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Analysis of MEOR Efficiency to Increase Recovery in an Iranian Reservoir

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Rock samples from the Asmary outcrop formation of the Ahwaz oil rich zone with a porosity of 16% and permeability of 1 md and MIS crude oil with an API value of 42.5 and moderate asphaltene content of 3%, were used to study the effect of the incubation time and flow rate of the displacing fluid in MEOR operations. Five species of rod shaped, gram positive, thermophile and facultative bacteria were isolated and purified from the crude. Due to the high sweep efficiency prevailing in the core flooding system, the effect of the displacing brine flow rate on the oil recovery efficiency was found not to be significant. On the other hand, a 100% increase in incubation time from 7 to 14 days resulted in an increase from 3% to 4% in the total cumulative production. Application of a cyclic operation was not effective in promoting the efficiency of the MEOR operation, probably due to the stronger effect of flooding on the removal of valuable metabolites, as compared to undesired ones, before the stationary phase of the microbial kinetics. While qualitative measurements did not show a strong change in the water-rock contact angle, more than a 4-fold increase in capillary number occurred after microbial treatment, implying that reduction of interfacial tension was the stronger mechanism of oil recovery in this work.

INTRODUCTION

Water flooding is one of the most well-known methods used in the secondary recovering period of the reservoir. But, unfavorable conditions, such as heavy oil, an oil wet matrix and high interfacial tension (IFT) between the oil and water, decrease the efficiency of water-flooding. As a remediation, some chemicals, including surfactants, are used to overcome these problems. But, these materials are expensive and their application in many reservoirs cannot be commercialized. Fortunately, microorganisms have the potential capability to produce such chemicals in the reservoir by utilizing hydrocarbons at a low expense.

Microbial Enhanced Oil Recovery (MEOR) is an economical, feasible method that can be applied to many reservoirs [1-4]. The ability of bacteria to produce appropriate chemicals and, in particular, biosurfactants, using the reservoirs hydrocarbons as the main nutrient source, is a great advantage of internally applied MEOR to other EOR methods [5-7].

In application of the internal MEOR to a field, one major parameter to success is a fundamental knowledge of the physico-chemical nature of the rock/brine/crude system. In fact, lacking such knowledge may even lead to un-anticipated problems and/or damage to the candidate reservoir [8]. Interactions of the reservoir with the microbes and their metabolites should also be carefully studied to lower this risk. Therefore, it is necessary to determine the main obstacles in recovering crude from the reservoir and the proper methodology to overcome these barriers, via application of the MEOR protocols.

The primary forces causing the flow of petroleum in a porous media are gravity and capillary forces [9]. The petrophysical properties of the reservoir and the production history are the two important parameters that determine which of these forces have a stronger influence on the crude production rate. In a naturally fractured carbonate rock reservoir with a mixed-wet low-permeablity matrix, the capillary forces are not favorable to oil production in waterflooding operations. To displace the wetting oil phase by water, in this case, it may be recommended to neutralize the threshold

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capillary pressure beforehand. Following this pretreatment, displacement of the wetting oil phase by water could be materialized via the drainage mechanism [10].

The efficiency of this immiscible displacement can be enhanced in two ways. The first is by reducing the interfacial tension between the oil and water, by means of surfactants. This IFT reduction empowers the effect of gravity and viscous forces and leads to increased oil production [11]. The second is altering the wettability of the reservoir rock to a water-wet condition. This alteration is equal to increasing the capillary pressure, in favor of the imbibition of water and, finally, the main mechanism of oil production will shift to capillary imbibition [12]. In this paper, the potential of some isolated bacteria and their secreted biosurfactants, to be applied in MEOR processes, via these two mechanisms, is presented.

EXPERIMENTAL

Materials

Crude Oil

MIS crude oil samples with no solvent dilution or asphaltene removal were used in this study. Some of the physical properties of the crude are listed in Table 1.

Rock

Rock samples from the Asmary outcrop formation, about 60 km north of the Ahwaz oil rich zone, located in the south west of Iran, were used. 31.5 cm long and 3.7 cm diameter core samples were cut from these rocks. Some of the petrophysical properties of these cores are given in Table 2. Although the core samples were not completely homogeneous, their petrophysical properties were very similar, being cut from the same block. This provides the possibility of a comparison of the results.

Brine

Analytic grade salts and other reagents (Merck, Germany) were dissolved in deionized water to formulate brine and a microbial culturing media. A 5% aqueous solution of NaCl was used as synthetic brine. The physical properties of this brine are given in Table 3.

Table 1. Physical properties of crude oil samples.

Viscosity (cp)	3.5
Density (API)	42.5
Interfacial Tension (dyne/cm)	23.3
Acid No. (mg KOH/gr Oil)	0.06
Asphaltene%	3

Table 2. Petrophysical properties of core samples.

Sample No.	Porosity%	Permeability (md)
1	16	1.0
2	15.4	1.2
3	15	1.3
4	16.2	1.1
5	15.8	1.0
6	16.2	1.1

Table 3. Physical properties of synthetic brine.

