WETTABILITY EVALUATION OF THE UNAYZAH RESERVOIR IN CENTRAL SAUDI ARABIA

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ABSTRACT

Unayzah Formation in Central Saudi Arabia is an important source of light (48-52 API gravity) sulfur frees (0.02-0.07%) crude oil (Arabian Super Light). In 1989, the first oil discovery was made at Hawtah. Subsequently, a number of other oil discoveries were made at various fields (Umm Jurf, Ghinah, Nuayyim, Hazmiyah, etc.). Oil production from Central Saudi Arabia fields started in August 1994. As part of special core analysis program to support reservoir management in development of these fields, intensive SCAL studies were completed and crucial data required for field simulation were provided to proponents.

This paper summarizes the results of a set of consistent methods used in determining wettability of Unayzah reservoir. Both quantitative methods (Amott, USBM, and contact angle) and qualitative method (oil/water relative permeability) were used to evaluate the variation of wettability in Central Saudi Arabia fields. In this work, direct wettability tests were carried out on a large number of native core plugs from Unayzah reservoir. Moreover, several waterflood tests were conducted at reservoir conditions on composite cores using recombined reservoir fluids. Data from relative permeability curves were used for comparison with wettability results obtained from direct wettability tests.

Amott and USBM wettability indices indicated that Unayzah reservoir core material represented a range of wettabilities, but tended towards neutral to slightly to strongly water-wet. Contact angle results for rock material recovered from Unayzah reservoir showed water-wet characteristics for both oil-brine/rock system and oil-brine/quartz system. Moreover, the values of wettability indices are in agreement with relative permeability results which reflect a behavior of water-wet core material based on Craig’s rule of thumb.

INTRODUCTION AND BACKGROUND

Saudi Aramco has an interest in several central area fields that produce from Upper Carboniferous and Lower Permian Unayzah reservoir. The Unayzah formation is a heterogeneous, friable, and fluvial to eolian clastic rock which contains detrital clays. Oil production from Central Saudi Arabia fields started in August 1994. As part of special core analysis program to support reservoir management in development of these fields, intensive SCAL studies were completed and crucial data required for field simulation were provided to proponents.

Wettability of hydrocarbon reservoirs has profound effect on oil production in oil fields, which are being produced by waterflood and water-drive mechanisms. Therefore, it is necessary to determine the preferential wettability of the reservoir, whether this be to water, or oil or somewhere between two extremes i.e. intermediate. The importance of wettability has been established by a number of researches when water-driven systems were evaluated (Amott, 1959; and Donaldson et al., 1969). Due to this importance, many reviews of wettability and its effect on oil recovery have been published (Cuiec, 1991, Buckley, 1998, and Tong, Z., J., and Morrow, N. R., 2005).

Wettability plays profound role in the microscopic distribution of fluids within oil reservoirs. This distribution in turn affects the displacement of reservoir fluids. For better prediction of reservoir performance under natural mechanisms or when the reservoir is planned for secondary recovery methods, wettability and capillary pressure become as key parameters. Wettability is not easy to quantify and therefore various quantitative and qualitative methods have been proposed. Quantitative methods include Amott, USBM, and contact angle; while qualitative methods include relative permeability, NMR, logs, etc. All methods have advantages and limitations. These methods were reviewed carefully by Anderson (1986).

This study was conducted to evaluate wettability of Unayzah reservoir using both quantitative methods (Amott, USBM, and contact angle) and qualitative method (oil/water relative permeability) in Central Saudi Arabia fields. Moreover, several waterflood tests were conducted at reservoir conditions on composite cores using recombined reservoir fluids. Data from relative permeability curves were used for comparison with wettability results obtained from direct wettability tests.

RESERVOIR MINERALOGY

XRD and XRF analyses of some Unayzah reservoir rock material revealed that the most predominant mineral in Unayzah sandstone rocks is quartz (79-88 weight %). The other minerals are kaolinite (2-7 weight %), microcline (8-10 weight %), albite (4-8 weight %), sylvite (3 weight %), and trace amounts (< 0.5 weight %) of illite.

