions were compatible. With similar wettability conditions, we were able to compare the methods of capillary pressure measurement. This confirmed our experience that it was only for core plugs aged for long period of times, submerged in crude oil, that the diffusion of fresh oil into the core sample produced a radial non-uniform wettability distribution (Ref. 3,4).

MRI of the axial wettability distribution along the length of core plug PH-4, a core plug aged during flushing by crude oil, showed that only insignificant effects on the wettability distribution from the flood direction can be identified in short core plugs (Ref. 4). No significant radial non-uniform wettability distributions were identified for the core plugs aged during oil flooding.

Wettability may also be calculated by the obtained capillary pressure curves. The wettability indices calculated from uncorrected Pc-curves differ from values obtained by the conventional Amott test. According to some studies in the literature (Ref. 12,13,14,15) this may partly be due to differences imposed by the co-current spontaneous imbibition experienced in the centrifuge compared to counter-current spontaneous imbibition present in a conventional Amott test. This may cause the wettability index to obtain a less water-wet value for the latter test. However, to explore the differences in the current experiments we are more concerned about uncertainties in absolute water saturation values due to difficulties with obtaining reliable absolute values of S_w in the MRI because of 1) temperature effects on images of octadecane, 2) that software and hardware changes to the MRI may have resulted in some variation in measured image intensity and 3) that damage to the plugs from extensive handling have resulted in lost material and fractures that affect the processing of the images to obtain Sw for Pc. In this study there is available information from the Amott tests on both the water saturation endpoints after imbibition and after high rate waterflooding with similar N_c as valid for the lower part of centrifuged plugs at S_{wf}. The water saturations were therefore normalized so that the Pc-scanning curves reflected the measured Amott wettabilities.

Capillary pressure measurements: Results on the capillary pressure curves obtained by the conventional centrifuge technique are reported in Ref. 6. Fig. 9 and Fig. 10 summarize the measured conventional Pc-data for the primary/secondary drainage and forced imbibition, respectively. More readable versions of Fig. 9 and Fig. 10 are available in Ref. 6. Fig. 11 summarizes the Pc-scanning curves obtained by the DMS method. Fig. 12 shows the details on the positive part of the Pc-imbibition curve. Fig. 13 and Fig. 14 offer a detailed comparison with the results from the conventional technique.

Primary and secondary Pc-drainage data: For practical reasons, for all core plugs aged to a less-water-wet state, there is not any available capillary pressure primary drainage curve. However, for the core plugs included in the experimental set# 2, secondary drainage capillary pressure curves were also measured. Fig. 13 shows a detailed comparison of primary and secondary capillary pressure drainage curves obtained at the different wettabilities using the two Pc-measurement methods.

At strongly-water-wet conditions and at moderately-water-wet conditions at Iw=0.7, there were good agreement within the data. Two reference Portland Chalk plug samples PA and PB, not included in the tables, with similar properties are compared to the samples used in this study.

At Iw=0.4, the secondary capillary pressure drainage curve measured by the DMS method shows consistently higher Pc-values than those obtained by the conventional centrifuge method. PH-4 was the most water-wet plug among the plugs at I_w=0.4. However, we speculate that since the aging time for the plugs aged submerged in crude oil, exhibiting I_w=0.4, was as long as 30 days, these plugs may have a radial non-uniform wettability distribution and hence not be compatible to the wettability present in PH-4, even though the imbibition characteristics did not differ significantly. In Ref. 3, we showed that after 50 days of aging submerged in crude oil, significant radial non-uniformity in wettability distributions was observed in core plug CP-4. The same argument may be used to explain the high Swi observed in the secondary capillary pressure curve for CP-5 at I_w=0.1.

Forced water imbibition Pc-data: Fig. 14 shows a detailed comparison between the two different methods for measuring the capillary pressure for the negative capillary pressure data obtained during the forced imbibition, at various wettabilities.

