INVESTIGATION OF THE EFFECT OF TEMPERATURE AND PRESSURE ON INTERFACIAL TENSION AND WETTABILITY

Taha M. Okasha
Saudi Aramco EXPEC Advanced Research Center,
Dhahran, Saudi Arabia

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Trondheim, Norway, 27-30 August 2018

ABSTRACT
Both interfacial tension (IFT) and wettability of the fluids/rock system affect the distribution of fluids within reservoir rock. The fluid distribution strongly affects the flow behavior and oil recovery. Most of the available data on wettability of core samples including contact angle and IFT for crude oil/brine systems are for room temperature and atmospheric pressure. Since actual values of reservoir temperature and pressure are frequently encountered in oilfields simulation models, a need to study IFT and wettability at reservoir conditions was recognized. This paper is an investigation of the influence of temperature and pressure on IFT and wettability. Contact angle measurements were used to quantify wettability on calcite and natural rock.

Experimental results of IFT for both dead oil-brine and live oil-brine systems as well as contact angles of live oil-brine/calcite and live oil-brine/rock systems over a range of temperature and pressure will be presented and analyzed. The IFT between dead oil and brine decreased with increasing temperature and increased with increasing pressure at constant temperature. For live oil-brine system an opposite trend of increase in IFT values with temperature was found. A significant increase in IFT values occurred with time. At reservoir conditions, the IFT of live oil was higher than that of dead oil. Contact angle values for live oil-brine/rock system (at P = 3,000 psig) increased with temperature and with aging time. Four to six days are required to stabilize and obtain constant values of contact angle. Data reflects neutral to slightly water-wet character of the tested carbonate rock samples.

INTRODUCTION
Interfacial tension and contact angle measurements at reservoir conditions are essential for quantifying these capillary forces and original fluid saturations. The capillary pressure-saturation relation has importance in determining several reservoir properties, like irreducible water saturation, transition zone thickness, oil column height and pore size distribution.[1,2]

The accurate method for wettability determination is the contact angle technique. The contact angle is a measure of the relative strength of adhesion of fluids to solid. The main interest in the contact angle is its contribution to the capillary pressure and multi-phase flow in reservoir rocks.

The importance of wettability has been realized by a number of researches when water-driven systems were evaluated.[3-6] Capillary pressure and contact angle measurements at reservoir conditions play an important role in formation evaluation, wireline based measurements; water cut prediction, wettability determination, and reservoir performance evaluation.

Reservoir simulation requires a realistic spatial distribution of capillary pressure and fluids saturation throughout the reservoir. Capillary pressure data is used to relate the wetting phase saturation with basic core properties of porosity and permeability and height above either oil-water or gas-oil contact. This information helps engineers to calculate oil in place at different locations in the reservoir.

The objective of this study is to investigate the effect of temperature and pressure on interfacial tension and wettability of carbonate rock using pendent drop tensiometer.

EXPERIMENTAL APPROACH

Fluids and Materials

Both dead and recombined live oil samples represented oleic phases were used in this study; while synthetic brine was used as an aqueous phase. Both dead oil and synthetic brine was filtered through 0.2 μm filter paper prior to usage in systems. Pure calcite plates and rock plates were used as solid substrates in contact angle measurements.

Apparatus

Interfacial tension and contact angle were measured using a high temperature/high pressure pendent drop instrument. Figure 1 shows a schematic of the experimental equipment used for measurements in this study. It consists of IFT cell, hand pump for injection of oil or water using two way valve, vibration free table, needles, imaging system (video camera with computer display, monitor, and software data storage and calculation of both contact angle and interfacial tension), temperature control system (water bath), lamp, transfer cells, and pressure transducers (+/- 0.2% full scale) with digital display.

Recent progress in image analysis and data acquisition systems make it possible to obtain a direct digitization of the drop image with the aid of a video frame grabber. The imaging and image analysis module was DROP image program which has a number of features that make the procedure of interfacial tension and contact angle measurements easy and versatile.

Cleaning Procedure

A very important step in measuring interfacial tension and contact angle is a thorough cleaning of the apparatus, because any trace amounts of contamination can alter the results. Oil flow line was cleaned first with toluene until very clean toluene is flowing out. Ten pore volumes of methanol were used to flush the lines. The line was then dried by flowing dry air. Water flow line was first flushed with ethanol followed by ten pore volumes of de-ionized-distilled water. Brine was then used to flush the lines for at least five pore volumes.