Viscosity (cp)	1.02
Density (g/cm^3)	1.04
Surface Tension (dyne/cm)	72.3
pH	7.4

Microorganisms

Five species of bacteria were isolated and purified from MIS oil samples. The bacterial phenotype and proper growth condition were determined at ambient pressure. All of these bacteria were rod shaped, gram positive, thermophile and facultative. To simulate the natural microbial ecosystem of the reservoir, optimization of the growth condition and application in the core flood experiments were carried out using the mixed culture, including all five species.

Apparatus

Tensiometer

A ring type tensiometer (duNouy, Kruss, Germany) was used for surface and interfacial tension measurements. The sensitivity of the tensiometer was 0.1 dyne/cm. All measurements were carried out at 25°C.

Microscope

All microscopic observations were carried out via a light microscope set at 1200 magnification (Olympus, Switzerland).

Core Holder

A core flood apparatus was designed and assembled for high pressure flooding experiments in this study. It could produce flow rates as low as 0.05 ml/min at pressures and temperatures up to 10000 psi and 250°F, respectively. The overburden pressure could be raised to 10000 psi, as well. A digital computerized control system regulated flow rate and temperature. Data logging at time intervals was adjustable via

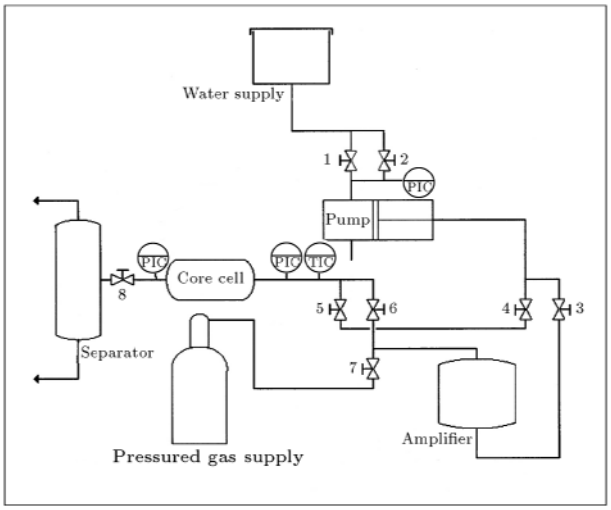

Figure 1. Core holder PFD.

the computer control system. The schematic Process Flow Diagram (PFD) of the apparatus is shown in Figure 1.

Design of Experiments

Among various factors affecting oil recovery in a MEOR operation, the incubation time and flow rate of the displacing fluid are the two most important. The incubation time is expected to provide the necessary time for the bacteria to excrete biosurfactants. The previous laboratory scale study to maximize bacterial biosurfactant production at atmospheric pressures suggested that the best incubation period lay between 7 to 14 days [13]. These data were adopted and used to set the incubation time in this study.

Aside from its effect on the amount of biosurfactant concentration in the system, incubation time supports biosurfactants to interact with the three phase system to improve the oil production conditions. The flow rate of displacing water on the other hand, influences the oil recovery procedure through viscose forces. It may also affect the probable bacterial adhesion on the rock surface, leading to a change in the permeability of the rock. It goes without saying that the flow rate is limited by reservoir conditions, such as the oil drainage rate from the matrix into the fractures. In this study, these two factors were studied at two levels in 6 experimental runs. Table 4 illustrates the specifications of these runs in more details.

Test Procedure

As-received core samples were dried completely at 100°C overnight before being used in the core flood experiments. Then, they were saturated with brine by immersing in brine solution for 24 hours and their porosities were measured, via the weight increase

Table 4. Array of high pressure experiments.

No.	Incubation Time (day)	Flow Rate (ml/min)
Exp # 1	14	0.1
Exp # 2	14	0.2
Exp # 3	7	0.1
Exp # 4	7	0.2
Exp # 5	14+5	0.2
Exp # 6	7+7	0.2

method. After installation of the core in the core holder system, brine was injected at a rate of 0.2 ml/min until back pressure fluctuations were damped and a steady state condition prevailed. The absolute permeability of the samples was measured through a perm plug method [9]. Figure 2 provides a sample of the diagrams produced in this method.

After this stage, at least 3 pore volumes of crude oil were injected at a rate of 0.2 ml/min and water saturation reduced to its irreducible value, resembling the reservoir connate water. The core was then left to age at 60°C and 600 psi pressure overnight. Afterwards, brine was injected at the same flow rate of 0.2 ml/min until no more oil was produced and the residual oil saturation was determined.

At this stage, microbial broth was injected at the same flow rate for two pore volumes. The viable bacteria were detected in the produced water by microscopic observation. The back pressure was regulated at 600 psi during the experiments, which is equal to the pressure of MIS well head pressure. The core was then incubated at 60°C and 600 psi for the desired time span. Later, a waterflood was conducted to bring the core to a new residual oil saturation value. The flow rate of brine in this stage was equal to its designed value, as shown in Table 4.

