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IMPACTS OF WETTABILITY ON CAPILLARY PRESSURE AND RELATIVE PERMEABILITY

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Abstract
Capillary pressure and relative permeability have been measured in chalk core plugs at strongly-water-wet, moderately-water-wet and nearly-neutral-wet conditions. Plug wettability was selectively altered by aging outcrop chalk plugs, at Swi, in crude oil at an elevated temperature for selected periods of time. This procedure reproducibly produced the desired wettability while keeping the pore network structure and the mineralogy constant. Aging to a less-water-wet state, significantly reduced spontaneous brine imbibition rate and endpoint. However, it did not reduce the total movable oil, i.e. imbibition plus forced displacement. In fact, the total movable oil generally increased slightly with reduced water wettability, however, at the cost of higher differential pressures. Reduced water wettability also lowered the drainage threshold pressure. Repeated imbibition tests on individual plugs indicated that the wettability alteration was permanent.

Introduction
Special core analysis (SCAL) is important to obtain more detailed information on reservoir parameters not available through standard core analysis and usually includes capillary pressure, relative permeability and wettability measurements. SCAL is also some times needed to obtain more reliable input parameters for reservoir simulations and this paper concentrates on the latter for a mechanistic study of recovery mechanisms in fractured chalk reservoirs.

Hydrocarbon recovery results from a competition between capillary and viscous forces and gravity. In most chalk reservoirs spontaneous imbibition is the major recovery mechanism. This dominance of capillary forces 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 but fractured chalk reservoirs with very low matrix permeability are in particular sensitive to these interactions. Questions arise about how and when fractures are crossed by the wetting fluid and if there is a component to oil recovery from viscous forces, and if so, when and how this occurs. The impacts of these parameters at the different wettability conditions seem to be the clue to the understanding of the oil recovery mechanisms in these reservoirs.

Wettability is a major factor controlling the location, flow and distribution of fluids in a reservoir. Wettability is defined as the tendency of one fluid to spread on or adhere to a solid surface in the presence of other immiscible fluids and has a major impact on the capillary pressure and the relative permeabilities (Ref. 1-3). In this study measurements of capillary pressure and relative permeability 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 produced chalk at the desired wettability conditions. Capillary pressure and relative permeabilities were then obtained, at various wettability conditions, employing standard industrial methods; capillary pressures were obtained by centrifuging and relative permeabilities by using a Penn-State steady state technique (Ref. 4) utilizing X-ray attenuation to obtain saturations.

To evaluate the quality of the obtained experimental values of capillary pressure and relative permeability iterative interactions between experimental measurements and numerical simulations of waterfloods in well characterized fractured chalk blocks at desired wettabilities have been performed. Capillary pressure and relative permeability, experimentally measured at each given wettability, were used as input for the simulations. Optimizing either capillary pressure data or relative permeability curves in the history matching of the waterfloods indicated which of these input data could be most trusted.

The methods most often used to measure wettability in core plugs are the Amott test (Ref. 5) and the USBM-method (Ref. 6). In this paper the Amott wettability index for water and the imbibition characteristics, mainly imbibition rate, induction time and imbibition endpoint values, will be used to characterize the wettability of the cores. The USBM method and the Amott test give only one and two parameters, respectively, to characterize the average wettability of the cores. Both methods have serious weaknesses with respect to discriminating between different wettabilities in a certain range of wettability (Ref. 1). Lately a new test has been proposed where the early imbibition rate was used to determine the core wettability (Ref. 7).

Experimental

A total of 15 dried chalk core plugs, cut with the same orientation from large blocks of outcrop chalk, were vacuum evacuated 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.

Stock tank oil was used as the crude oil and in-line filtered through a chalk plug, CP-15 Table 4, at 90ºC before it was used to oilflood the samples to initial water saturation. 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 until it was filtered while establishing $S_{wi,}$ the plug was sequentially flooded from both ends. For the chalk cores, oil flooding at 8 bars pressure differential gave initial saturations in the range 25-30%. The initial water saturation used in this study was 25%PV. The core samples, at initial water saturation, were aged in closed, crude-oil-filled containers using an oven set at 90.0±0.5°C for different lengths of time. All aging was performed in duplicate sets of plugs to determine experimental repeatability. Core weight was measured both before and after aging to determine whether any water evaporated.