Extra attention was given to the cleaning of calcite and rock plates because it is extremely important to the measurements of contact angle. Plates were washed by mild soap solution, de-ionized-distilled water and ethanol. De-ionized-distilled water was used to rinse the plates thoroughly. Following this, the plates were boiled in hydrogen peroxide for at least five minutes. De-ionized-distilled water was used again to rinse them and then they were rinsed and soaked in prepared synthetic brine for 24 hours before the experiments.

Interfacial Tension Test Procedure

To determine the interfacial tension (IFT) of crude oil/brine interface we used pendent-drop tensiometry, with a small oil drop formed upwards at the tip of stainless-steel needle immersed in the aqueous brine. The following experimental procedures were followed:

1- Run a calibration test first by placing stainless steel ball inside empty IFT cell.
2- Set up the image system to be ready to take picture.
3- Select calibration option and run the program to adjust the horizontal/vertical apex ratio.
4- Remove the ball from IFT cell and fix the position of the camera.
5- Pump synthetic brine into the IFT cell to full level.
6- Pump oil very carefully through the bottom needle to get a stable oil drop on the top of the needle inside the cell.
7- Set temperature at reservoir value using temperature control to obtain temperature equilibrium inside the whole cell. Use the heating jackets wrapped around the cell and water bath to control the system temperature.
8- Pump brine into the cell to increase the pressure inside the cell to reservoir pressure. At the same time, oil should be pumped to keep the oil drop still on the top of the bottom needle.
9- Take pictures at reservoir temperature and pressure.
10- Run the image drop image program to calculate IFT values.

Contact Angle Test Procedure

The following procedures were followed during contact angle measurements:

1- Fix calcite or rock plate to the upper needle using high quality cementing material (epoxy).
2- Place the plate inside the cell at suitable position to be seen in the image system (Figure 2).

3- Pump synthetic brine into the IFT cell to full level.
4- Rise up the bottom needle to be close to the plate.
5- Place an oil drop on the surface of calcite or rock plate.
6- Move the bottom needle carefully down.
7- Run the program on contact angle measurement mode.

RESULTS AND DISCUSSION

Interfacial Tension

Dead Oil/Brine System

The interfacial tension between dead oil and synthetic brine was measured at various temperatures (up to 90 ^{o}C) and pressures (up to 3,000 psig). Table 1 lists the IFT values at various temperatures and pressure.

Figures 3 shows plots of IFT versus temperature and pressure. Data in Table 1 and Figure 3 indicate a decrease in IFT of dead oil/brine system with increasing temperature. The decrease of IFT values at higher temperature can be attributed to the weakening of intermolecular forces at the oil/brine interface. These results are consistent with results published by Hjemeland and Larrondo, 1982.[7]

Variation of IFT values with pressure at various temperatures is shown in Figure 3. The pressure was increased from atmospheric to 3,000 psig. The IFT increased with pressure at constant temperature. For example, at 90 ^{o}C the IFT values increased from 18.9 dyne/cm to 21.0 dyne/cm when the applied pressure increased from 600 psig to 3,500 psig. A similar trend of increase in IFT with pressure was reported by Wang and Gupta (1995).[8]

The interfacial tension at the liquid interface can be related to the drop shape through the following equation:

$$\sigma = \Delta\rho\, g\, R_0^2 / \beta \qquad (1)$$

Where:

σ = interfacial tension, $\Delta\rho$ = density difference between the two immiscible fluids

g = acceleration due to gravity, R_0 = radius of curvature at drop apex, β = shape factor

Observing Eq. 1, IFT depends on the density difference of two fluids ($\Delta\rho$) in the IFT system. Both temperature and pressure will affect the densities of fluids. Because oil is more compressible than water, $\Delta\rho$ will increase with pressure and consequently IFT increases with pressure all the time. Increasing temperature will decrease the density of both brine and oil, which will lead to decrease in IFT (Figure 3).

Recombined Live Oil/Brine System

The interfacial tension between recombined live oil and synthetic brine was measured at various temperatures (up to 90 ^{o}C) and pressure of 3,000 psig. Table 2 lists the IFT values at various temperatures. The plot in Figure 4 shows an increase in IFT values with temperature. Due to presence of dissolved gas in the recombined oil, temperature will be expected to have more effect on oil than brine. This will also lead to the increase in density difference ($\Delta\rho$) between oil and brine. This is may be the reason that IFT increases with temperature in this study.