PLUG SELECTION AND TEST FLUIDS

Preserved core material from Unayzah sandstone reservoir was cut with a KCl brine and packed under de-aerated KCl brine in plastic tubes. Core plugs of approximately 2 inches in length and 1.5 inches in diameter were drilled from the whole core at 0.5-foot intervals with brine identical to the preserving brine. After trimming, the plugs were wrapped with silver paper and then placed in sealed container completely submerged in evacuated KCL brine.

Visual inspection, brine permeability at remaining oil saturation, and CT scans were performed as screening tests to assist in sample selection. The screening tests were combined with a review of conventional core data and geological description of the core material to ensure that anomalous samples were not tested. Cores that were fractured, broken, or displayed brine permeability less than 1 millidarcy (mD) were excluded from further testing.

Wellhead oil from Unayzah reservoir was used as the oleic phase in the wettability experiments; while recombined live with dynamic viscosity of 0.46 mPa.s at reservoir condition (temperature = 195 ^{o}F and pressure = 3,800 psig) was used in relative permeability tests. The aqueous phase was synthetic brine (similar to reservoir brine). The viscosity of this brine is 0.35 mPa.s at reservoir condition. The brine used was Hawtah/Unayzah aquifer water with a density of 1.004 g/cm^3 at room temperature. The salts used to prepare the brine are sodium chloride (3.50 g/L), calcium chloride (1.80 g/L), magnesium chloride (0.63 g/L), sodium bicarbonate (0.34 g/L), and sodium Sulfate (2.22 g/L).

EXPERIMENTAL APPROACH

Amott Method

Wettabilities of preserved core plugs were measured by Amott method (Amott, 1959). The Amott method combines spontaneous imbibition and dynamic displacement that were performed under ambient condition with simulated formation brine and stock tank oil.

For spontaneous processes, the sample is submerged in the fluid to be imbibed and the displaced volume of the other fluid is measured. The dynamic displacement involves flowing the imbibing fluid through the sample and measuring the volume of the other fluid displaced. The displacement volumes (both spontaneous and total) are measured for both oil and water. The ratio of the spontaneously displaced volume to the total displaced volume is calculated for both the oil and water phases. The Amott-Harvey wettability index is the displacement-by-water ratio minus the displacement-by-oil ratio. For purpose of discussion, the wettability index range from +1 to –1 was divided and classified as follows: neutral or mixed (-0.1 to 0.1), slightly water-wet (+0.1 to +0.3), water-wet (+0.3 to +1), slightly oil-wet (-0.1 to –0.3), and oil-wet (-0.3 to –1).

USBM Method

United States Bureau of Mines (USBM) method is also used to measure wettability. The maximum speed used in USBM method for this study was 2,400 revolutions per minute. USBM wettability index is obtained from hysteresis loop of centrifuge capillary pressure curves (Donaldson et. al., 1969). The areas under the curves represent the thermodynamic work required for the respective fluids to displace each other. The logarithm of the ratio of the area of oil-displacing-brine to brine-displacing-oil is used to identify the USBM wettability index.

Contact Angle Test

The contact angle measurements were made with Unayzah reservoir oil-brine/rock and oil-brine/quartz systems at reservoir conditions (90 ^{o}C and pressure of 2500 psig). Contact angles were measured on a smooth substrate using pendant drop apparatus.

The system permitted measurements of the angle made by an oil drop pending on the brine-solid interface. Quartz was chosen since it represented the major component of Unayzah reservoir.

Relative Permeability Measurement

The procedure of relative permeability measurements included the use of composite core (Huppler, 1969) assembled from core material cut with KCl brine and preserved at the well site. The unsteady-state relative permeability tests were conducted at simulated reservoir conditions of 195°F, and 3,800 psig net confining pressure using recombined (live) and synthetic brine similar to reservoir brine.