After aging the crude was displaced by 5PV decahydronaphthalene (decalin), at 90°C. The decalin was flushed by injection of 5PV decane, at 90°C, before the temperature was lowered to room temperature. The decane then represented the oil phase throughout the experiment. Decane has been shown to not alter wettability in chalk. Decalin was obtained from Pihl Inc. and had an isotopic purity of >98 %. Decane was obtained from Pihl Inc. and had an isotopic purity of >95 %. Both hydrocarbons were used as received. The physical properties of the fluids are summarized in Table 1.

Bottle tests have shown precipitation of asphaltenes when the reservoir crude oil was contacted by refined oil (Ref. 8). Thus refined oil should not be used to displace the reservoir crude oil. Bottle tests on decahydronaphthalene did not show incompatibility with the reservoir crude oil nor the refined oil. Decahydronaphthalene was therefore used as a buffer between the crude oil and the decane when crude oil was exchanged with decane.

Oil recovery by spontaneous, room temperature imbibition, followed by a waterflood, was used to produce the Amott water index. The core plugs containing brine and decane were cooled to room temperature for at least 12 hours and then placed in a graduated imbibition cell. 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 (1 cm^3/min.) to drive them to a viscous endpoint.

This method for altering the wettability of outcrop chalk has been reported to be stable and reproducible (Ref. 9). The aging technique was found to be reproducible and could alter wettability in Rørdal chalk selectively, from strongly water-wet to nearly-neutral-wet. A consistent change in wettability towards a less water-wet state with increased aging time was observed.

The Rørdal chalk used in this study was obtained from the Portland cement factory in Ålborg, Denmark. The rock formation is Maastrichan age and consists mainly of coccolith deposits (Ref. 10) with about 99 % calcite and 1 % quartz. The brine permeability and porosity for the Rørdal chalk cores ranged from 1-4 mD and 45-48 %, respectively. 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. The chalk cores were dried at 90°C for at least seven days before being used. A summary of the core plugs used is found in Table 2.

The composition of the brine was 5 wt. % NaCl + 5 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 obtained from Pihl Inc. with a purity of 99.5%, $CaCl_2$ obtained from Pihl Inc. with a purity of 99.5%, Sodium azide had a purity of 99.5%. The materials were used as received. Physical properties of the fluids are summarized in Table 1.

Results and Discussion

Relative permeability.

Table 3. contains the core data, experimental schedule and flood history for the four core plugs used to measure relative permeabilities; the four core plugs were all 5cm in diameter and 7-8cm long. Porosity was measured at 45-47% and permeability was 5mD for all of the four plugs. Two core plugs were used as back up, the actual tests were conducted on the samples labelled PC2-11 and PC2-13. Room temperature imbibition characteristics, after aging, for all of the four core plugs prepared, containing brine and decane, are shown in Figure 1. As can be seen from the figure the imbibition characteristics are reproduced for each set of two cores. The two cores prepared to a wettability condition of Iw=0.5-0.6, using an aging time of 83 days, had a water endpoint saturation after imbibition of ca. 50%PV. Both the imbibition rate and the endpoint saturation were significantly lower than for the two typical strongly-water-wet cores included in the figure for comparison. A further consistent reduction in imbibition rate is observed for the two other core plugs prepared to a wettability condition of Iw=0.3-0.4, using an aging time of 161 days. The final water saturation after spontaneous imbibition for these two core plugs was ca. 40%PV. A subsequent high rate waterflood, 60ml/hour for all plugs except PC2-11 and PC2-12 for which a flood rate of 70 ml/hour was used, exhibited a final water saturation in the range of 65-80%PV. Amott water index was calculated for each plug and can be found in Table 3. Endpoint effective permeabilty to water at residual oil saturation for all cores was less than 2mD. To enhance the X-ray attenuation in the oil phase during the steady state relative permeability test the decane was replaced with iododecane, by flushing 5PV of iododecane through the core plugs at residual oil saturation. To test the stability of the wettability alteration and to see if the iododecane gave different wettability indices a second Amott test was conducted for each plug, the results are listed in Table 3. As can be seen from this data and from the imbibition characteristics using iododecane, Figure 2., an excellent reproduction of the first Amott test was obtained for all the core plugs. The core plugs were then shipped to Core Petrophysics in Houston, Texas, who performed the relative permeability tests. A service company for the oil industry was selected because the objective was to obtain relative permeability data similar to a normal field evaluation, thus give an indication of the quality of the standard procedure for obtaining steady state relative permeabilities.

