ESTABLISHING MIXED WET CONDITIONS IN CHALK - EMPHASIS ON WETTABILITY ALTERATION AND OIL RECOVERY

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ABSTRACT

Oil/brine/rock systems at various wettabilities were prepared using different crude oils, synthetic formation brine and Portland outcrop chalk. Various mixed wettability conditions were achieved and quantified by the Amott test for 75 core plugs. Several trends were observed. The established wettability conditions varied from neutral wet to strongly water-wet. Endpoint water saturation after spontaneous imbibition (S_{wsp}) increased with increase in initial water saturation (S_{wi}). For some selected core plugs, repeated Amott tests were conducted and showed good reproducibility and proved stable wetting conditions. Maximum oil recovery after forced imbibition (S_{orw}) occurred at slightly water-wet conditions.

INTRODUCTION

Wettability has shown to be an important parameter determining oil recovery mechanisms (Anderson, 1986, 1987). The microscopic fluid distribution and fluid flow in a porous media are controlled by the wettability conditions. Capillary pressure, relative permeability, electrical properties and simulated tertiary oil recovery are all affected by wettability. Improved fundamental understanding of wettability and its effect on oil recovery is therefore important to improve waterflood oil recovery and to enable additional oil recovery during ultimate tertiary production.

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” (Craig, 1971). This means that in a rock/oil/brine system, the wettability is a measure of the rock’s preference for either oil or brine. In a water-wet rock the water will occupy the small pores and serve as a water film between the rock and the oil in the larger pores. On the other hand, in an oil-wet rock the oil will be the phase wetting the mineral surface, thus the wettability has a great impact on the behavior and the distribution of the fluids. Salathiel (1973) introduced the term mixed wettability where the oil-wet surfaces form continuous paths for oil through the larger pores and where the smaller pores remain water-wet.

Earlier work showed that the wettability conditions for an oil bearing reservoir rock, was partly determined by the polar components in the crude oil (Buckley, 2002 and Fan, 2002). The chemical composition of a crude oil changes with geographic location, the reservoir's geological age and lateral and vertical locations within the same reservoir.

EXPERIMENTAL

Fluids

Eight different crude oils, denoted A-H, were used as the oil phases in the aging process. Oil H was mainly used in the aging process because of easy accessibility and good aging properties. A summary of the crude oil characterizations are given in Table 1. Data on the synthetic formation brine, decalin and decane used in the experiments are given in Table 2.

Core Plugs

A total of 75 core plugs were cut from several blocks of Rørdal chalk obtained from the Portland quarry at Ålborg in Denmark. 23 cores were cut to a length and diameter of 6 cm and 3.8 cm, respectively. The remaining 52 cores were cut to a length of 8 cm and diameter of 5.1 cm. The core samples were dried in an oven at 90°C for at least two day. The dry core plugs were evacuated and saturated with brine. Porosity was determined from the change in weight. Absolute permeability was measured.

Core Plug Preparation

In an oven holding 80°C all core plugs were oilflooded from both directions by crude oil. The differential pressure was gradually increased to a maximum pressure drop of 2 bar/cm. Oil injection was continued until the desired water saturation was established.

After establishing a uniform distribution of the initial water saturation, the core plugs were kept in the core holder at constant temperature of 80°C, and the aging process was initiated by oil flooding with a constant flow rate of 1.5 ml/h for the 3.8 cm diameter core plugs and 3 ml/h for the 5.1 cm diameter core plugs. Flood times ranged from 12 hours to 10 days. The flow direction was reversed at midway through the flooding cycle to achieve a uniform wettability distribution in the core plugs (Graue, 2000). The method used for altering the wettability is based on chemical interaction at elevated temperature between the crude oil and the rock surface (Graue 2000, 2003 and Aspenes 2003).

After aging, the crude oil was replaced by decane to establish a stable and reproducible fluid rock system, with a similar mobility ratio at room temperature as experienced in a reservoir at elevated temperature. The exchange was performed by flushing first five PV of decalin and then five PV of decane through the core plugs. Decalin was used to prevent destabilization of the crude oil.

Tests were also run on cores for which there was no aging at elevated temperature. These core plugs were drained from both ends by decane at 2 bar/cm pressure drop at room temperature.

Initial Saturation Classification

The initial water saturation, S_{wi}, varied from 19-34%. The core samples were therefore classified into four saturation groups at S_{wi}: 19-23%, 23-26%, 26-29% and 29-34%. The four saturation groups will be referred to as Saturation group 1, 2, 3 and 4.

