NEW SATURATION FUNCTION FOR TIGHT CARBONATES USING ROCK ELECTRICAL PROPERTIES AT RESERVOIR CONDITIONS

Oriyomi Raheem and Hadi Belhaj
The Petroleum Institute, Abu Dhabi, UAE

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ABSTRACT

In the present study, a core analysis program including NMR measurements were performed to get a better petrophysical characterization of carbonate reservoir transition zone in the Abu Dhabi region. The results reveal three distinct rock types with average NMR-T_2 cutoffs of 292 ms, 164 ms and 63 ms for the topmost, middle and lowermost samples of the reservoir respectively. Electrical resistivity and capillary pressure-water saturation were also measured at ambient and reservoir (2500 psi and 85 °C) conditions using a DCI Pc-RI systems mimicking drainage and spontaneous imbibition to investigate the hysteresis and variation in saturation exponent.

It was found that the cementation exponent increases from 1.9 to 2.4 under overburden conditions and decreases in a stepwise manner during reduction of overburden, but not to the initial value due to hysteresis. This implies that the electrical parameters at ambient condition would lead to underestimation of water saturation. The saturation exponents estimated during drainage and spontaneous imbibition at reservoir conditions range from 1.5 – 4.0 for the different rock types tested in this study.

New saturation functions were developed for each rock type from the measured electrical parameters at reservoir conditions by using the modified Archie's equation for the transition zone of this carbonate reservoir. The outcomes of the present study lead to a correction of the field resistivity log data that, overestimate the water saturation and hence predictions of saturation distributions, mobility and original oil in place.

INTRODUCTION

To understand wettability distribution variation across a particular reservoir, a meticulous understanding of the reservoir mechanisms (fluid flow behavior) is required to predict the original oil in place. Both fluid dynamic properties of reservoir and geological understanding will aid for the determination of both water saturation and wettability distribution throughout the reservoir. Electrical resistivity of a reservoir rock is a very important petrophysical attributes of log analysis. Rock electrical properties measured in the lab are widely employed in well logs interpretation and calibration. It is used to estimate the Archie's parameters which are later used in log porosity-saturation estimation. The Archie cementation factor m of reservoir rock sample is an important parameter as it significantly influences the porosity and permeability of rocks in a carbonate reservoir. Carbonate reservoirs usually show thick transition zone which is traditionally defines as the reservoir interval that extends from the oil-water contact (OWC) up to the reservoir level where water saturation reaches its irreducible level. As transition zone contains significant volume of oil, its characterization is utmost important for reserve estimation. Therefore, estimations of electrical resistivity, and water saturation at reservoir conditions are required to better understand the saturation distribution with ultimate focus on the transition zone.

High pressure and elevated temperature are observed due to increasing depth of hydrocarbon bearing carbonate rocks in the reservoir. The effect of confining pressure on the cementation factor *m* have been studied by many investigators, mostly on sandstone rocks, but occasionally on carbonate rocks [1-3]. Further investigations on water saturation exponent *n* as well as cementation factor *m* are highly recommended to draw a clear concept on the variation of these parameters at reservoir conditions. Particularly carbonate samples from transition zone and their characterizations are crucial in this contest to get a better understanding of the fluid flow behavior and initial water saturation distribution. The cementation and saturation exponent values in the empirical equations of Archie are assumed to be independent of reservoir fluid, solid surface properties, temperature and pressure [3]. Longeron et al. [1] found out that sandstones reached equilibrium rather quickly after an increase in confining pressure, but carbonate samples in turn required several days to reach equilibrium. They concluded that cementation factor *m* increases with pressure. Several authors observed that the saturation exponent n reflected the wettability effect on rock electrical properties. While some researchers concluded that *n* depends on the microscopic distribution of fluids during drainage or imbibition [1,2,4], other researchers stated that *n* is a function of rock wettability and showed that *n* increases as the oil wettability of a rock increases.

The task ahead involved developing a saturation function to correct the field logs using the carbonate plug samples in the Abu Dhabi region. For this purpose, the present work uses the 2D NMR and conventional core analysis for the petrophysical characterization of transition zone plug samples. Electrical resistivity and capillary pressure-water saturation values, at ambient and reservoir conditions, were also measured using a DCI Pc-RI systems.