After the relative permeability measurements had been performed using standard procedures for steady state relative permeability tests (Ref. 4), the core plugs were shipped back to the University of Bergen and a repeated wettability test was performed. The results are found in Table 3. and in Figure 3 where a comparison with the earlier imbibition characteristics for these core plugs is shown. The results indicate that the wettability has not been changed towards more water-wet conditions although 50PV of water and 70PV of oil had been flushed through each core during the steady state relative permeability test, at a maximum flow rate of 240ml/hour and a maximum differential pressure of 1.8 bar/cm. In fact, if the significance of the imbibition characteristics should be trusted, after the extensive experimental schedule on the two core plugs and the two shipments across the Atlantic, the results indicate that a slightly less water-wet state had been obtained.

The results on the measured relative permeabilities are found in Figure 4. The figure shows that the results are consistent with earlier tests reported in the literature (Ref. 3) with respect to expected relative permeability values at each saturation distribution when moving towards less water-wet conditions. The trend is that water relative permeability, at a given saturation, increases at less water-wet conditions. However, the water relative permeability for either Iw=0.5 or Iw=0.3 is somewhat offset as Iw=0.5 is expected to lie between the other two curves. The oil relative permeability stayed the same. The wettability alteration did not show explicit oil wetness as indicated by a lack of oil imbibition during the Amott tests.

There is a reason to believe that the induced wettability condition was a mixed wettability state; less water-wet with some surfaces exhibiting affinity to oil since the curved negative capillary pressure curves showed a resistance to water injection. With regard to endpoint saturation values, at residual oil saturation, the measured relative permeability curves at less water-wet conditions were not consistent with an expected trend of obtaining lower residual oil saturations associated with a change in wettability towards less water-wet conditions.

Capillary pressure.

Table 4. contains the core data, experimental schedule and flood history for the 11 core plugs used to measure capillary pressures, the core plugs were all 3.8cm in diameter and ca. 4cm long. Porosity was meaured at 43-48% and permeability was 3-5mD. Two core plugs were kept as back up plugs, while tests were conducted on the nine samples labelled CP-3 through CP-5 and CP-7 through CP-14. The capillary pressure data was obtained by the standard centrifuge technique, running three samples at a time. Room temperature imbibition characteristics, after aging, for all of the eleven core plugs, containing brine and decane, are shown in Figure 5. Imbibition characteristics for two typical strongly-water-wet core plugs are included for comparison. As can be seen from the figure the imbibition characteristics are reproduced at the desired wettability conditions, Iw=0.7 and Iw=0.4, for each set of four cores. Two of the cores at Iw=0.4 had a lower initial water saturation than the other two at 25%PV. From the imbibition characteristics it can be seen that the imbibition rate and the oil produced are, however, similar and the Amott water index yields 0.4. The three cores prepared to a wettability condition of Iw=0-0.1, using a total aging time of 50 days, did not imbibe any significant amount of water and exhibited water saturation endpoints after imbibition of less than 30%PV. These cores stood out as odd samples according to our experience with the aging technique. Measuring the capillary pressure for one of theses samples using direct measurement of saturation with Magnetic Resonance Imaging (MRI) after elevated temperature centrifuging with an oil that solidifies at room tempereture exhibited a range of wettabilities with the outside edge of the plugs less water-wet than the inside (Ref. 11).

A subsequent high rate waterflood, 34ml/hour for all plugs exhibited a final water saturation in the range of 63-70%PV. Amott water index was calculated for each plug and can be found in Table 4. The final water saturations after spontaneous imbibition for the core plugs at Iw=0.4 was ca. 40%PV. A subsequent high rate waterflood, 34ml/hour, exhibited a final water saturation in the range of 63-70%PV. Endpoint effective permeabilty to water at residual oil saturation for all cores was less than 2mD.

Figure 6 shows the measured positive capillary pressure curves for the primary drainage process for the strongly-water-wet plugs and the secondary drainage process for the less water-wet plugs. Since wettability measurements had been made on the less water-wet core plugs, the starting point for the capillary pressure measurements was residual oil saturation, thus the secondary rather than the primary drainage curve was determined. For the strongly water-wet samples the results from utilizing the Direct Measurement of Saturation technique (Ref. 12-14) are included. A very good agreement with the standard centrifuge technique was obtained, thus there is a justified argument that results obtained on positive capillary pressure imbibition data using this technique can be trusted.

