HYSTERESIS EFFECTS IN CAPILLARY PRESSURE, RELATIVE PERMEABILITY AND RESISTIVITY INDEX OF NORTH SEA CHALK

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ABSTRACT

Accurate estimation of capillary pressure and relative permeability curves are very important for evaluating hydrocarbon recovery processes. Also, resistivity index data are important in evaluating fluid distributions in reservoirs during these processes. All these parameters are path dependent i.e. different in drainage and imbibition processes, commonly known as hysteresis, which makes them complicated to predict. Laboratory tests have therefore been performed on four North Sea chalk core samples to measure the wettability index and determine the hysteresis in capillary pressure, relative permeability and resistivity index. The cores were extracted using toluene and methanol, and a light oil (*n*-decane) and brine saturation equivalent to the formation water were used in the displacement processes. Varying levels of hysteresis were observed. Hysteresis effects were significant in capillary pressure and relative permeability curves and not so pronounced for the resistivity index.

1. INTRODUCTION

Knowledge about the flow paths of wetting and non-wetting phases is basic in understanding multi-phase flow in hydrocarbon reservoirs from initial oil migration in source rocks to primary and tertiary recovery processes. The flow paths of the displacing and displaced fluids are governed by the distribution of the fluids in the pores, the pore size distribution, and the interaction between the fluid and the rocks (wettability), among others.

In order to estimate the *in situ* water and hydrocarbon saturations, resistivity tests are carried out and then combined with a saturation model. Although there exists many saturation models, results in this study have been based on Archie's (1942)-saturation model. The saturation exponent n is determined from log-log plot of I_r versus S_w, which is usually assumed to be linear. Extraction of cores, geological features, wettability, vugs, electrical conductive minerals, microporosity and rugged grain surfaces have been found to cause deviation from the linearity scale (Stalheim and Eidesmo, 1995). This results in either an increased n with decreasing S_w (positive curvature), or a decreasing n with decreasing S_w (negative curvature). Hysteresis effects in the n-value during the drainage and imbibition processes have also been observed by many researchers (Wei and Lile, 1993; Lewis *et al*, 1988).

Relative permeability depends on a combined effect of pore geometry, fluid distribution, wettability, and fluid saturation history, among others. Therefore relative permeability curves will show that during drainage and imbibition processes, the fluids can exchange positions and flow behaviour resulting in hysteresis effects (Geffen *et al*, 1951). Like relative permeability, capillary pressure/saturation relationship depends on the composite interaction of wettability, pore structure, initial saturation and saturation history. Generally there is hysteresis in capillary pressure as the saturation is varied in drainage and imbibition processes.

2. EXPERIMENTAL WORK

The work included the following in chronological sequence: cleaning and drying, porosity and absolute permeability determination, capillary pressure and Amott wettability index determination, relative permeability determination by the unsteady state technique and resistivity measurements. The procedures for the hysteresis studies are as follows:

Capillary pressure was obtained by the centrifuge method. The cores were saturated with the wetting phase (brine) and rotated in the non-wetting phase (*n*-decane) at increasing speeds. The Hassler and Brunner (1945) corrected water saturations at each speed were calculated. The cores were then removed and submerged in brine for minimum 300 hours and spontaneously produced oil was recorded. The positive part of the imbibition curve was modelled (Hegre, 1992). The cores were then centrifuged in brine and negative capillary pressure data were obtained. The core plugs were submerged in oil for minimum 300 hours to determine the spontaneously taken up oil. The end point saturations were used to calculate the Amott (1959) wettability index.

Relative permeability was measured by the unsteady state method under constant differential pressure (5 bar) during the drainage and imbibition cycles. First, the cores were saturated with 100 per cent water and then desaturated by injecting oil until no more water production was obtained, defining the initial water saturation, S_{wi}. Oil was then displaced by brine until no more oil production was observed. During displacement experiments no measurement points are possible before breakthrough for both drainage and imbibition (see Table 1 for breakthrough saturations). Also, the measurements points after breakthrough are normally scattered. Relative permeability curves consisting of scattered points and no points before breakthrough are not suited for practical applications. Therefore, numerical simulations were conducted using a commercial reservoir simulator and relatively smooth curves covering important range of water saturation were obtained from Corey exponent representation through history matching of the oil and water production data.