EXPERIMENTAL METHODOLOGY

The core samples were selected at different depth domains in the transition zone of the carbonate reservoir. They were cut and trimmed to a maximum of 2 inch length and 1.5 inch diameter. The samples were cleaned by Soxhlet extraction method. NMR T_1T_2 maps were used to ascertain the crude oil or tar absence from the samples before further analysis. De-ionized water and different salts were mixed in appropriate proportions to prepare the formation brine in the laboratory to recreate the aquifer brine.

The core samples were vacuumed and saturated with brine at a pressure of 2000 psi and kept pressurized for a period of 24 hours in a saturator. Nuclear magnetic resonance was used to group the fully saturated plugs into different static rock types, based on similar pore size distributions. Centrifugation technique was used to develop air-brine capillary measurements and get irreducible water saturation and subsequent T_2 cut-off values.

The effect of both confining pressure and temperature on the cementation and saturation exponents of the core samples were studied with the help of a porous plate DCI equipment that measures resistivity at ½ in. intervals along the core. The cementation factor *m* and saturation exponent *n* estimated from electrical resistivity measurements are tagged as 1_2, 1_3, 2_3 and 1_4 along the samples. Subsequently, the capillary pressure curves and the resulting irreducible water saturation at reservoir conditions were compared with centrifuge and NMR ambient values. The saturation exponent *n* was also derived during drainage and imbibition processes at 2500 psi and 85^{o}C. A curve fitting by least squares regression was used to estimate the saturation function using the fundamental Archie's equation [5].

RESULTS AND DISCUSSION

Carbonate rocks are dissimilar to sandstones, having more complex pore system which may due to diagenesis, compaction and stress changes thereby causing dual porosities. Figure 1 depicts the unimodal pore size distribution of the selected plug samples. The wider NMR T_2 spectrum indicates large porosity and a wider pore size range. Using Centrifuge-NMR technique, Figure 2 clearly shows the cumulative NMR T_2 distribution. The cementation factor *m* and formation factor *FF* of all the core samples used in this study were found to increase with confining pressure from 500psi to 2500psi and corresponding temperature variation from 25 °C to 85 °C as shown in Figure 3. The increase was slight for the rock samples closer to aquifer. From Table 1 it is confirmed that the 'm' decreases with increasing depth.

The saturation exponents, *n* determined from both the logarithmic slopes during drainage and imbibition cycles are shown in Figures 4, 5, 6 for three rock samples. The detailed results are shown in Table 2. The *n* values estimated from force fitting to cross (RI;Sw)=(1;1) samples 1_8 and 1_30 were greater than 2 (oil-wet) during drainage. However, the *n* values of samples 1_30 and 2_1 increased during spontaneous imbibition (more oil wet). This change in wettability was attributed to the 40 days ageing effect. During long term ageing the polar organic compounds of the crude oil are believed to be adsorbed onto the rock surface and change of wettability. The estimated *n* values for sample 1_8 was initially greater than (oil-wet) during drainage but decreased further during spontaneous imbibition (less oil wet) (table 2). This confirms wettability changes with depth [4]. The average *n* values estimated at both frequencies (1 kHz & 10 kHz) were approximately the same during drainage and spontaneous imbibition (table 2). The S_{wi} values estimated from the capillary pressure curves were found to be 16% less than that estimated at ambient conditions, as shown in Figures 7 and 8. By substituting RRT-1 (m = 2.25, n = 4.0), RRT-2 (m = 1.95, n = 2.6) and RRT-3 (m = 1.95, n = 1.1) values in the equation 1 below, the saturation functions can be developed accordingly.

$$S_w = \left[\frac{aR_W}{\emptyset^m R_T}\right]^{1/n} \quad (1)$$

Where R_w is the resistivity of formation brine, R_t is the true formation resistivity and a is the lithology factor. Due to the changes in pore volumes and resistivity noticed between atmospheric and 500 psi confining pressure which are assigned to poor electrode contact, the baseline for comparison were set at 500 psi and room temperature. Measurements of resistivity and saturation during the porous plate test were taken at equilibrium. In summary, electrical resistivity was influenced by changes in confining pressure and temperature. Due to the increase in brine conductivity due to temperature, the electrical resistivity across the core samples were found to decrease with temperature as shown in Figure 9. However, as the confining pressure was increased in the test cell cart, the electrical resistivity showed a reverse trend, increasing by about 56% within 500 psi and 2500 psi due to compaction or pore volume reduction (Figure 10). The results prove that electrical resistivity measurements performed in the laboratory simulating reservoir conditions are preferably more accurate.