Contact Angle and Wettability

Recombined Live Oil/Brine/Calcite System

In this study, both pure calcite plates and natural rock plates were used as substrates in contact angle measurements. XRD and XRF analyses of natural rock samples revealed that the most predominant mineral in carbonate rocks is calcite (90-100 weight %). The other minerals are dolomite (0-8 weight %), and trace amounts (< 0.5 weight %) of quartz, pyrite, ankerite, gypsum, and siderite. On calcite, there was little variation in contact angle values with increase of temperature for live oil/brine system at reservoir pressure (3,000 psi) as shown in Table 3. The contact angle values varied from 41 to 44^{o} which revealed strong wettability character.

Recombined Live Oil/Brine/Rock Material System

Effect of temperature on contact angle behavior for live oil/brine/rock system is shown in Figure 5. A general trend of increase in contact angle values with increase in temperature was observed. The increase in contact angle values with temperature may be attributed to instability of water film between the oil drop and rock surface.[9] The presence of some other minerals like quartz, pyrite, ankerite, and gypsum may lead to adsorption of oil film and consequently increase in contact angle value (76^{o}) which revealed neutral to slightly wettability character of tested carbonate material.

Aging Effect

Figure 6 showed the plots of contact angle as a function of aging time for three rocks . The test for samples #3 and #4 was conducted at reservoir pressure (3,000 psi) and room temperature (26.6 ^{o}C). The test for sample # 5 was carried out at reservoir conditions of 3,000 psi pressure and 90 ^{o}C temperature. Aging time in these plots means the oil droplet is brought into contact with rock surface immersed in the brine and left for aging time before contact-angle measurements. After four (4) days, the contact angle reaches equilibrium for rock samples #3 and 4. For rock sample # 5, the test was terminated after 4 days because of leakage problems.

An increase of contact angle values with time was observed in the three plots. The increase of contact angle values with time could be related to wettability alteration arising from an asphaltene coating deposited on the rock surface. This will lead to adhering of oil to rock surface and consequently to significant change in behavior of contact angle with time over days. Our findings and behavior of contact angle with time are in agreements with the results obtained by Freer et al., (2003) and Treiber et al., (1972).[10,11]

The contact angle values (68^o-76^o) for rock sample # 5 reflect neutral to slightly water-wet wettability character of carbonate rock material.

CONCLUSIONS

1. The interfacial tension between recombined live oil and synthetic brine increased with increasing temperature at reservoir pressure (3,000 psig).
2. The interfacial tension of dead oil/brine system increased with increasing pressure at constant temperature. On the other hand, it decreased with increasing temperature at constant pressure.
3. Dead oil and live oil from the same reservoir and under similar experimental conditions exhibit different IFT values. The IFT values for live oil/brine system were greater than those of dead oil/brine system by 83%.
4. Contact angle of live oil/brine/rock material system increased with increasing temperature as well as with aging time. Four to six days are required for contact measurements to obtain representative and constant values for contact angle.
5. Contact angle data revealed neutral to slightly water-wet characteristics of carbonate rock material.

REFERENCES

1. Rose, W., and Burce, W.A., "Evaluation of capillary pressure in Petroleum Reservoir Rock" Pet. Trans; AIME, May 1949, 127.
2. Jennings, J. B., "Capillary Pressure Techniques: Application to Exploration and Development Geology" AAPG Bulletin: Vol. 71 No. 10, October 1987, 1196.
3. Donaldson, E., Thomas, R., and Lorenz, P. "Wettability Determination and Its Effect on Recovery Efficiency", SPEJ, pp. 113-20, 1969.
4. Morrow, N. R, "Wettability and Its Effect on Oil Recovery", Journal of Petroleum Technology, December 1990, pp 1476-1484.
5. Zhang, P. and T. Austad, "Waterflooding in Chalk: Relationship Between Oil Recovery, New Wettability Index, Brine Composition and Cationic Wettability Modifier" 94209-MS SPE, SPE Europe/EAGE Annual Conference, Madrid, Spain, 13-16 June 2005.
6. Dong, H., Y. Hong, W. Rui, and D. Fan., "The Effect of Wettability on Oil Recovery of Alkaline/Surfactant/Polymer Flooding", SPE ATCE, San Antonio, Texas, U.S.A, 24-27 September 2006.
7. Hjelmeland, O. S., and Larranodo, L. E.: "Experimental Investigation of the Effects of Temperature, Pressure, and Crude Oil Composition on Interfacial Properties", Paper SPE 12124 presented at the 1983 SPE Annual Technical Conference and Exhibition, San Francisco, CA, Oct. 5-8.

