THE EFFECT OF WETABILITY ON ARCHIE SATURATION EXPONENT FOR LIBYAN NUBIAN SANDSTONE RESERVOIRS

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Abstract: The estimation of oil intially in place is an important issue and since the saturation exponent is the most important factor in determining the hydrocarbon/water saturations from the electrical resistivity measured on core plugs or from wireline logs using the Archie equation, the value of saturation exponent should be determined accurately.

Laboratory measurements methods were undertaken on core samples selected from three different fields (S, T, and U) from the Nubian Sandstone Formation of the central graben reservoir in Libya. The experimental data includes porosity, permeability, and wettability. This includes determining the saturation exponent (n) in the laboratory at two stages. The first stage was before wettability measurements were conducted on the samples, and the second stage was after the wettability measurements in order to find any effect on the saturation exponent.

Changes were also observed in the saturation exponent (n) and water saturation (S_w) before and after wettability measurement. Samples with an oil-wet tendency have higher irreducible brine saturation and higher Archie saturation exponent values than samples with a uniform water-wet surface. A significant change in slope (saturation exponent, n,) between resistivity index and water saturation after wettability measurement was observed.

Keywords: Wettability, Saturation, resistivity, Sandstone, permeability, core, reservoir

INTRODUCTION

Reservoir description plays an important role in the petroleum industry. The understanding of reservoir rock properties such as porosity, permeability, water saturation, and resistivity assists engineers to improve the characterisation of the reservoir. In this work the experimental data includes porosity, capillary pressure by using porous plate method, and wettability were obtained. This includes determining the saturation exponent (n) in the laboratory at two stages. The first stage was before wettability measurements were conducted on the samples, and the second stage was after the wettability measurements in order to find any effect on the saturation exponent.

Generally, reservoir rocks are often assumed to be water wet and their saturation exponent (n) is generally assumed to be close to 2. However, it is substantially affected by wettability as well as the pore geometry and often no longer equals 2. Killer (1953) presented evidence that the saturation exponent could be substantially different from 2. He found that Archie's saturation exponent (n) varies from 1.5 to 11.7 for the same rock, depending on how cores were treated. For the same water saturation, the resistivity of an oil reservoir can vary by three orders of magnitude for different wetting conditions. The wettability played a significant role in the fluid distribution within the rock pore space by changing the relative position of the conducting fluid with respect to the rock surface, which affected the electric behaviour of fluid-filled rocks.

Sweeny and Jenning (1960) found that the resistivity of hydrocarbon bearing rocks is strongly affected by the wettability. Their data showed that

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the resistivity is greater when the wetting conditions are changed from water-wet to oil-wet. They concluded that the conducting fluid (water) exists in discrete non-connected globules when the rock is oil-wet, which are unable to conduct electric current. Archie's saturation exponent varies from 1.6 to almost 8.0 for water-wet and oil-wet carbonate cores respectively.

Mungan And Moore (1968) pointed out that an Archie's saturation exponent as high as 9.0 can be calculated when the conductive liquid is non-wetting. For strongly water-wet rocks, a unique relationship exists between Archie's saturation exponent and resistivity as described by Archie's law. At lower saturation, Archie's saturation exponent becomes larger and more saturation dependent. They attributed the change of saturation exponent (n) to higher values at lower water saturation to the fact that water is becoming discontinuous and not contributing to the flow of current. For the same core specimen, cleaning may have some impact on the wettability conditions of the rock. Archie's saturation exponent varied from 1.91 to 2.71 for extracted and non-extracted cores respectively.

Location and Geology of the Nubian Sandstone Formation in Sirt Basin

The Sirt Basin is the youngest of the Libyan basins (Fig. 1). It has the largest petroleum reserves in Libya and is ranked the 13th among the world's petroleum basins. The basin's recoverable reserves are about 45 billion barrels of oil and 33 trillion cubic feet of gas. The Sirt Basin contains some sixteen giant oil fields with about 117 billion barrels of proven oil-in-place. The two principal source rocks in the Sirt Province are the Upper Cretaceous Rachmat Shale and the Sirte Shale. Hydrocarbon distribution in the Sirt Basin has been controlled by major tectonic events. This is particularly true of reservoirs related to Cretaceous and Eocene to Miocene rift structures. These reservoirs in the Sirt Basin are composed of 58% clastics, mostly of Mesozoic age and 42% of carbonate rocks mostly of Tertiary age.