CONCLUSIONS

Based on the results of the present work, the following conclusions can be drawn as follows:

1. Pore size distribution by NMR T_2 study indicates three different rock types along the different depth of the reservoir.
2. The estimated S_{wi} values at reservoir conditions are 16% lower than that measured at ambient conditions, underestimating oil saturation. Electrical resistivity is influenced by changes in confining pressure and temperature. By running sensitivity analysis, 17% error occurred in S_w determination when m and n are not measured at reservoir conditions.
3. The saturation exponent n values calculated during spontaneous imbibition are higher than values determined during drainage for oil-wet system and vice versa for water-wet system. Estimated saturation exponents from force fit were minimally affected by changes in frequency.
4. There is a possibility of wettability change as water saturation decreases up the transition zone which is influenced by its thickness.

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Table 1. Calculated values of cementation exponent ‘m’.

					Amb. Cond. [AC]				**Res. Cond.[RC]**				**[AC]**	**[RC]**
Sample	**Depth from (ft)**	**Por. (%)**	**K_{air} (mD)**	**T2 CUTOFF (ms)**	**m 1-2**	**m 1-3**	**m 1-4**	**m 2-3**	**m 1-2**	**m 1-3**	**m 1-4**	**m 2-3**	**m_{av}**	**m_{av}**
1_8	9523	17.74	1.13	156	2.1	1.9	1.9	1.8	2.3	2.3	2.3	2.3	1.9	2.3
1_9	9526	11.53	0.12	152	2.0	1.9	1.9	1.9	2.2	2.1	2.2	2.1	1.9	2.2
1_15	9547	10.88	0.12	115	1.8	1.7	1.7	1.6	2.1	2.0	2.0	1.9	1.7	2.0
1_30	9592	17.53	0.92	115	1.6	1.7	1.6	1.7	2.0	1.9	1.9	1.8	1.6	1.9
1_32	9596	17.49	0.96	115	1.9	1.7	1.7	1.6	2.1	1.9	1.9	1.7	1.7	1.9
2_1	9597	16.39	0.55	79	1.6	1.7	1.6	1.7	2.0	1.9	1.9	1.8	1.6	1.9
2_4	9606	14.24	0.31	79	1.8	1.6	1.6	1.6	2.1	1.9	1.9	1.8	1.6	1.9
2_6	9612	18.67	0.71	60	1.8	1.7	1.7	1.7	2.1	1.9	2.1	1.8	1.7	2.0

Table 2. Calculated values of saturation exponent ‘n’ at different frequencies.

DRAINAGE										
	Resistivity @ 1khz					**Resistivity @ 10khz**				
Sample	**n 1-2**	**n 1-3**	**n 1-4**	**n 2-3**	**n avg**	**n 1-2**	**n 1-3**	**n 1-4**	**n 2-3**	**n avg**
1_8	3.0	2.7	2.6	2.5	2.7	3.0	2.8	2.6	2.7	2.8
1_30	2.7	2.6	2.6	2.4	2.1	2.8	2.6	2.6	2.5	2.1
2_1	2.0	2.0	1.9	1.8	1.9	2.0	2.0	1.9	1.8	1.9
IMBIBITION										
	Resistivity @ 1khz					**Resistivity @ 10khz**				
Sample	**n 1-2**	**n 1-3**	**n 1-4**	**n 2-3**	**n avg**	**n 1-2**	**n 1-3**	**n 1-4**	**n 2-3**	**n avg**
1_8	2.8	2.6	2.4	2.3	2.5	2.9	2.7	2.4	2.6	2.6
1_30	3.0	2.9	2.9	2.7	2.7	3.2	3.0	2.9	2.8	2.6
2_1	2.7	2.4	2.4	2.2	2.4	2.7	2.5	2.4	2.2	2.5