At strongly-water-wet conditions and at moderately-water-wet conditions of Iw=0.7 and Iw=0.4, there are fairly good agreement in the data. The Pc-curves measured by the DMS method at Iw=0.4 show consistently lower Pc-values and a sharper curvature than those obtained by the conventional centrifuge method. This may be due to less representative wettability conditions for the core plugs included in the conventional centrifuge test, but it may also show that the conventional method may be erroneous due to an inappropriate choice of a model to determine inlet face saturations. Still, the negative capillary pressure curves for forced imbibition showed a consistent development. At less water-wet conditions, all the capillary pressure curves exhibited less curvature and the residual oil saturations consistently decreased.

Spontaneous imbibition Pc-data: Fig. 12 shows the positive part of the capillary pressure imbibition curves, reflecting the development of the capillary pressure during the spontaneous brine imbibition at various wettabilities. From the figure it can be seen that as the wettability changes toward less-water-wet conditions, the Pc-spontaneous imbibition curve shifts towards lower water saturation values at a given capillary pressure, except at high Pc-values. The Pc-cross over point, when capillary pressure equals zero after the spontaneous imbibition was completed, moves towards lower water saturation endpoints at less-water-wet conditions. This is a result of the normalization according to the conventional understanding of the spontaneous imbibition process.

The Pc=0 cross over point reflects the water saturation endpoint after co-current imbibition in the centrifuge measurements. In our work on oil recovery in chalk, we have observed that there is a discrepancy between the endpoint after spontaneous imbibition depending on if the process has been counter-current, like in 3D-imbibition cells, or co-current, like in centrifuge measurements or 1D-imbibition experiments. Also some waterfloods at strongly-water-wet conditions, reflecting co-current oil production, show higher water saturation endpoints compared to 3D-imbibition of strongly-water-wet core plugs. This observation is in accordance with findings reported in ref 13,14,15. Further investigation is in progress.

CONCLUSIONS

- Imbibition characteristics for cores treated to less water-wet conditions showed that reproducible and stable wettability conditions were generally obtained.
- Capillary pressure curves demonstrated consistent trends when moving toward less-water-wet conditions, and reproducible results were obtained for the capillary pressure data.
- Drainage capillary pressure curves for decreasing water-wet conditions exhibited lower drainage threshold pressure and sharper curvature for the drainage curves near Swi. Higher Swi for the less-water-wet condition, Iw = 0.09, was observed.
- Drainage capillary pressure curves and forced imbibition negative capillary pressure curves at strongly-water-wet and moderately-water-wet conditions, employing standard industrial centrifuge techniques, were found to be similar to results utilizing the DMS method.
- Negative capillary pressure curves for forced imbibition showed a consistent development. At less water-wet conditions, the capillary pressure curves exhibited less curvature and the residual oil saturations consistently decreased.
- The positive part of the capillary pressure imbibition curve was measured at different wettabilities using the DMS method. For given low values of the capillary pressure the Pc-curves showed a consistent trend of shifting towards lower water saturations as the wettability changed towards less-water-wet conditions.

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Table 1. Summary of Core Plugs

Wettability	Core #	Diam.	Por.[%]	Perm. [mD]	Used for
0,48	PH-4	1,5"	45	4	Direct Saturation Measurement
0,62	PH-2	1,5"	46	4	Direct Saturation Measurement
0,67	PH-3	1,5"	46	4	Direct Saturation Measurement
0,69	PH-6	1,5"	44	3	Direct Saturation Measurement
0,82	PH-5	1,5"	44	3	Direct Saturation Measurement
0,91	PH-7	1,5"	43	3	Direct Saturation Measurement
1,00	PH-9	1,5"	44	3	Direct Saturation Measurement
1,00	PH-10	1,5"	44	3	Direct Saturation Measurement
0,00	CP-3	1,5"	48	4	Pc-centrifuge Measurement.
0,07	CP-4	1,5"	48	5	Pc-centrifuge Measurement.
0,09	CP-5	1,5"	48	4	Pc-centrifuge Measurement.
0,42	CP-11	1,5"	46	4	Pc-centrifuge Measurement.
0,43	CP-7	1,5"	48	5	Pc-centrifuge Measurement.
0,45	CP-8	1,5"	48	5	Pc-centrifuge Measurement.
0,45	CP-14	1,5"	47	4	Pc-centrifuge Measurement.
0,70	CP-9	1,5"	46	4	Pc-centrifuge Measurement.
0,70	CP-12	1,5"	47	4	Pc-centrifuge Measurement.
0,73	CP-10	1,5"	46	4	Pc-centrifuge Measurement.
0,76	CP-13	1,5"	47	4	Pc-centrifuge Measurement.