Figure 6 shows that at less water-wet conditions the positive secondary capillary drainage curves have lower capillary threshold pressure and are more curved than at strongly water-wet conditons. Extrapolations of the curves towards higher capillary pressures than actually used indicate that the immobile water saturations are higher at less water-wet conditions than at strongly water-wet conditions. The very low immobile water saturations are due to the fact that the saturations have been converted from average saturations obtained by material balance calculations to Hassler-Brunner saturations reflecting the inlet end face saturations of the core plugs under centrifugation.

Figure 7 shows the measured negative capillary pressure curves for the third forced imbibition process, for all the wettabilities. The results obtained from utilizing the Direct Measurement of Saturation technique for the strongly water-wet samples are not shown because the other curves would than not be readable, but again a very good agreement with the standard centrifuge technique was obtained.

Figure 7 shows that the negative capillary pressure imbibition curves become flatter for less water-wet conditions. The potential for increased oil recovery by increasing the viscous pressure drop during waterfloods are exhibited by the fact that a substantial oil production may be obtained for this oil/brine/rock system for relatively small additional pressure drops. At wettability conditions closer to neutral-wet the results indicate that a significantly higher pressure drop is needed to obtain the same residual oil saturations compared to more water-wet conditions. The residual oil saturations at less water-wet conditions exhibits a consistent trend of smaller values when moving towards less water-wet conditions.

Numerical simulations of waterflooding chalk blocks at the different wettability conditions, first as whole blocks then fractured, using the experimental results for capillary pressure and relative permeabilities, have been performed (Ref. 15,16). The objective was to obtain a quality control on the measurements of capillary pressure and relative permeability at strongly-water-wet, moderately-water-wet and nearly-neutral-wet conditions by iterative comparison between experimental measurements and numerical simulations of waterfloods in fractured chalk blocks. Optimizing either capillary pressure data or relative permeability curves in the history matching of the waterfloods indicated which of these input data could be most trusted. Large scale, nuclear-tracer, 2D-imaging experiments monitored waterflooding the chalk blocks, first whole then fractured. This data provided in-situ fluid saturations for validating numerical simulations and evaluating capillary pressure- and relative permeability input data used in the simulations. History matching both the production profile and the in-situ saturation distribution development gave confidence to the simulations. The results indicated that using the experimental capillary pressure data and optimize the steady state relative permeability input data the simulator history matched the experiments very well, while using the experimentally measured relative permeability data and optimize the capillary pressure curve did not provide the correct input data for the simulator to reproduce the experimental results.

Conclusions

- Imbibition characteristics for cores treated to less water-wet conditions showed that reproducible and stable wettability conditions had generally been obtained.
- Capillary pressure curves and relative permeability curves showed mostly consistent trends when moving towards 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, sharper curvature for the drainage curves near Swi and higher Swi at the less-water-wet conditions.
- Drainage capillary pressure curves and forced imbibition negative capillary pressure curves at strongly-water-wet conditions employing standard industrial centrifuge techniques were found to be similar to results when utilizing the Direct Measurement of Saturation technique.
- Negative capillary pressure curves for forced imbibition showed a consistent development. At less water-wet conditions the capillary pressure curves became flatter and the residual oil saturations exhibited a consistent trend of smaller values when moving towards less water-wet conditions.

Nomenclature

k	permeability
L	length of core samples
p	pressure
S	saturation
t	time
V	volume
PV	pore volume

Greek

μ	viscosity
ρ	density
σ	interfacial tension, IFT
φ	porosity

Subscripts

f final
i initial
o oil
w water

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Table 1. Fluid Properties

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

Table 2. Summary of Core Plugs

Wett.1	Wett.2	Wett.3	Core #	Diam.	Por.[%]	Perm. [mD]	Used for
0,32	0,32	0,29	PC2-11	2"	47	5	Steady State Rel. Perm. Test
0,31	0,33		PC2-12	2"	47	5	Spare plug
0,52	0,55	0,57	PC2-13	2"	45	5	Steady State Rel. Perm. Test
0,54	0,55		PC2-15	2"	47	5	Spare plug
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.

Wett.1 Wettability test with decane as oil phase after aging with crude oil.

Wett.2 Wettability test where iododecane as the oil phase has replaced the decane.

Wett.3 Wettability test with decane as oil phase, after steady state relative permeability tests.

Table 3. Core Data, Experimental Schedule and Flood History for Core Plugs. used for steady state relative permeability tests.