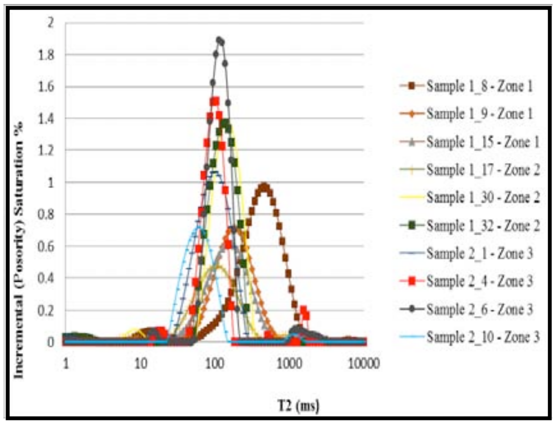

Figure1. NMR Pore Size Distribution.

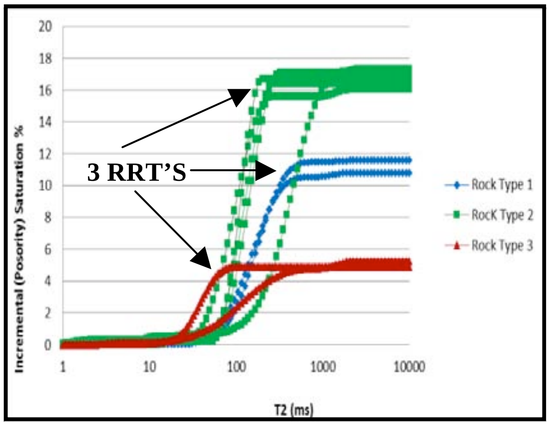

Figure 2. NMR Incremental Saturation vs. T2.

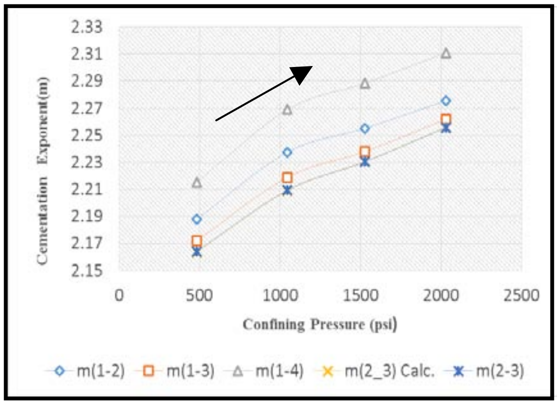

Figure 3. Plot of "*m*" vs. Pressure (1_8).

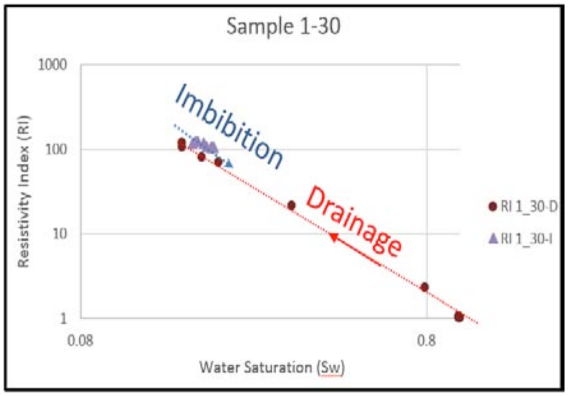

Fig. 4. Drainage & Spont. Imb in RI vs Sw (1_30).

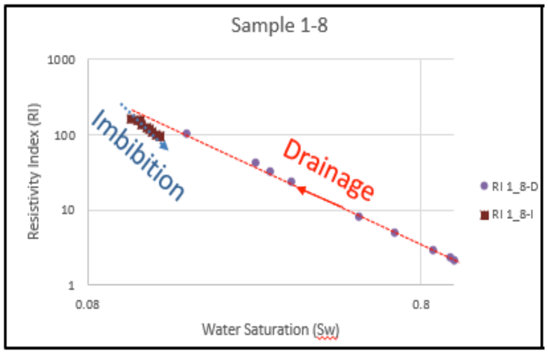

Fig. 5. Drainage & Spont. Imb. in RI vs Sw (1_8).