Electrical resistance of the cores was determined at laboratory conditions by a two-electrode method using the ratio of voltage decrease between a reference resistor and a core sample in series. The cleaned and dried cores were 100 % saturated with formation brine and placed in the resistivity cell to measure R_o. The cores were then placed in a

core holder and the brine was displaced by *n*-decane using a pump. Saturation changes were measured by weighing and double-checked by the amount of brine produced. At each reduction in saturation, the core was transferred to the resistivity cell and the drainage resistivity indices were determined. Saturation and resistivity indices for the imbibition cycle were achieved similarly, but instead *n*-decane was displaced with brine in steps until S_{or} was reached.

3. RESULTS AND DISCUSSIONS

The key rock parameters and results of the multiphase experiments are given in Table 1. The fluid data is as follows: Brine density; 1.05 g/cc, oil density; 0.73 g/cc, brine viscosity; 1.05 cp, oil viscosity, 1.36 cp and brine/oil interfacial tension; 13.56 dynes/cm.

Table 1: Key parameters from displacement experiments on the chalk core samples.

Core number	2	3	4	6	Core number	2	3	4	6
Core length (cm)	4.27	4.22	4.15	3.79	Oil index, r_o	0	0	0	0
Core diameter (cm)	3.74	3.75	3.74	3.71	$I_{Amott} = r_w - r_o$	0.34	0.35	0.39	0.53
Pore volume (cm^3)	8.92	12.26	8.69	12.66	*n* Drainage	1.6	-	1.4	1.7
Porosity (fraction)	0.19	0.26	0.19	0.31	Imbibition	1.4	-	1.4	1.6
Air permeability (md)	0.20	1.35	0.36	2.60	$S_{wi\,(H\,\&\,B)}$	0.19	0.10	0.19	0.11
Liquid permeability (md)	0.09	0.64	0.12	1.94	$S_{or\,(H\,\&\,B)}$	0.18	0.20	0.17	0.24
Entry pressure (bar)	0.67	0.24	0.42	0.22	k_{ro} at S_{wi}	0.77	0.85	0.74	0.79
Water index, r_w	0.34	0.35	0.39	0.53	k_{rw} at S_{or}	0.17	0.20	0.21	0.29
Water saturation at breakthrough					Drainage	0.48	0.63	0.59	0.53
					Imbibition	0.69	0.49	0.53	0.51

Capillary pressure/saturation relationship results from centrifuge experiments and imbibition cell are shown in Fig. 1 and 2. Capillary hysteresis can clearly be observed from the primary drainage and spontaneous imbibition data. The final hysteresis loop will consist of a spontaneous uptake of oil and the secondary drainage curve. An example of a complete capillary pressure curve is shown in Fig. 2.
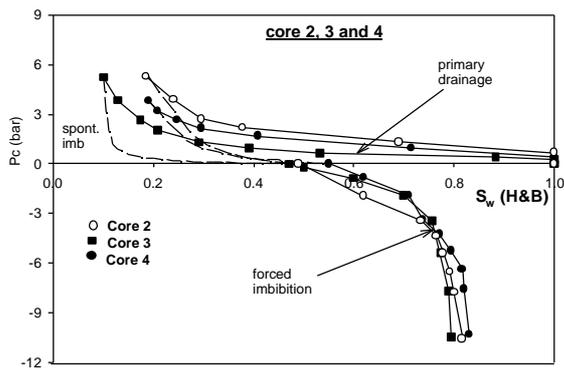