Core #	PC 2-11			PC 2-12		PC 2-13			PC 2-15	
Length [cm]	7,81			7,38		7,54			7,36	
Diameter [cm]	5,08			5,08		5,08			5,08	
Porosity [%]	47			47		45			47	
Pore volume [ml]	74			70		68			70	
Abs. permeability [mD]	5			5		5			5	
Oilflood #:	1	2	3	1		1	2	3	1	
Oil viscosity [cP]	2,7	0,92	0,92	2,7		2,7	0,92	0,92	2,7	
Swi [%PV]	100	78	71	100		100	73	65	100	
dSw [%PV]	75	52	43	75		75	48	41	75	
Swf [%PV] a)	25	26	28	25		25	25	24	25	
Aging:										
Aging temperature [^{o}C]	90			90		90			90	
Aging time [days]	161	b)	b)	161		83	b)	b)	83	
Oil flooding prior to spontaneous imb. :	1	2	3	1	2	1	2	3	1	2
Decaline [PV]	5	0	0	5	5	5	5	0	5	5
n-Decane [PV]	5	0	2	5	0	5	0	2	5	0
Iododecane [PV]	0	2	0	0	2	0	2	0	0	2
Endpoint eff. perm. [mD]	9,9 c)	2,8	6,5 c)	7,7 c)	3,2	5,5 c)	2,1	4,5	9,7 c)	2,7
Spontaneous imbibition #:	1	2	3	1	2	1	2	3	1	2
Oil viscosity [cP]	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92
Swi [%PV]	25	26	28	25	25,8	25	25	24	25	25
dSw [%PV]	17	14	11	17	15,2	25	22	20	26	22
Swf [%PV]	42	40	39	42	41	50	47	44	51	47
Oil recovery [%OIP]	23	19	15	23	20	33	29	26	35	29
Waterflood #	1	2	3	1	2	1	2	3	1	2
Flow rate [ml/hr]	70	60	60	70	60	60	60	60	60	60
Swi [%PV]	43	42	39	43	41	50	47	44	52	47
dSw [%PV]	35	28	27	37	31	23	18	15	21	18
Swf [%PV]	78	70	66	80	72	73	65	59	73	65
Recovery [%OIP]	69	57	53	72	62	64	53	46	63	53
End point eff. perm. [mD]	1,5	1,4	1,3	1,3	1,5	1,4	1,1	1,4	1,9	1,6
Wettability index	0,32	0,32	0,29	0,31	0,33	0,52	0,55	0,57	0,54	0,55

a) Swf is the final water saturation after the first oilflood, corresponding to the Swi during aging.
b) No additional aging was performed between the repeated imbibition tests.
c) Endpoint relative permeability is higher than the absolute permeability.

Table 4. 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 [^{o}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^{o}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.

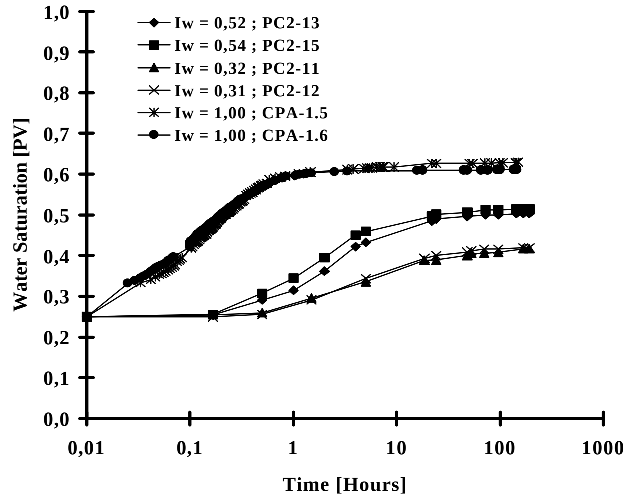

Figure 1. Imbibition characteristics for core plugs used for steady state relative permeability tests compared to typical strongly-water-wet plugs.