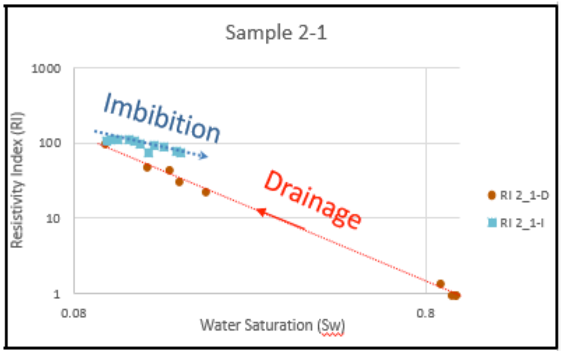

Figure 6. Drainage & Spont. Imb. in Pc vs Sw (2_1).

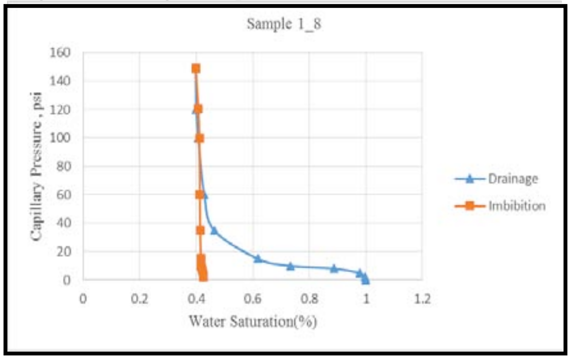

Figure 7. Drainage & Spont. Imb. in I vs Sw (1_8).

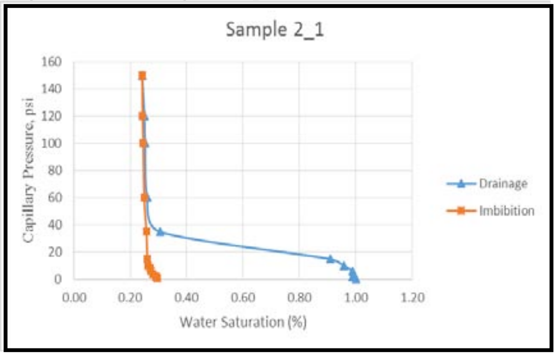

Fig. 8. Drainage & Spont. Imb. in Pc vs Sw (2_1).

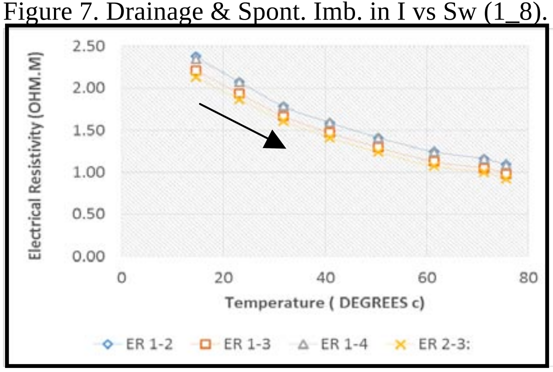

Figure 9. Plot of resistivity vs. temperature (1_8).

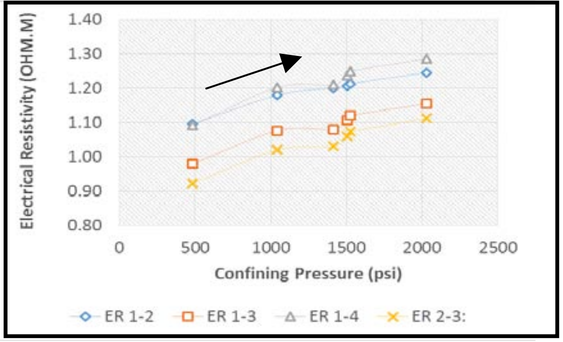

Figure 10. Plot of resistivity vs. pressure (1_8).