8. Wang, W., and Gupta, A. : "Investigation of the Effect of Temperature and Pressure on Wettability Using Pendent Drop Method", Paper SPE 30544 presented at the 1995 SPE Annual Technical Conference and Exhibition, Dallas, Oct. 22-25.
9. Morrow, N. R., "Interfacial Phenomena in Petroleum Recovery", Volume 36, Marcel Dekker, Inc. New York, 1991.
10. Freer, E. M., Svitova, T., and Radke, C. J.: "The Role of Interfacial Rheology in Reservoir Mixed Wettability", Journal of Petroleum Science and Engineering, Vol.39, (2003), 1137-158.
11. Treiber, L. E., Archer, D. L., and Owens, W. W.: "A Laboratory Evaluation of the Wettability of Fifty Oil Producing Reservoirs," SPEJ (Dec. 1972) 532-540.

TABLE 1. Interfacial Tension of Dead Oil/Brine System at Various Temperatures and Pressures.

Parameters	Interfacial Tension (dyne/cm)					
P, (psig) / T, (°C)	14.7	600	1000	2000	2500	3000
26.6	24.3	25.3	25.5	26.2	26.2	26.5
40	23.1	23.3	23.4	23.8	24.1	24.0
60	22.8	23.0	23.0	23.3	23.4	23.4
90	18.2	18.7	18.9	20.1	20.4	21.0

TABLE 2. Interfacial Tension of Live Oil/Brine system at Reservoir Pressure and Various Temperatures.

Temperature (°C)	Interfacial Tension (dyne/cm)
26.6	29.6
40	32.6
60	37.1
90	38.5

TABLE 3. Contact Angle Values for Live Oil/Brine/Calcite System at Various Temperatures.

Temperature (°C)	Contact Angle	
	Calcite Sample #1	Calcite Sample #2
26.6	43	41
40	43	43
60	44	43
90	44	43

Table 4. Contact Angle for Live Oil/Brine/Rock Material System at Various Temperatures.

Temperature (°C)	Contact Angle	
	Rock Sample #1	Rock Sample #2
26.6	47	46
40	52	49
60	58	56
90	76	74

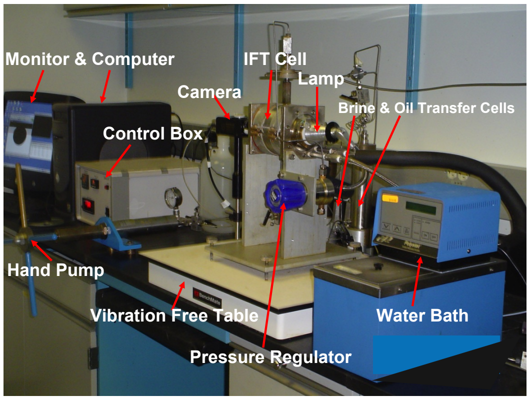

Figure 1. Reservoir Conditions Interfacial Tension and Contact Angle System.

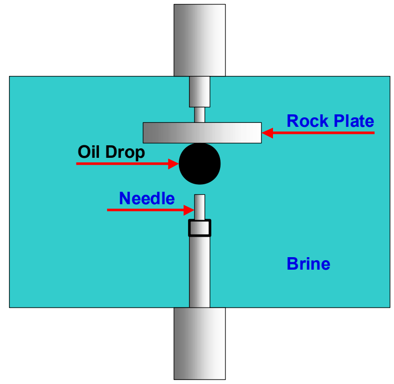

Figure 2. A Schematic of Cross-Sectional View during Contact Angle Measurements.