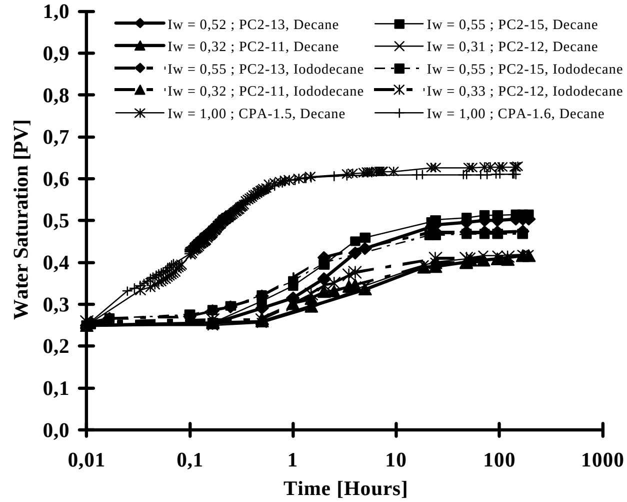

Figure 2. Imbibition characteristics for core plugs used for steady state relative permeability tests. Comparison of imbibition characteristics with decane and iododecane as oil phase.

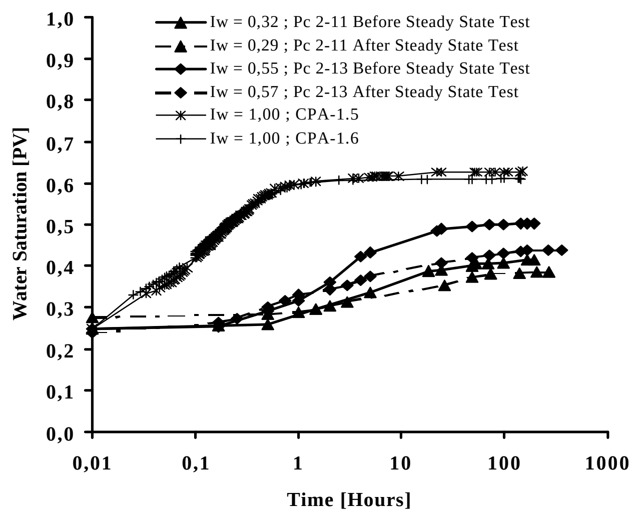

Figure 3. Imbibition characteristics for core plugs, before and after steady state relative permeability tests. Typical strongly-water-wet cores included for comparison.

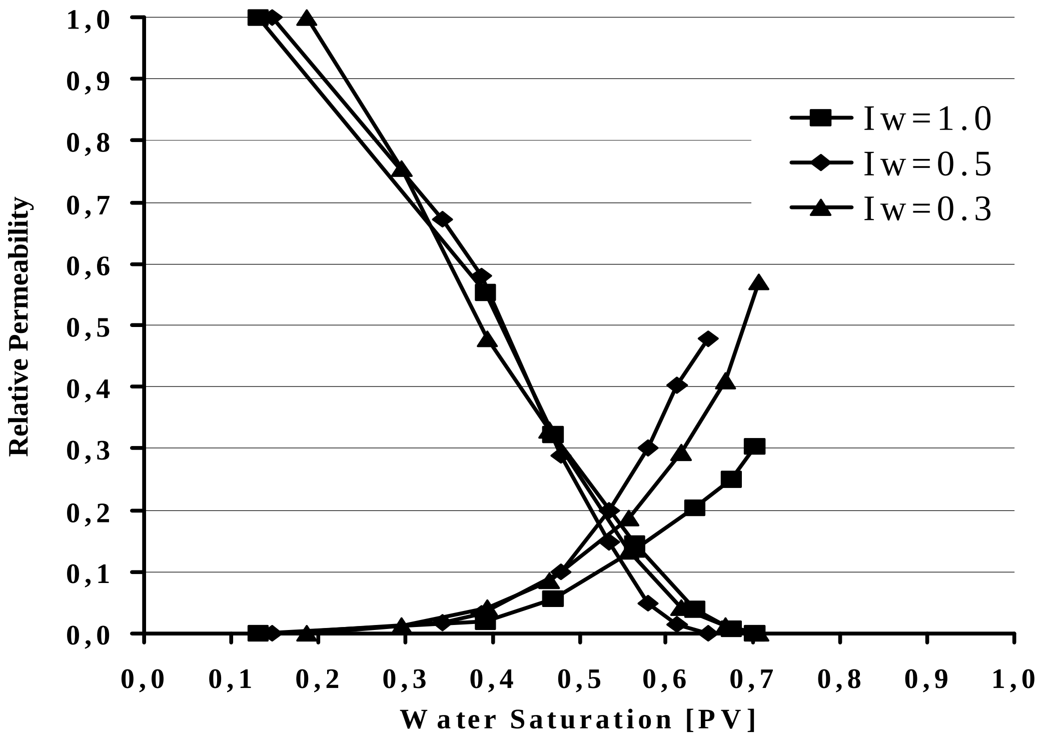

Figure 4. Experimental relative permeability measurements at different wettabilities.