In preparation for testing, a brine-saturated composite core (length = 15 centimeter) was assembled, placed into a rubber sleeve, and loaded into horizontal coreholder. Dead oil was flushed through the composite at backpressure condition to displace gas and ensure complete fluid saturation. Reservoir condition of 195°F and 3,800 psig net confining pressure was established. Recombined live oil was injected to displace the dead oil. After three weeks of aging, the core was stabilized by pumping several pore volumes of live oil until a constant pressure drop was obtained. After pressure stabilization, baseline oil permeability was determined. Methane-saturated brine was injected to simulate a waterflood processes. A constant flow rate of 120 cm^3/h (8.2 ft/day) was maintained. This rate was chosen to minimize capillary end effects. These effects are minimal when the scaling factor is greater than 2 (Rapoport and Leas, 1953). Both oil and water volumes were measured at reservoir condition by an acoustically monitored separator. Relative permeabilities were calculated using JBN method (Johnson E. F. et.al., 1959).

At the end of waterflooding, the core composite was allowed to cool. All extruded fluids were collected. The core holder was disassembled. The cores were weighed and placed in the Dean Stark extraction apparatus where water and oil were extracted using toluene. The extracted samples were then dried in a vacuum oven at 150 °F for two days. Air permeability and porosity for each plug was measured at stressed condition (3,800 psig).

RESULTS AND DISCUSSION

Amott and USBM Wettability Results

In this study wettability indexes were obtained from USBM and Amott methods. Tables 1 and 2 list Amott data and USBM data, respectively. The results of wettability tests showed full range of wettability indices that ranged from 0.12 to 0.73. The distribution of wettability index with depth is shown in Figure 1. The scale of the plot is from –1 (strongly oil wet) to +1 (strongly water wet). The plot in Figure 1 showed that Unayzah core material varied in wettability character from neutral to slightly and strongly water-wet in character with a tendency for increasing water-wet characteristics with depth. Core material recovered from up-structure level interval revealed neutral and slightly water-wet character; while the plugs from mid-structure and down-structure region showed slightly to strongly water-wet character.

Contact Angle Results

The contact angle is a measure of the relative strength of adhesion of fluids to solid. It is commonly used to measure the wetting properties of the solid surface with respect to two immiscible fluids. It has a major influence on the hydrocarbon distribution as well as water within reservoir rock. The range of contact angles has been rather arbitrarily divided into three regions. From 0 to 75^o is termed water-wet, 75 to 105^o neutrally-wet, and 105 to 180^o oil-wet (Treiber et al., 1972).

In this study both pure quartz plate and natural rock plate were used as substrates in contact angle measurements. Table 3 lists **c**ontact angle values of Unayzah oil/brine/rock system and Unayzah oil/brine/quartz system. Data in Table 3 revealed little increase in contact angle values for both systems with increase of temperature. The range contact angle (79 – 82^o) for Unayzah oil/brine/rock system reflects neutral wetting behavior. The results obtained from Amott and contact angle methods are in agreement to some extent.

Relative Permeability Results

Three core composites taken from a range of locations ranging from up-structure (composite 1), mid-structure (composite 2), and down-structure (composite 3) were used in relative permeability tests. Composites are used because they are believed to be least impacted by core-scale heterogeneities, are more precise data because the pore volume and pressure drop are both larger, and are least impacted by capillary and inlet end effects. Table 4 summarizes the recovery performance of all three composite cores that were used in the relative permeability experiments.

Results in Table 4 showed that oil recovery ranged from about 41 to 52 % of pore volume. The irreducible water saturation (S_{wi}) ranged from about 35 to 41 %. These values are in agreement with S_{wi} values obtained from logs (16 to 42%). The residual oil saturation (S_{or}) varied between 6 and 19 % of pore volume.

Semi-log plot of relative permeability curves versus water saturation ratio for these composites is shown in Figure 2. The plot reflects water-wet behavior of these composites, based on Craig's (1971) rule of thumb. Relative permeability to water at the end of waterflooding (K_{rw}) ranged from 13 to 40 %. Saturations at which oil and water relative permeabilities are equal are greater than 50 % for the three composites. Therefore, it can be stated that results obtained from quantitative and qualitative methods for evaluation of wettability of Unayzah reservoir are in agreement.

SUMMARY

1. Amott and USBM wettability indices indicated that Unayzah reservoir core material represented a range of wettabilities, but tended towards neutral to slightly to strongly water-wet.
2. A general trend of increasing water-wet characteristics with depth was observed.
3. Contact angle results showed water-wet characteristics for both oil-brine/rock system and oil-brine/quartz system.