Spontaneous and Forced Imbibition Tests

At S_{wi} the core plugs were set to spontaneous imbibition in brine at room temperature. Spontaneous oil production was measured as a function of time. After spontaneous imbibition in brine, the cores were placed in core holders and forced brine injection from both directions was performed using a constant pressure drop of 2 bar/cm. The pressure drop was gradually increased. The waterflood was stopped after 5 – 25 PV of brine injection when no more oil was produced.

RESULTS AND DISCUSSION

Core Samples

Porosity and permeability for all core plugs varied from 43-49% and 2.8-6.1 mD, respectively. The pore-size distribution for Portland chalk is uniform and narrow (Graue, 1999). The core plugs could therefore be characterized as homogeneous and comparable to each other.

Amott Index and Oil Recovery

Table of detailed core plug data were not included due to space limitation. The Amott indices (Amott, 1956) varied from almost 0 to 1. None of the core plugs were altered to oil-wet conditions. For all crude oils used during aging, longer aging time resulted in less water-wet condition. Figure 1 presents spontaneous imbibition curves for eight core plugs selected as representative for each saturation group and at wettability conditions varying from neutral wet to strongly water-wet. Imbibition rate decreased systematically at less water-wet conditions. Oil recovery by imbibition exhibited a maximum at $I_w = 0.80$, and has been attributed to increased microscopic displacement efficiency (Salathiel, 1973).

Oil recovery after spontaneous imbibition and oil recovery after waterflooding for all core plugs are shown in Figure 2. Oil recovery by spontaneous imbibition increased almost linearly with increase in Amott indices until it reached a maximum at $I_w = 0.85$ with $R_f = 0.60$. For Amott indices exceeding the maximum value of oil recovery decreased to about $R_f = 0.50$ at strongly water-wet conditions. Oil recovery after waterflooding as a function of wettability indicated by Amott indices gave a dome shaped curve with maximum recovery at about $I_w = 0.4$. A similar trend was reported by Zhou (2000).

Reproducibility

For some selected core plugs, repeated Amott tests were conducted to test reproducibility and to determine if the wetting conditions were stable. Figure 3 shows the two subsequent spontaneous imbibitions (denoted 1 and 2) for the core plugs 4 and 8. The shape of the curves for these imbibitions was almost identical with the same endpoint saturations in the repeated imbibitions for both samples. The established wettability was therefore assumed to be stable and not changing with time.

The Effect of Initial Water Saturation

The initial water saturations varied from 19-34%, depending on the crude oil and core plug heterogeneities. The effect of initial water saturation, S_{wi}, on the endpoint water saturation after spontaneous imbibition, S_{wsp}, and after waterflooding, S_{orw}, for the four saturation groups are shown in Figure 4. Endpoint saturation after spontaneous imbibition increased systematically with increase in initial water saturation. After waterflooding the endpoint water saturations indicated increased S_{orw} with increased S_{wi}. Maximum water saturation after waterflooding was obtained at about the same wettability condition for all four saturation groups. The decrease in S_{wsp} with decrease in S_{wi} at any wettability was consistent with reduced water wetness.

CONCLUSIONS

- A range of wettability conditions from neutral wet to strongly water-wet conditions were obtained for 75 Rørdal outcrop chalk core plugs.
- For each oil type longer aging time resulted in less water-wet conditions. None of the oils resulted in oil-wet conditions after aging. Consistent longer induction time for the spontaneous imbibition was observed for less water-wet cores.
- Oil recovery by spontaneous imbibition passed through a maximum in oil recovery at slightly less water-wet conditions than at very strongly water-wet conditions.
- Excellent reproductions of wettability measurements were obtained for various wettability conditions.
- Increased initial water saturation, S_{wi}, during aging resulted in increased endpoint water saturation after spontaneous imbibition S_{wsp}.
- Oil recovery by waterflooding was observed to have a maximum value at about I_w = 0.4, independent of the initial water saturation S_{wi}.

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Table 1. Results from crude oil analysis.