Table 2. Core Data, Experimental Schedule and Flood History for Core Plugs used for capillary pressure curve measurements.

Core	CP-3	CP-4	CP-5	CP-7	CP-8	CP-9	CP-10	CP-11	CP-12	CP-13	CP-14	CP-15 a)
Length [cm]	3,62	3,72	3,87	3,97	3,82	4,08	4,08	3,93	3,91	3,94	3,95	3,92
Diameter [cm]	3,81	3,81	3,81	3,81	3,81	3,78	3,81	3,82	3,80	3,80	3,80	3,79
Porosity [%]	48 %	48 %	48 %	48 %	48 %	46 %	46 %	46 %	47 %	47 %	47 %	43 %
Pore volume [ml]	20	20	21	22	21	21	22	21	21	21	21	19
Abs. permeability [mD]	4	5	4	5	5	4,1	4,2	3,7	4,2	3,8	4,0	3,2
Oilflood #:	1	1	1	1	1	1	1	1	1	1	1	1
Oil viscosity [cP]	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7
Swi [%PV]	100	100	100	100	100	100	100	100	100	100	100	100
dSw [%PV]	83	80	79	80	81	74	75	74	74	74	75	77
Swf [%PV] b)	17	20	21	20	19	26	25	26	26	26	25	23
Aging:												
Aging temperature [°C]	90	90	90	90	90	90	90	90	90	90	90	90
Aging time [days]	50	50	50	3	3	3	3	30	3	3	30	filter
Oil flooding prior to spontaneous imb. :	1	1	1	1	1	1	1	1	1	1	1	
Decaline [PV]	5	5	5	5	5	5	5	5	5	5	5	
n-Decane [PV]	5	5	5	5	5	5	5	5	5	5	5	
Endpoint eff. perm. [mD]	10 c)	10 c)	10 c)					5,9 c)			5,9 c)	
Spontaneous imbibition #:	1	1	1	1	1	1	1	1	1	1	1	
Oil viscosity [cP]	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	
Swi [%PV]	17	20	21	20	19	26	25	26	26	26	25	
dSw [%PV]	0	5	6	20	20	26	29	19	31	29	21	
Swf [%PV]	17	25	27	40	39	52	54	45	57	55	46	
Oil recovery [%OIP]	0	6	7	25	25	35	39	26	42	39	28	
Waterflood #	1	1	1	1	1	1	1	1	1	1	1	
Flow rate [ml/hr]	34	34	34	34	34	34	34	34	34	34	34	
Swi [%PV]	17	25	27	40	39	52	54	45	57	55	46	
dSw [%PV]	57	58	57	27	24	11	11	26	13	9	26	
Swf [%PV]	74	83	84	67	63	63	65	71	70	64	72	
Recovery [%OIP]	69	78	80	59	54	50	53	61	59	51	63	
End point eff. perm. [mD]	1,2	1,4	1,2	1,1	1	1,0	1,1	1,4	1,1	1,1	1,3	
Wettability index	0,00	0,07	0,09	0,43	0,45	0,70	0,73	0,42	0,70	0,76	0,45	

a) Filter plug for crude oil filtered at 90°C.
b) Swf is the final water saturation after the first oilflood, corresponding to the Swi during aging.
c) Endpoint relative permeability is higher than the absolute permeability.

Table 3. Core Data, Experimental Schedule and Flood History for Core Plugs used for Direct Saturation Measurement Method