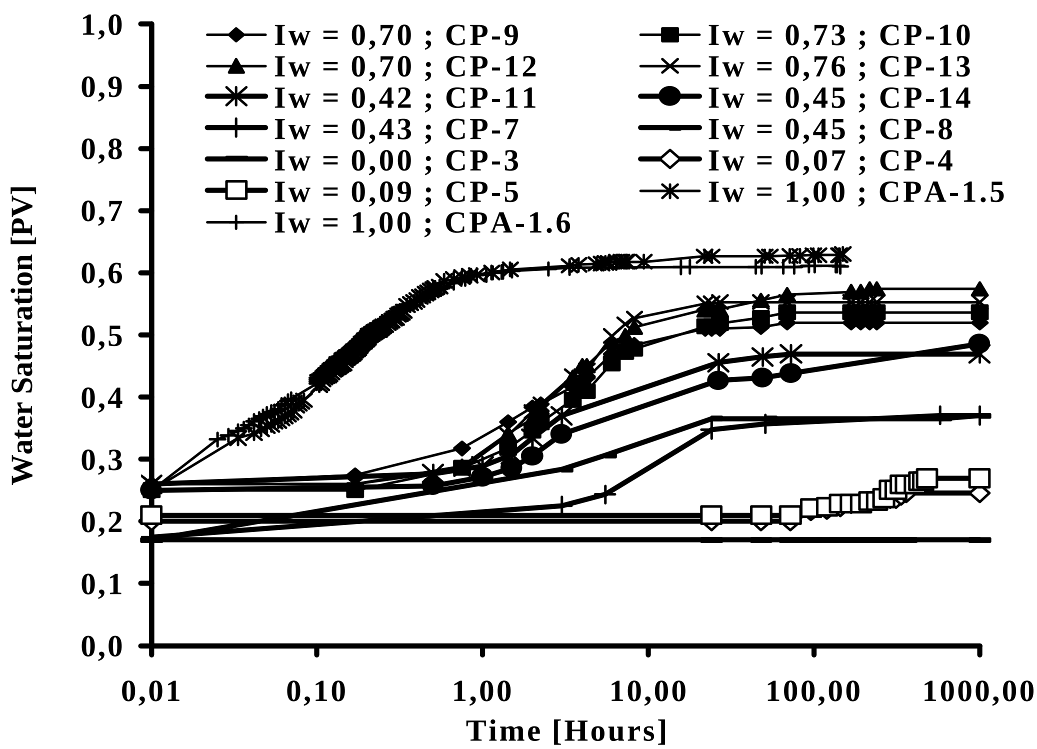

Figure 5. Imbibition characteristics for core plugs used for capillary pressure measurements. Typical strongly-water-wet cores included for comparison.