4. Values of wettability indices are in agreement with relative permeability results which reflect water-wet behavior of core material based on Craig's rule of thumb.

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Table 1- Amott Wettability Indices for Unayzah core plugs.

Sample No.	Porosity (% PV)	Permeability (mD)	Oil-Wet Index	Water-Wet Index	Amott-Harvey Index
1	19.9	183	0	0.19	0.19
2	7.8	113	0	0.33	0.33
3	11.2	13	0	0.33	0.33
4	9.7	29	0	0.26	0.26
5	12.6	127	0	0.31	0.31
6	18.4	173	0.02	0.48	0.46
7	15.6	417	0.07	0.78	0.71
8	10.8	423	0.08	0.67	0.59
9	17.6	352	0.06	0.52	0.46
10	9.8	33	0	0.55	0.55
11	16.2	653	0	0.56	0.56
12	18	22.6	0	0.35	0.35
13	14.5	2498	0	0.73	0.73
14	16.2	402	0	0.51	0.51

Table 2- USBM Wettability Indices for Unayzah core plugs.

Sample No.	Porosity (% PV)	Permeability (mD)	USBM Index
15	16.7	102	0.12
16	21.6	2690	0.14
17	15.3	696	0.37
18	18.5	1216	0.22

Table 3. Effect of Temperature on Contact Angle for Unayzah Oil/Brine/ Rock Material and Unayzah Oil/Brine/Quartz Crystal Systems.

Temperature (^oC)	Contact Angle at Pressure = 2,500 psig	
	Oil/Brine/Quartz Crystal	Oil/Brine/Rock Material
25	75	79
50	77	80
75	78	81
90	79	82

Table 4- Summary of Waterflood Performance Data for Composite Cores.

Composite No.	Porosity (% PV)	K_a (mD)	S_{wi} (% PV)	S_{or} (% PV)	K_{rw} at Floodout (%)	Oil Recovery (% PV)	Oil Recovery (% OOIP)
1	19.3	622	41	6.6	40.5	52.4	88.8
2	18.0	1714	38.9	19.3	36.3	41.8	68.4
3	14.6	374	35.7	17.0	13.17	45.2	76.2

S_{wi} = initial water saturation S_{or} = residual oil saturation
K_{rw} = relative permeability to water PV = pore volume
OOIP = original oil in place K_a = permeability to air

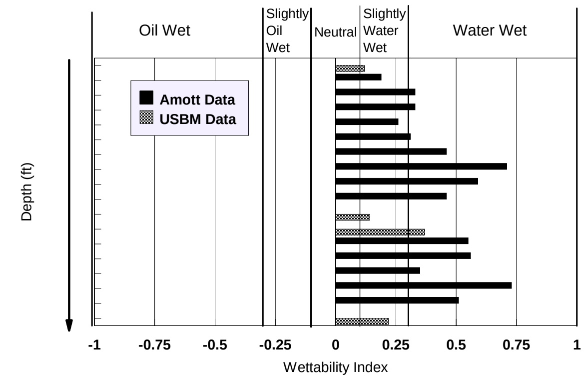

Figure 1- Amott and USBM Wettability Indices Distribution.

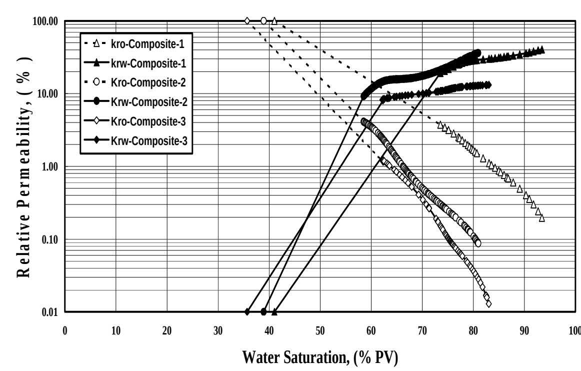

Figure 2- Semi-log plot of Relative Permeability Curves for three composites (Unayzah Reservoir).