Core	PH-3	PH-7	PH-9	PH-10	PH-2	PH-4	PH-5	PH-6
Experimental Set #	1	1	1	1	2	2	2	2
Length [cm]	5,98	6,04	6,03	6,03	6,04	5,96	5,98	5,96
Diameter [cm]	3,82	3,83	3,81	3,81	3,81	3,81	3,81	3,82
Porosity [%]	46 %	43 %	44 %	44 %	46 %	45 %	44 %	44 %
Pore volume [ml]	31	30	30	30	32	30	30	30
Abs. permeability [mD]	4	3	3	3	4	4	3	3
Oilflood #:	1	1	1	1	1	1	1	1
Oil viscosity [cP]	2,7	2,7	0,9	0,9	2,7	2,7	2,7	2,7
Swi [%PV]	100	100	100	100	100	100	100	100
dSw [%PV]	75	75	75	75	75	75	75	75
Swf [%PV] a)	25	25	25	25	25	25	25	25
Aging:								
Aging temperature [ºC]	90	90	-	-	90	90	90	90
Aging time [days]	3	1,5	-	-	3	3	1,5	1,5
Filtration velocity [cm/hr]	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Crude oil injected [PV]	6	3	0	0	6	6	3	3
Oil flooding prior to spontaneous imb. :	1	1	-	-	1	1	1	1
Decaline [PV]	5	5	-	-	5	5	5	5
n-Decane [PV]	5	5	-	-	5	5	5	5
Endpoint eff. perm. [mD]	4	3	3	3	4	4	4	3
Spontaneous imbibition #:	1	1	1	1	1	1	1	1
Oil viscosity [cP]	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92
Swi [%PV]	25	25	25	25	25	25	25	25
dSw [%PV]	28	34	33	32	30	25	37	29
Swf [%PV]	53	59	58	57	55	50	62	54
Oil recovery [%OIP]	37	45	44	43	40	33	49	39
Waterflood #	1	1	1	1	1	1	1	1
Flow rate [ml/hr]	34	34	34	34	34	34	34	34
Swi [%PV]	53	59	58	57	55	50	62	54
dSw [%PV]	14	3	0	0	18	27	8	13
Swf [%PV]	66	62	58	57	73	77	70	68
Recovery [%OIP]	55	50	44	43	64	70	60	57
End point eff. perm. [mD]	1,1	0,7	??	??	1,1	1,2	0,9	0,9
Wettability index	0,67	0,91	1,00	1,00	0,62	0,48	0,82	0,69

a) Swf is the final water saturation after the first oilflood, corresponding to the Swi during aging.

Table 4. Fluid Properties

Fluid	Density [g/cm^3]	Viscosity [cP] at 20ºC	Viscosity [cP] at 90ºC	Composition
Brine	1,05	1,09		5 wt% NaCl + 3,8 wt% $CaCl_2$
n-Decane	0,73	0,92		
Decahydronaphtalene	0,896			
Crude oil	0,849	14,3	2,7	

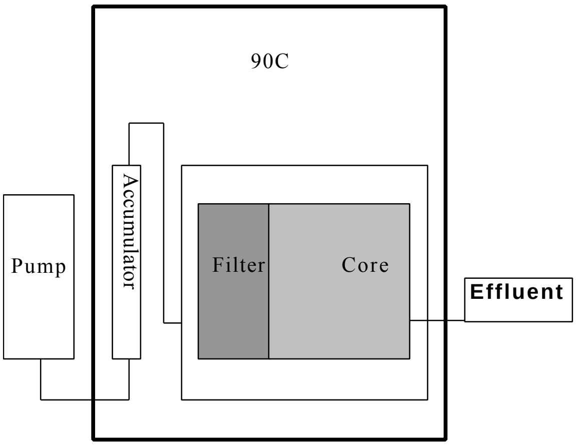

Figure 1. Schematics of experimental setup for the oilflooding and aging.

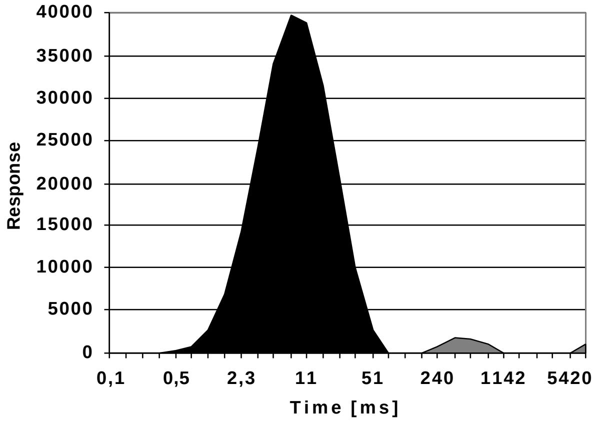

Figure 2. NMR spectroscopy results showing brine saturation and remains of decane saturations. Octadecane saturation is not visible.