The Nubian Formation of the eastern Sirt Basin, Libya, comprises mainly sandstones and shale resting unconformably on a basement of igneous and metamorphic rocks. The Nubian Formation has been subdivided into three members. Member 1 forms the uppermost part of the formation, and comprises mainly sandstones with intercalation of siltstones and shale of variable thickness, and has a maximum known thickness of about 1099ft. Member 2 represents the middle part of the Nubian Formation, and consists of shale and silty shale, with a maximum known thickness of 2362ft. Member 3 is the basal part of the formation, and rests directly on the crystalline basement. It comprises sandstones with subordinate intercalations of siltstones and shale, and exceeds 3002ft in thickness.

The sandstones tend to be fine to coarse grained, quartzitic, tan-grey coloured and are usually poorly sorted with a clay matrix. The finer sandstones are more poorly sorted, but the coarser sandstones have very little in terms of matrix and are thus very porous. The shale tends to be red, maroon, green, micaceous and laminated. There are also conglomerates containing rounded quartz pebbles within a sandstone and claystone matrix, (Barr and Weegar 1972). Much of the Nubian Formation was probably deposited in fluvial depositional systems (Barr and Weegar, 1972).

EXPREMINTAL PROCEDURES

Porosity, Permeability, and Grain Density Measurements

The 65 clean and dry plug samples were subjected to various analyses to determine porosity, permeability and grain density values where possible. The core analysis laboratory of the Libyan Petroleum Institute uses a twin cell helium expansion gas porosimeter for the plug sample grain volume measurement. The porosity and the grain density are then calculated by determining the bulk volume, and the weight of the sample. The positive displacement mercury pump is used to determine the bulk volume of each sample.

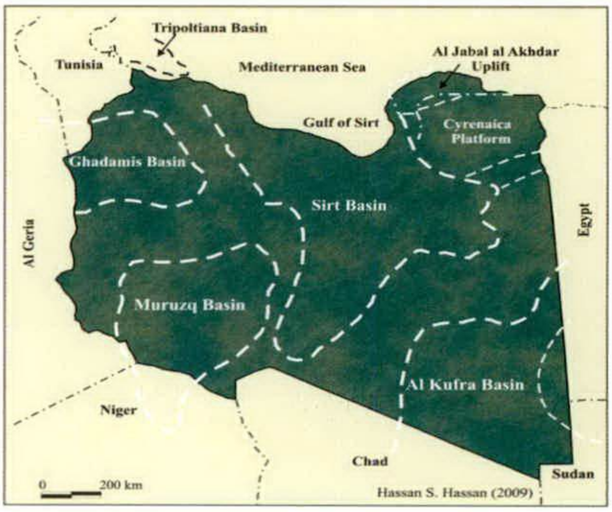

Fig. 1. Location of major sedimentary basins of Libya. (Hassan S.Hassan, 2009

A clean, dry sample is placed in the Hassler-type core holder and an overburden pressure of 200 psi (industry standard practice to sample) is applied to the cell, compressing the rubber sleeve around the sample. Nitrogen gas pressure is applied to one end face of the sample, whilst the other end face is open to atmospheric pressure, causing the gas to flow through the sample. The flow of gas is measured at the low pressure (downstream) end face of the sample. The flow rate is measured by passing the gas through one of three laminar flow orifices and the differential pressure developed across the orifice is also measured. The length of the sample, upstream and downstream pressures, and flow rate, viscosity of nitrogen, barometric pressure and temperature are entered into Darcy's equation for gas permeability, and the permeability of the sample is calculated.

Resistivity Index (RI) and Wettability Measurements

Twelve samples were selected for resistivity index measurements. These tests were conducted after the formation resistivity factor tests. The fully saturated samples were placed on a semi-permeable porous plate cell in a capillary pressure apparatus, to bring the samples to lower saturation. Air humidified by water was admitted at a controlled pressure to the apparatus and the volume expelled was monitored. When equilibrium saturation had been attained, the samples were removed from the cell, and their weight and electrical resistance were measured. The sample dry weight, the fully saturated weight and the weight after each desaturation step were used to calculate the average saturation of the sample. The resistance was used to calculate the true sample resistivity and the resistivity was divided by the sample resistivity at 100% liquid saturation which yield the resistivity index (RI). In the laboratory it is necessary to firstly determine the resisitivity at 100% water saturation (R_o) of the sample. Once this value has been established, the air as the non-conducting fluid is forced into the sample over a range of designated pressures to displace an increasing portion of the brine phase. At each stage, when the saturation is in equilibrium relative to the pressure, the true formation resistivity (R_t) is measured.