F ig. 1: Water-oil capillary pressure (core 2, 3 and 4).
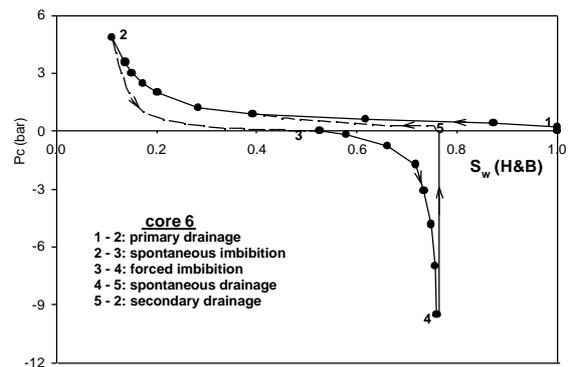

Fig. 2: Water- oil capillary pressure (core 6).

The Amott wettability indices were computed using the data from spontaneous and forced drainage and imbibition tests. The indices (0.34 - 0.53) are shown in Table 1 and reveal moderately water-wet conditions for all the chalk samples. There was no spontaneous uptake of oil. Since the cores were not aged after cleaning, the use of crude oil and ageing could result in different wettability indices. Tobola (1996) has reported similar low wettability indices in some North Sea chalk samples from tight formations with no visual evidence of fractures. The quartz content of chalks can also affect the capillary pressure/water saturation relationships and hence the wettability (Spinler, 1996), but the composition of the chalk was not investigated in this work. The drainage capillary pressure curves showed low entry pressures (0.22 - 0.67 bars), sharp curvature for drainage near S_{wi} and big saturation changes at slightly negative capillary pressures during the forced imbibition. The shape of the negative capillary pressure curve indicate that the forced imbibition has the potential of being an important production mechanism in chalk. Previous studies on North Sea chalk (Graue *et al*, 1999 and Tobola, 1996) reported similar production characteristics at less water-wet conditions.

Relative permeabilities are graphically shown in Fig. 3 and 4. The key end point saturation and relative permeability values are indicated in Table 1. The end-point values are typical and consistent with earlier tests on chalk reported in literature for water-wet conditions (Graue *et al*, 1999).
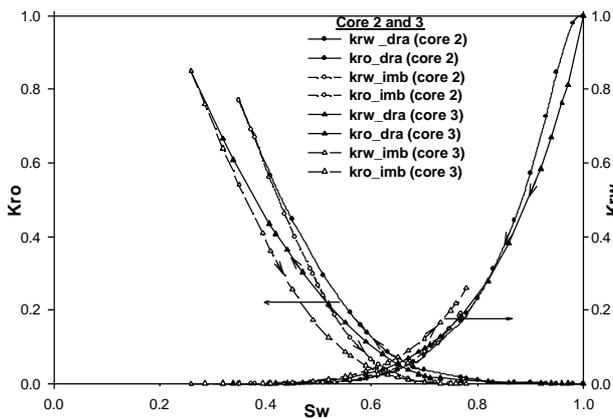

Fig. 3 Water-oil relative permeability (core 2 and 3).
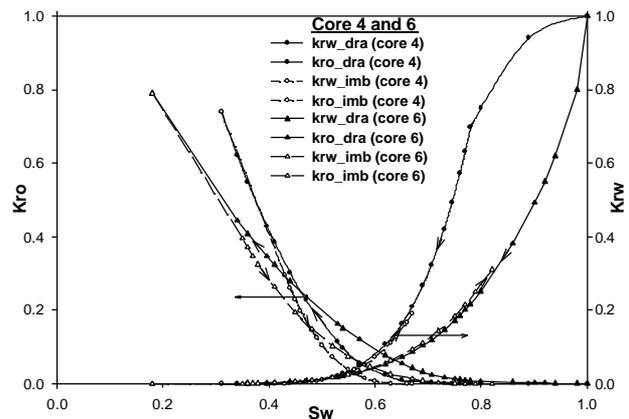
Fig. 4 Water-oil relative permeability (core 4 and 6).