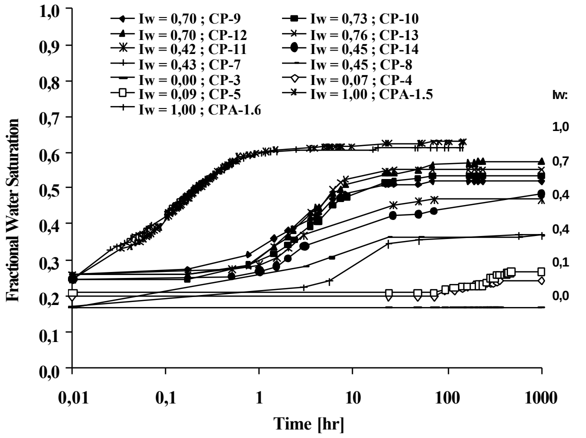

Figure 3. Spontaneous imbibition characteristics for all plugs used in the capillary pressure measurement using a conventional centrifuge technique.

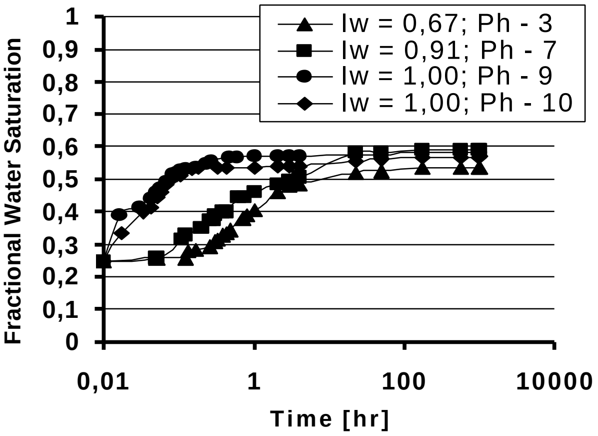

Figure 4. Spontaneous imbibition characteristics for the core plugs used in the first experimental set of core plugs used for capillary pressure measurements by the DMS method.

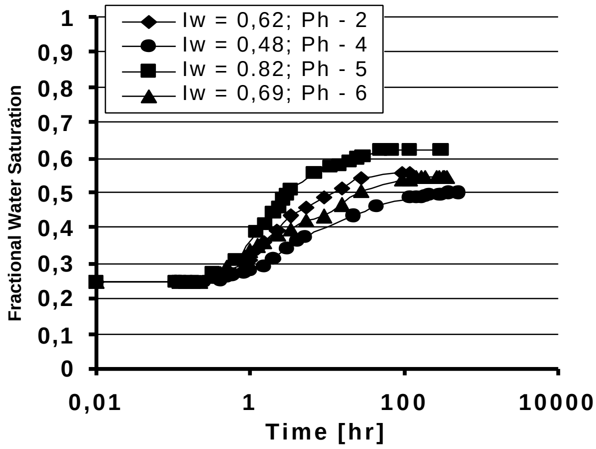

Figure 5. Spontaneous imbibition characteristics for the core plugs used in the second experimental set of core plugs used for capillary pressure measurements by the DMS method.

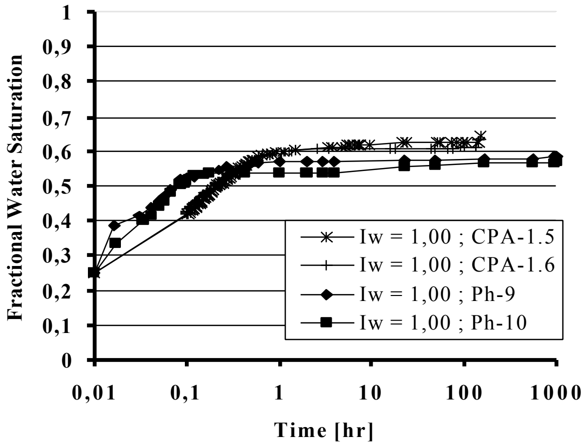

Figure 6. Comparison of the spontaneous imbibition characteristics for the strongly-water-wet samples. Amott wettability index Iw = 1.0.