The water saturation in hydrocarbon reservoirs is generally estimated from resistivity well logs. The interpretation of these logs is based on two empirical equations by Archie (1942). In clean formations (those containing little or no clay), Archie (1942) defined the resistivity index as the ratio of the resistivity of the formation (R_t), which is partially saturated to the resistivity of the same formation when it is entirely saturated with water (R_o). Therefore, the resistivity index can be expressed in terms of rock resistivities and water saturation as follows:

$$RI = \frac{R_t}{R_o} = S_w^{-n} \qquad (1)$$

Wettability measurements were performed for the same previous samples using the Amott method. This involves a static imbibition phase followed by forced displacement in a flow cell. With a core sample saturated with oil and water at irreducible water saturation, it was placed in an Amott cell under water for 1000 hours. The oil displaced by spontaneous water imbibition is monitored daily until a stable oil measurement was obtained ($V_{w,s}$). The rock sample was then placed in a flow cell and the oil is flushed with water down to residual oil saturation (S_{or}) and the oil displaced dynamically (approximately equal to the volume of water dynamically imbibed) is measured ($V_{w,d}$). Following brine displacement, the rock sample is placed in an Amott cell under oil for 1000 hours. The water displaced by spontaneous imbibition of oil was monitored daily until a stable water measurement was obtained ($V_{o,s}$). The core is then removed and placed in a flow cell and flushed with oil down to irreducible water saturation (Swirr) and the amount of water dynamically displaced (approximately equal to the volume of oil dynamically imbibed) was measured (Vo, d):

$$I_w = \frac{V_{w,s}}{V_{w,s} + V_{w,d}} \qquad (2)$$

$$I_o = \frac{V_{o,s}}{V_{o,s} + V_{o,d}} \qquad (3)$$

Where Iw and Io are the displacement ratios by water and oil ratios respectively. Care should be taken in the interpretation of this data due to the fact that sample wettability may be altered or reversed by a large number of factors (type of coring fluid, exposure to air, temperature, sample handling and plugging, cleaning, drying and preservation). The Amott-Harvey wettability index ($I_{w,AH}$) is a single number that combines the displacement by water and oil ratios:

$$I_{w,AH} = I_w - I_o \qquad (4)$$

RESULTS AND DISCUSSION

In this study the porosity and permeability of Nubian sandstone Formation which are determined from the laboratory are highly variable across the whole volume of the reservoir being moderate to good in the some intervals and poor in other intervals.

Core data of porosity and permeability plot as permeability versus porosity of Nubian Sandstone Formation (6 wells, S-01, S-02, S-03, T-01, U-01, and U-02) are shown in Fig. 2 and the values are presented in Table 1. The twelve representative sandstone core samples used had porosities between 8.01% and 17.91% and permeabilities between 4.9 mD and 1146 mD.

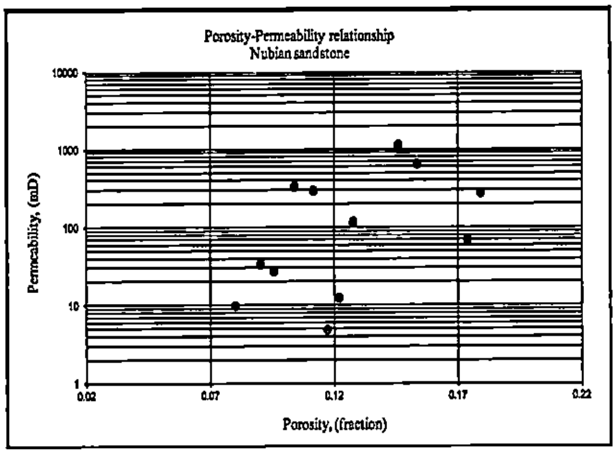

Fig. 2. Porosity Vs. Permeability for the studied area

Table 1. Porosity and permeability values of the selected representative samples

Samples#	Well Name	Ø (%)	K(mD)
1	S1	10.39	337.5
2	S2	9.01	34.11
3	S3	12.17	12.55
3	T1	14.59	1146
5	S3	8.01	9.910
6	U2	17.38	69.86
7	U1	15.34	660.4
8	S3	11.71	4.901
9	U2	17.91	279.7
10	S1	11.16	297.7
11	S2	9.56	27.73
12	S2	12.76	118.1

Saturation exponent (n), capillary pressure(Pc) and resistivity index (RI) before and after wettability measurement

Saturation exponent (n) values are normally determined experimentally in the laboratory on core samples of the actual formation under consideration. Due to the fact that the saturation exponent varies with both lithology and wettability a suite of saturation exponent value measurements is often conducted on samples with a range of porosity, permeability and lithology which may be present in the formation (Bennion *et al*, 1996). Saturation exponent values were determined on the twelve representative core samples from porous plate capillary pressure measurements in the laboratory.