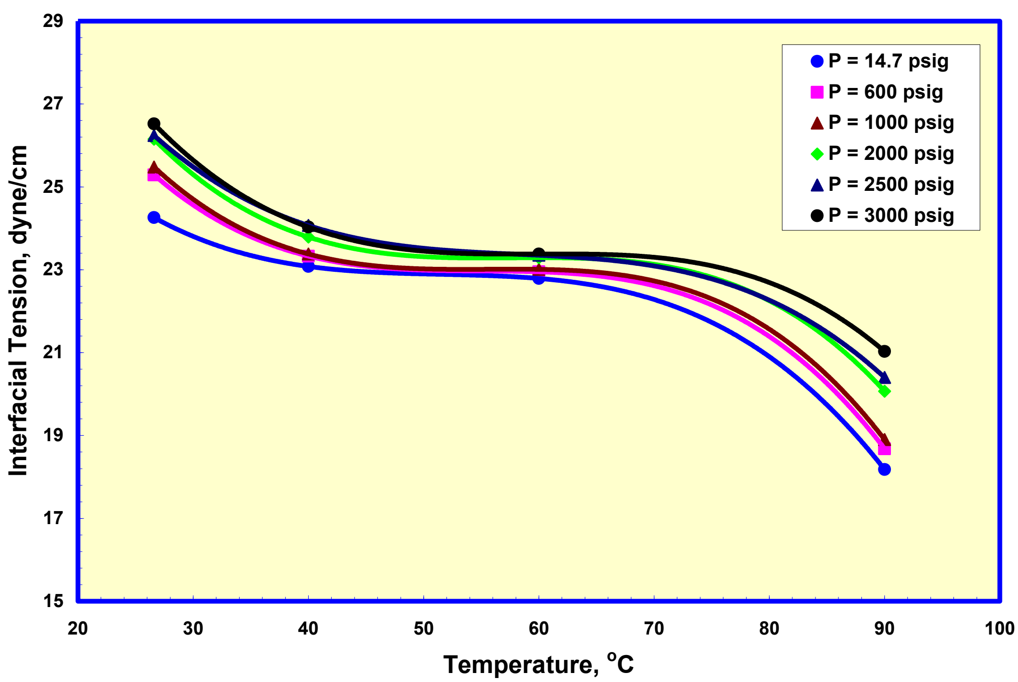

Figure 3. Effect of temperature and pressure on interfacial tension of dead oil/brine system.

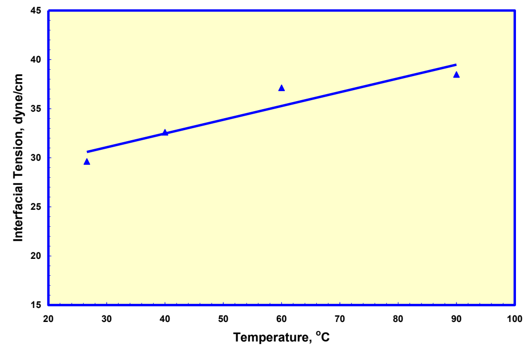

Figure 4. Effect of temperature on interfacial of live oil/brine system at P = 3000 psig.

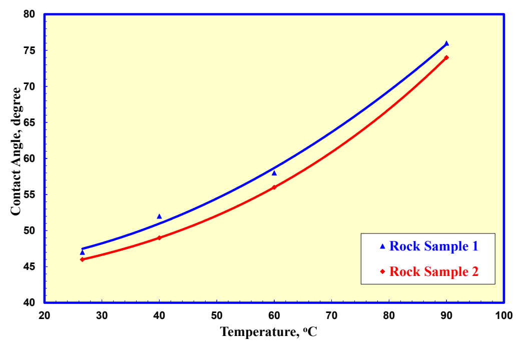

Figure 5. Effect of temperature on contact angle for live oil/brine/rock sample system at P = 3000 psi.

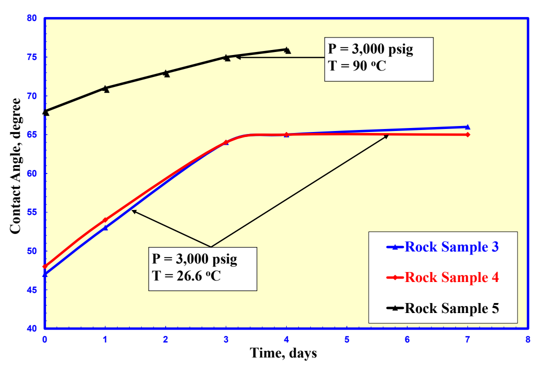

Figure 6. Contact angle vs. time for live oil/brine/rock sample system.