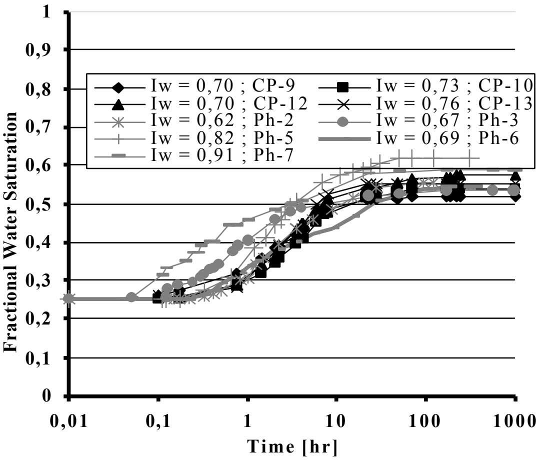

Figure 7. Comparison of the spontaneous imbibition characteristics for the moderately-water-wet samples. Amott wettability index Iw 0.7.

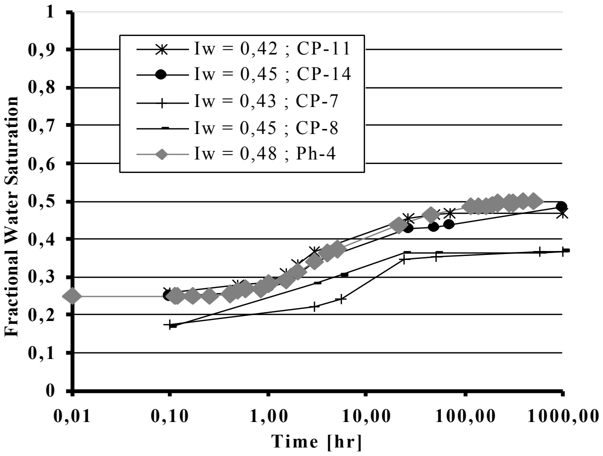

Figure 8. Comparison of the spontaneous imbibition characteristics for the moderately-water-wet samples. Amott wettability index Iw 0.5.

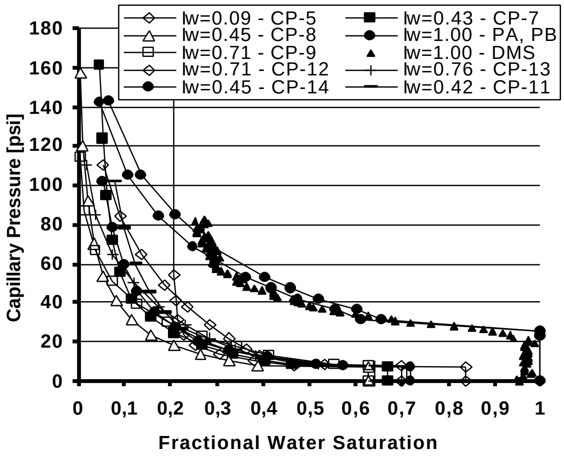

Figure 9. Primary and secondary drainage capillary pressure curves measured using a conventional centrifuge technique.

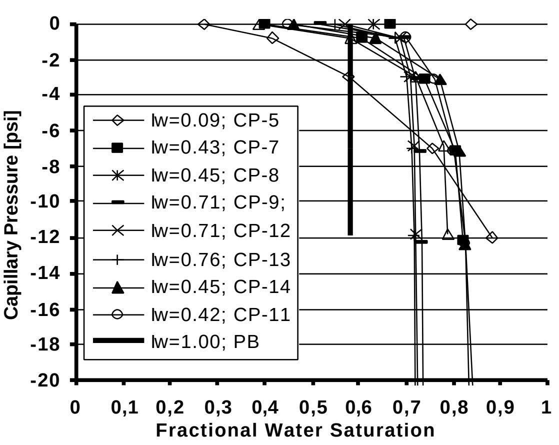

Figure 10. Forced imbibition capillary pressure curves measured using a conventional centrifuge technique.