The selected plugs were taken from six wells from the Nubian Sandstone Formation. The samples were cleaned in hot solvents, dried and then mounted into the core holder. All the samples were saturated with the brine (salinity 135,000 ppm). Powder was used between the samples and the porous plate to maintain hydraulic contact during the test. During the measurement, the pressure was increased in steps and the final equilibrium produced volumes of the wetting phase were recorded for each step. In the present work, the output data of capillary pressure for sample #3 before and after wettability measurement is displayed in Table 2 and in Fig. 3 and 4. Because the wettability affects waterflood performance, Amott wettability measurements were made on the same samples.

The saturation exponent for sample # 1 before wettability measurement was 1.39. When the wettability measurement was conducted on the

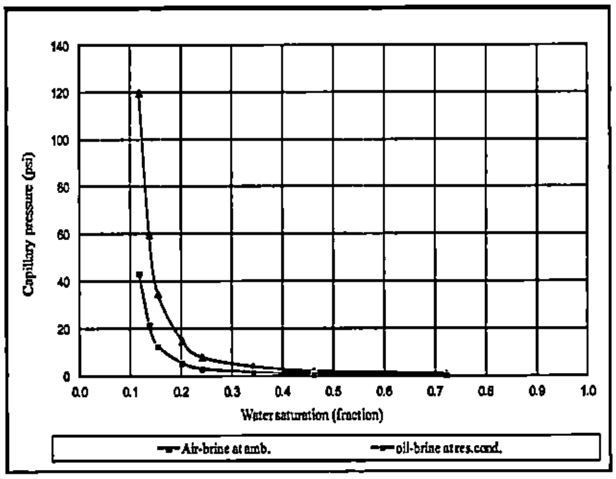

Fig. 3 Capillary pressure curves for sample # 1 before wettability measurement

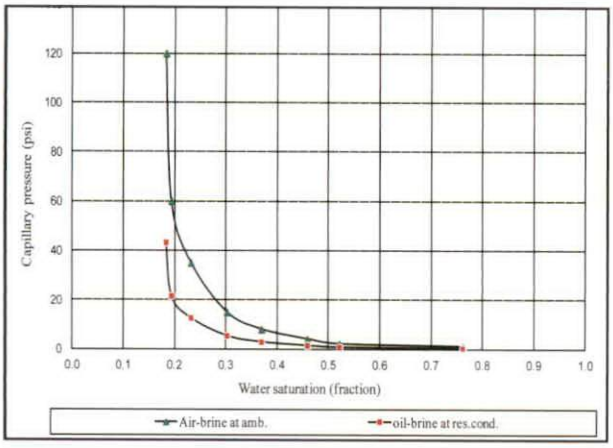

Fig. 4 Capillary pressure curves for sample # 1 after wettability measurement

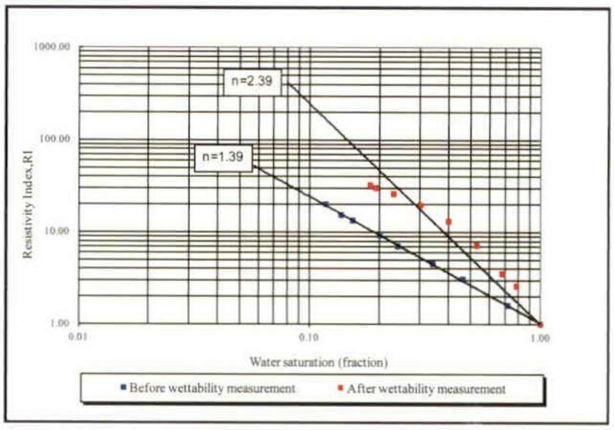

Fig. 5. Resistivity index versus water saturation before and after wettability measurement for sample # 1.

sample, the sample imbibed oil (tendency to be oil-wet), and the saturation exponent increased to 2.39 as shown in Table 3 and in Fig. 5.