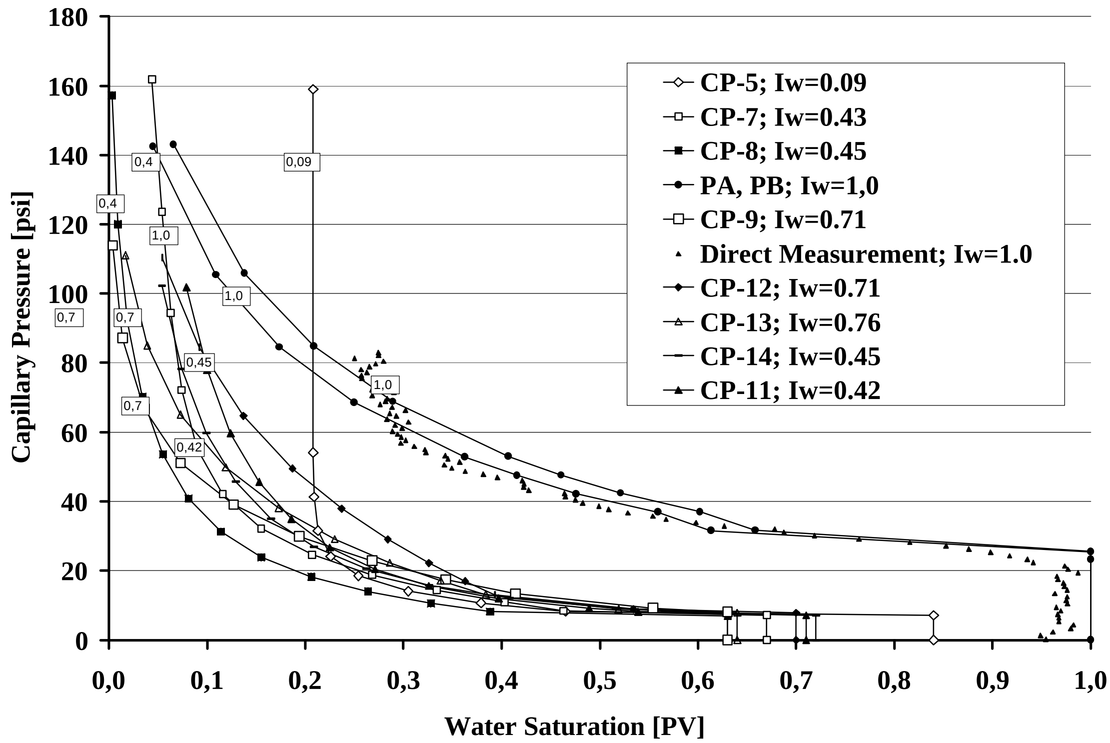

Figure 6. Secondary drainage capillary pressure curves with Hassler Brunner saturations, obtained by the centrifuge method.

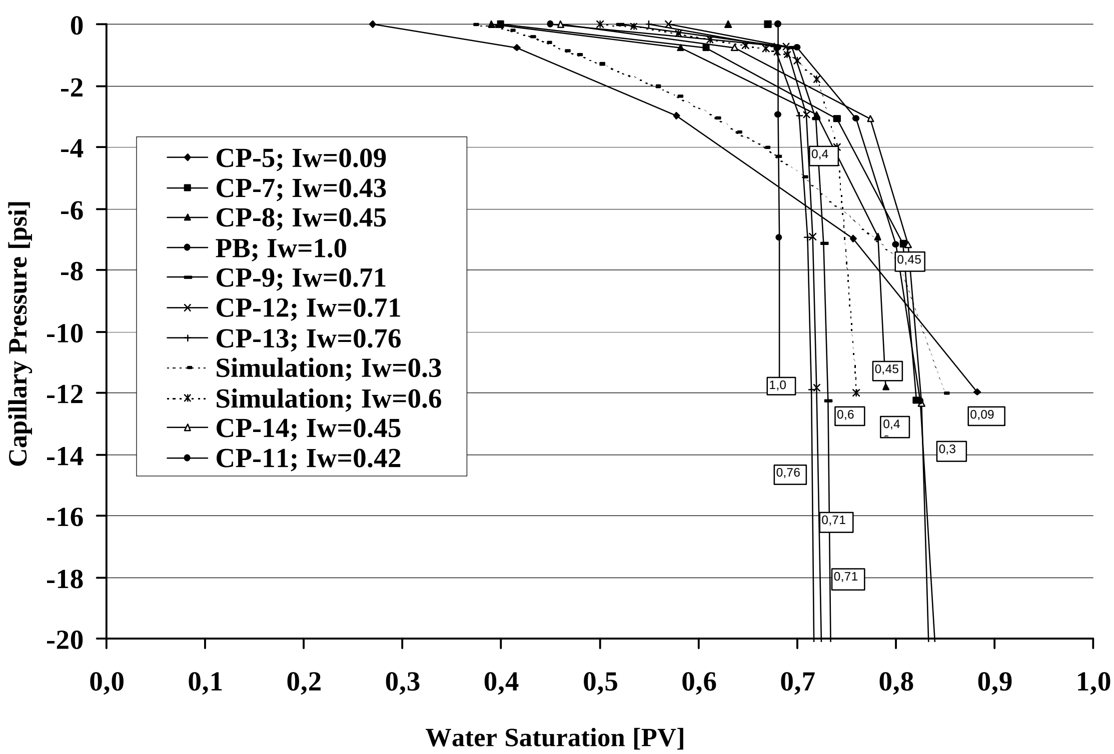

Figure 7. Negative capillary pressure curves with Hassler Brunner saturations, obtained by the centrifuge method. The curves for Iw = 0.3 and Iw = 0.6 have been generated by interpolation for input to numerical simulations of experiments at nearly-neutral-wet and moderately-water-wet conditions.