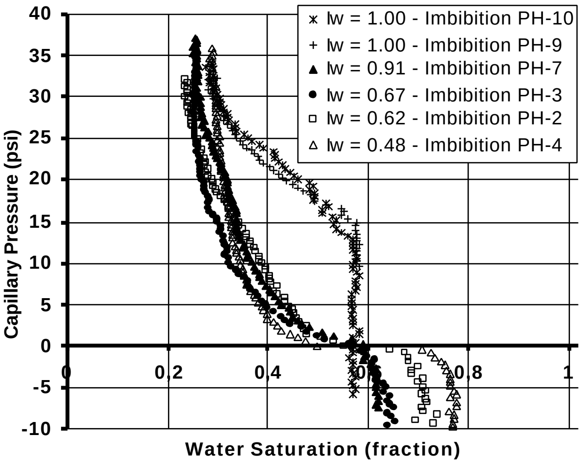

Figure 11. Capillary pressure scanning curves obtained by the DMS method.

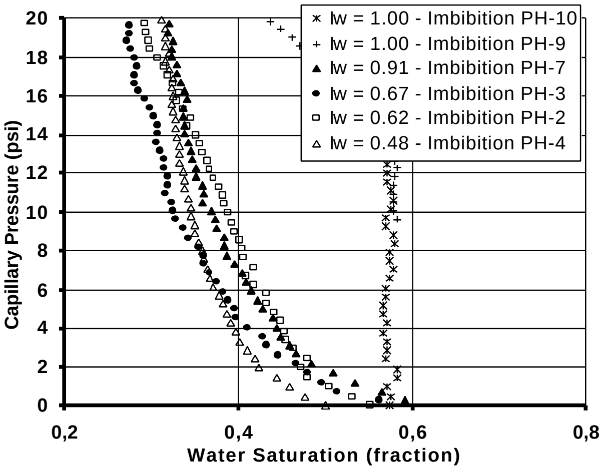

Figure 12. Comparison of the positive part of the capillary pressure imbibition curve.