Estimation of hydrocarbon reserves are strongly dependent of electric log data and on the value of saturation exponent (n) used. The saturation exponent is usually either assumed to be 2.0 regardless of reservoir wettability or is derived from laboratory measurement of electrical properties of the cores. It can vary between 1.2 and 2.2 (Serra, 1984) for water-wet rocks and can have a value from 2.2 or higher when the rock wettability changes towards oil-wet (Anderson, 1986). For sample #1 the saturation exponent before wettability measurement was 1.39, and when the wettability test was conducted the sample imbibed oil (tendency to be oil wet), and the saturation exponent increased to 2.39. In water-wet rock, the brine occupies the small pores and forms a continuous film on the rock surface. In an oil-wet rock, the brine is located in the centres of the large pores. This difference in brine distribution caused by the wettability becomes very important as the brine saturation is lowered. Generally, almost all of the brine in the water-wet rock remains continuous, so the resistivity increases because of the decrease in cross- sectional area that can conduct flow. In oil-wet rock, a portion of the brine will lose electrical continuity, so the saturation exponent will increase at a faster rate. In oil-wet rock, a fraction of the non-wetting phase (specially at low brine saturation) which is located in the middle becomes disconnected and surrounded by oil which acts as an insulator to the flow of electric current. The insulation of this portion of brine prevents it from contributing to the flow of electric current and hence leads to higher values of saturation exponent. Finally, in Fig. 6 Archie's saturation exponent increases as the rock becomes more oil wet.

Table 2. Resistivity index and water saturation for sample #1 from porous plate capillary pressure measurement.

Capillary pressure at ambient. (Psi)	Capillary pressure at reservoir (Psi)	Water Saturation Before Wettability Measurement (fraction)	Water Saturation After Wettability Measurement (fraction)	Resistivity Index (RI) Before Wettability Measurement	Resistivity Index (RI) After Wettability Measurement
1	0.36	0.7214	0.7873	1.451	3.997
2	0.72	0.4612	0.6843	1.460	3.327
4	1.44	0.3414	0.5300	1.407	3.099
8	2.89	0.2410	0.4000	1.371	2.799
15	5.42	0.2014	0.3018	1.387	2.475
35	12.6	0.1536	0.2315	1.382	2.223
60	21.7	0.1368	0.1935	1.371	2.072
120	43.3	0.1174	0.1832	1.400	2.047

Table 3. Saturation exponent values before and after wettability measurement.

Sample #	Well Name	Saturation Exponent (n) Before Wettability Measurement	Saturation Exponent (n) After Wettability Measurement
1	S1	1.39	2.39
2	S2	1.75	2.60
3	S3	2.06	2.79
3	T1	1.76	2.65
5	S3	1.93	2.18
6	U2	1.79	2.59
7	U1	1.87	2.50
8	S3	2.18	2.86
9	U2	1.91	2.65
10	S1	1.78	2.43
11	S2	1.97	2.49
12	S2	1.73	2.22

CONCLUSIONS

1. Changes were observed in the saturation exponent (n) and water saturation (Sw) before and after wettability measurement. Samples with an oil-wet tendency have higher irreducible brine saturation and higher Archie saturation exponent values than samples with an uniform water-wet surface.
2. A linear relationship existed between wettability index and the saturation exponent for the studied wells. Archie's saturation exponent increases with decreasing wettability index because the saturation exponent increases as the rock becomes more oil-wet.

NOMENCLATURES

I_w = Displacement by water ratio
I_o = Displacement by oil ratio
$I_{A/H}$ = Amott Harvey Wettability Index
K = Permeability, mD
n = Archie's saturation exponent, dimensionless
R = Resistivity, ohm.m
RI = Resistivity Index, dimensionless
R_t = True resistivity of the partially saturated rocks, ohm.m
R_o = Resistivity of fully saturated rock, ohm.m
R_w = Water resistivity, ohm.m

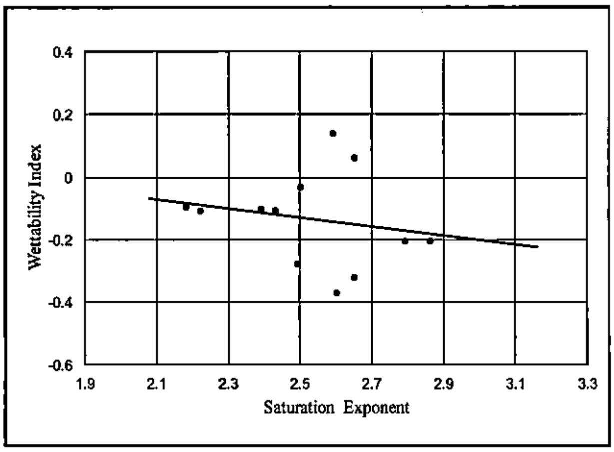

Fig. 6. Saturation exponent as a function of wettability index for the twelve selected representative samples.

S_w = Water saturation, fraction
S_{or} = Residual Oil Saturation, fraction
Vo,s = Volume of oil Spontaneously imbibed, cc
Vo,d = Volume of oil dynamically imbibed, cc
V_w = Water Volume, cc
Vw,s = Volume of water Spontaneously imbibed, cc
Vw,d = Volume of water dynamically imbibed, cc

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