The drainage and imbibition processes show hysteresis effects in the relative permeability curves. The hysteresis is more pronounced in the non-wetting phase than in the wetting phase. In improved recovery projects, we may often encounter a change from one process to another. The flow reversal may occur at any intermediate saturation and the relative permeability will follow an intermediate path.

The saturation exponent (*n*) was determined from log-log plot of I_r versus S_w for both the drainage and imbibition processes. Values from 1.4 to 1.7 were recorded. These are shown in Table 1 and on log-log graph (Fig. 5). Hysteresis in resistivity index was observed during the drainage/imbibition cycles of core 2 (Fig. 5) and core 6. The computed values of *n* for the drainage and imbibition processes in core 2 are 1.6 and 1.4 respectively. Values of *n* for core plug 6 are 1.7 and 1.6 for the drainage and imbibition cycles. Core 3 broke and core 4 had no hysteresis with *n*-value of 1.4. The relatively low values of *n* could be explained by the cleaning of the chalk cores; resulting in reduced oil-wet surface areas within the pore space, and maintaining of the lengths and conducting paths of brine in the sample for a wider range of saturations (Sweeney and Jennings, 1960).
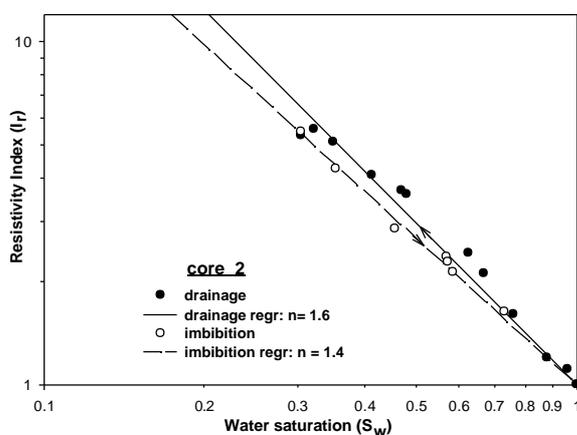
Fig. 5: Log-log plot of I_r versus S_w (core 2).

Other factors causing the variation in the saturation exponent of chalk may include the presence of micropores, irregular surfaces in the samples and the different degrees of wettability, Spinler and Hedges (1995). The presence of fractures have been found to cause negative curvatures as water saturation decreases (Rasmus, 1986). This behaviour can be seen in Fig. 5 for core sample 2 at water saturations below 30%. Although there was no attempt to correlate this variation, some North Sea chalk fields are highly fractured. Such variations could have significant effect on predictions of initial hydrocarbon estimates in place and on subsequent reservoir performance.

4. CONCLUSIONS

1. The North Sea chalk samples analysed with n-decane and simulated formation brine without ageing showed a moderately water-wet tendency. This was revealed by the positive wettability indices, the curvature of k_{rw} and k_{ro} curves and saturation and relative permeability end-points in the drainage and imbibition processes.

2. Significant capillary hysteresis effects have been observed in the drainage and imbibition capillary pressure curves for all the core samples. The forced imbibition is an important production mechanism for oil production from the tested chalk material.

3. The effect of saturation history on the distribution of fluids was also reflected in the hysteresis effect in drainage and imbibition relative permeability curves. However, hysteresis in the wetting phase (water) relative permeability was generally negligible.

4. A minor hysteresis in resistivity has been observed between drainage and imbibition in the tested chalk core samples.

NOMENCLATURE

I_r: resistivity index
k_{ro}: relative permeability of oil
k_{rw}: relative permeability of water
n: Archie's saturation exponent
P_c: capillary pressure
R_o: resistivity of core 100 % saturated with brine
r_w, r_o: water and oil indices respectively

$\overline{S}_w$: average water saturation
$S_w(H\&B)$: Hassler and Brunner corrected saturation
S_{or}: residual oil saturation
S_w: water saturation
S_{wi}: initial water saturation

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