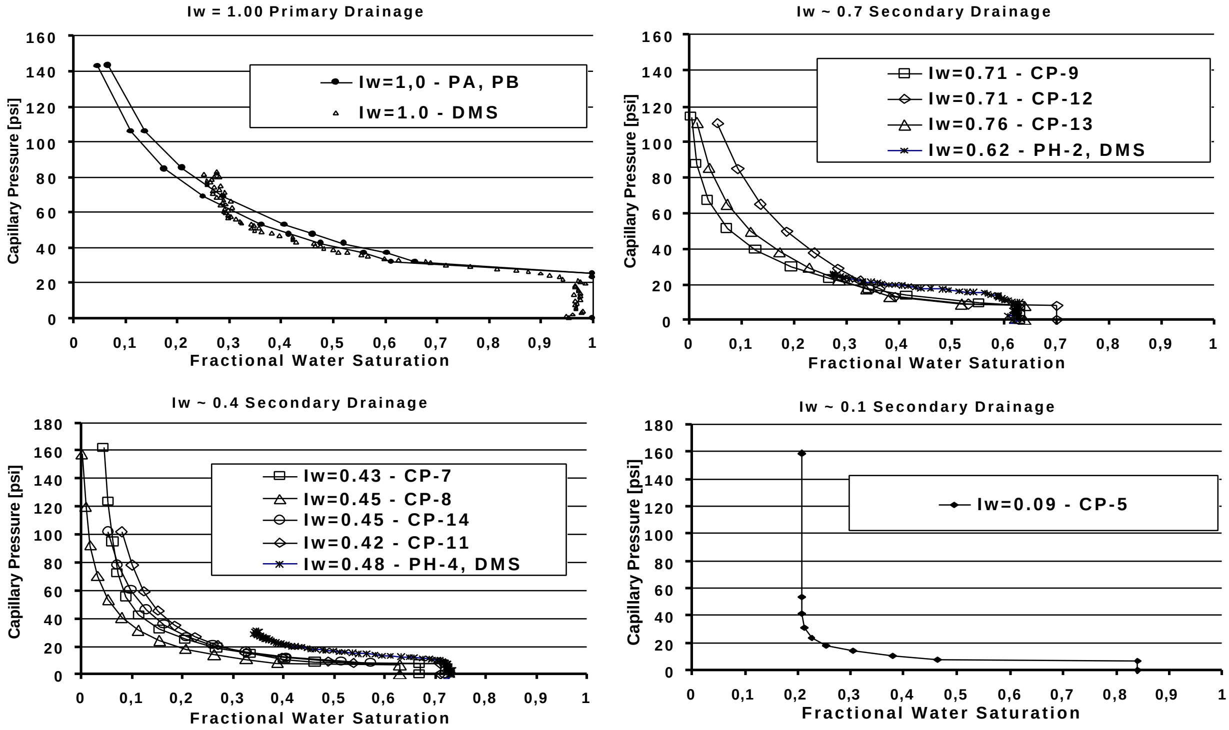

Figure. 13. Comparison of primary and secondary capillary pressure drainage curves at different wettabilities.

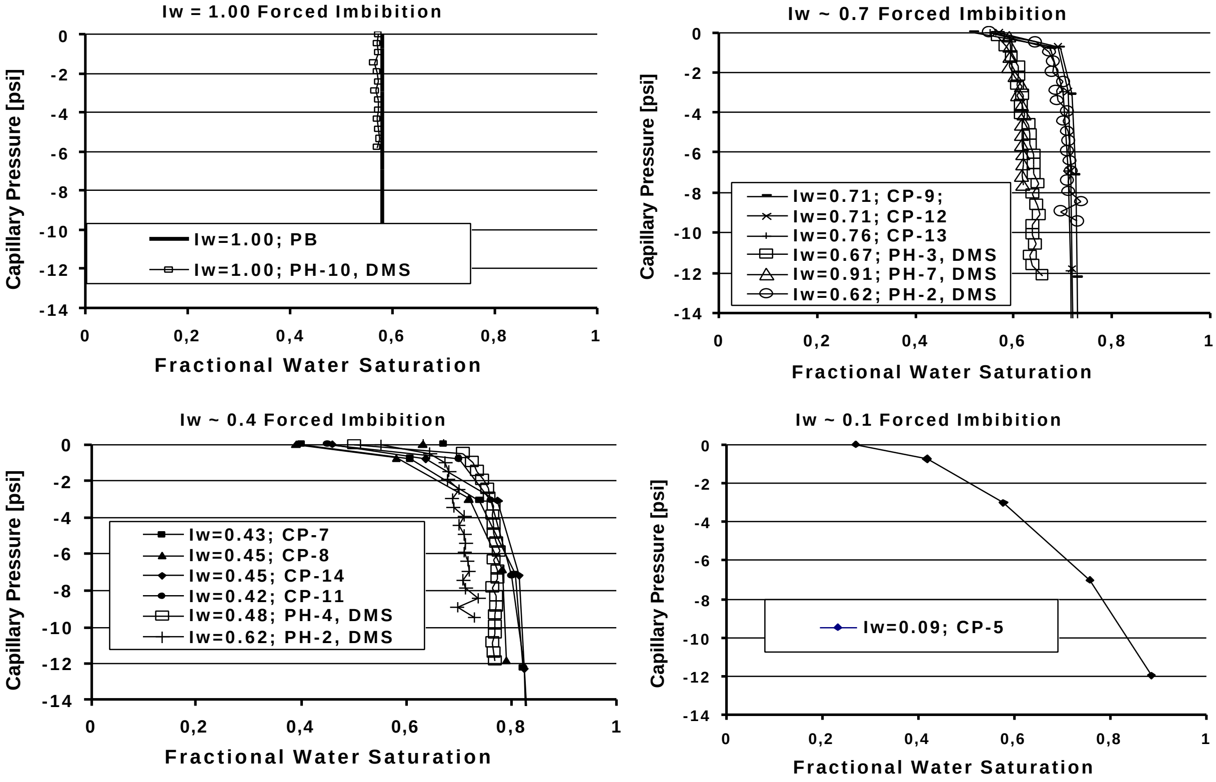

Figure. 14. Comparison of capillary pressure forced imbibition curves at different wettabilities.

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