Oil	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Acid number	1.03	0.09	0.34	0	0.26	0.18	0.18	0.09
Base number	1.76	0.44	0.55	0.11	0.26	0.66	0.66	1.18
IEP	3.4	4.5	3.9	4.3	5.2	4.9	5.4	
Viscosity 20°C [cP]	141.04	2.56	4.24	2.06	2.55	4.20	2.06	14.3
Density 20°C [g/ml]	0.915	0.802	0.824	0.794	0.803	0.818	0.806	0.85
Molecular weight [u]	335	188	204	171	172	204	154	
RI 20°C	1.514	1.450	1.460	1.446	1.451	1.457	1.453	
API 20°C	23.1	45.0	40.3	46.7	44.7	41.5	44.0	
Saturates %	83.1	85.5	76.5	82.6	78.8	83.3	62.8	53
Asphaltene %	2.1	0	0.52	0.008	0.11	0.008	0.32	0.90
Resins %	1.41	0.43	4.39	2.54	5.94	3.75	13.52	12
Aromates %	15.19	14.03	19.00	14.80	14.73	13.00	21.54	35

Table 2. Brine and mineral oils.

Fluid	Type/Content	Viscosity at 20°C [cP]	Density at 20°C [g/cm^3]
Brine	Distillate water 5 wt. % NaCl 5 wt. % $CaCl_2$ 0.01 wt. %NaN_3	1.057	1.09
n-Decane ($C_{10}H_{22}$)	Mineral oil	0.73	0.92
Decahydronaphtalene (Decalin, $C_{10}H_{18}$)	Mineral oil	0.90	0.85

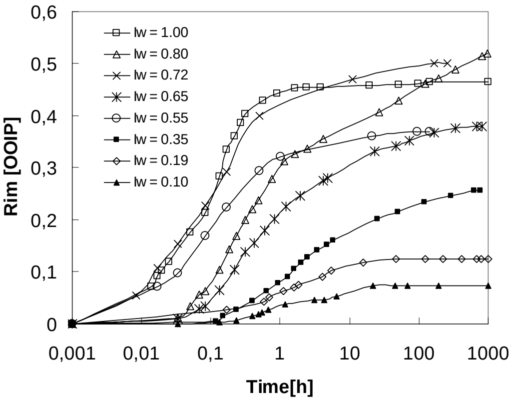

Figure 1. Spontaneous imbibition curves from eight selected core samples from all saturation groups and at wettability conditions varying from neutral wet to strongly water-wet.

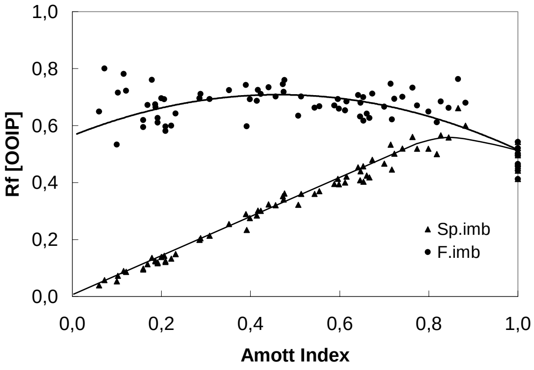

Figure 2. Oil recovery after spontaneous imbibition and after waterflooding versus Amott Imdex.

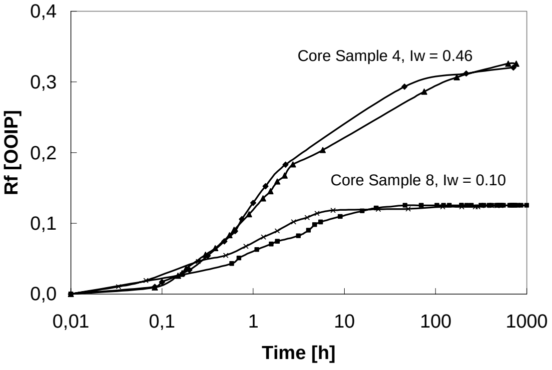

Figure 3. Reproduced spontaneous imbibition for two core samples.

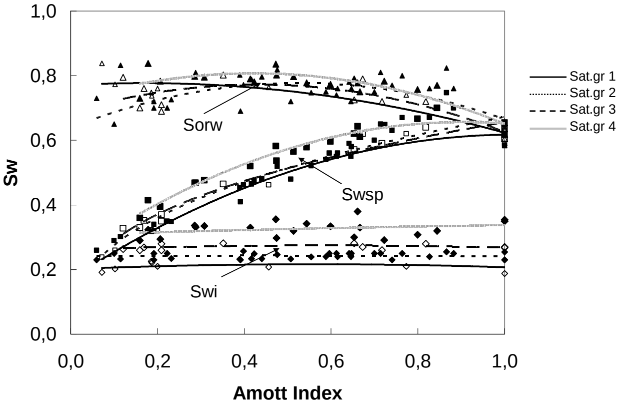

Figure 4. S_{wi}, S_{wsp} and S_{orw}, versus Amott Index to water for the four saturation groups.