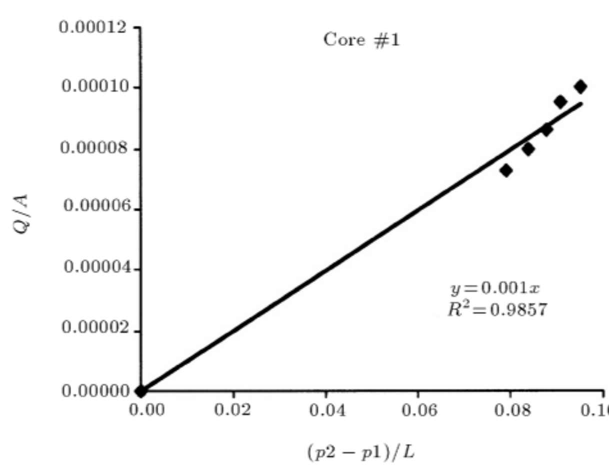

Figure 2. Absolute permeability measurement.

Analysis

The IFT of the produced oil and water was measured before and after microbial treatment. Reduction of residual oil saturation, cumulative oil production and relative permeabilities at residual oil saturation values, were determined. A capillary number was used to investigate the effects of capillary forces and IFT reduction on the oil recovery [14,15]. The capillary number is defined as the ratio of viscose to capillary forces as:

$$N_{\mathrm{Ca}} = \frac{v\mu}{\sigma},$$

where v and μ are the velocity and viscosity of the displacing fluid and σ is the oil water interfacial tension. It has been reported that an increase of four to six orders of magnitude in capillary number is required for significant reduction of residual oil saturation [16]. Reduction of IFT was used as the main means of increasing the capillary number in this study. Although no blank tests were performed in parallel to the MEOR tests, the reduction of IFT values measured at each case could be a strong sign that the bacterial action is at least one of the important parameters in occurrence of the final results.

RESULTS AND DISCUSSION

As illustrated in Table 4, six experiments differing in their treatment design were carried out in this study. The summary of experimental results is given in Table 5. The Sor decrease of each case is shown in Figure 3. In lieu of the experimental data depicted in Table 5, one may draw conclusions as to the influence of the flow rate of the displacing fluid and the incubation time on the overall effect of the microbial treatment of the core system on oil recovery. These two parameters are discussed below.

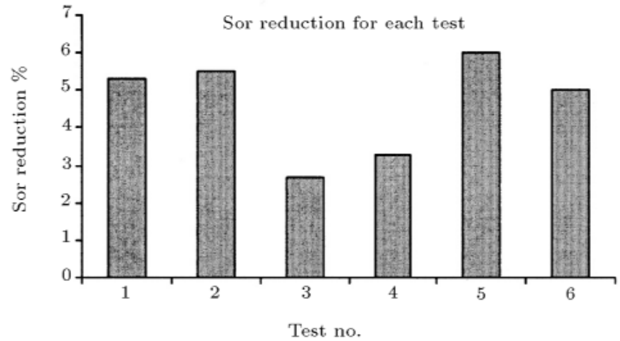

Figure 3. Results of Sor reduction for each test.

Effect of the Flow Rate of Displacing Fluid

In application of the MEOR protocols, one may speculate that the rate of water injection, after the microbial treatment of the reservoir, may have a meaningful effect on the obtained results. This speculation may be verified using the results of this study.

In reference to Table 4, it may be noticed that Experiments 1 and 2 have the same incubation time of 14 days but two different flow rates of 0.1 and 0.2 ml/min, respectively. Similarly, Experiments 3 and 4 have the same incubation time of 7 days and, again, two flow rates of 0.1 and 0.2 ml/min, respectively. Therefore, analysis of the collected data of these 4 experimental runs may reveal some facts as to the influence of the displacing fluid flow rate on the performance of the MEOR method.

Figure 4 illustrates how a change in the flow rate affects the two parameters of the average rate (equal to the average slope of the curve after microbial treatment) and final production of the crude after the two incubation times of 7 and 14 days. Average rate and final production of the crude in Experiment 1 are 0.034 and 79%, as compared to 0.058 and 81% in Experiment 2. Similar features of Experiment 3 are.017 and 76%, in comparison to .017 and 77% in Experiment 4. Despite the early expectations, mutual comparison of the 4 experiments shows that the total

Table 5. Summary of dynamic core holder experimental results.

No.	Incubation Time (day)	Flow Rate (ml/min)	Swi%	Sor (Before Incubation Time)%	Sor (After Incubation Time)%	Capillary Number Increase%	IFT After Incubation (dyne/cm)	Incremental Oil Production OOIP%
Exp # 1	14	0.1	20.2	34.5	29.2	455	5.1	6.6
Exp # 2	14	0.2	19.5	32.9	27.4	460	5.2	6.88
Exp # 3	7	0.1	19.3	31.3	28.6	307	7.5	3.8
Exp # 4	7	0.2	18.8	30.8	27.5	325	7.2	4
Exp # 5	14+5	0.2	20.7	33.6	27.8	468	4.9	7.1
Exp # 6	7+7	0.2	18.8	30.8 27.5	27.5 25.8	325 —	7.2 —	4 2

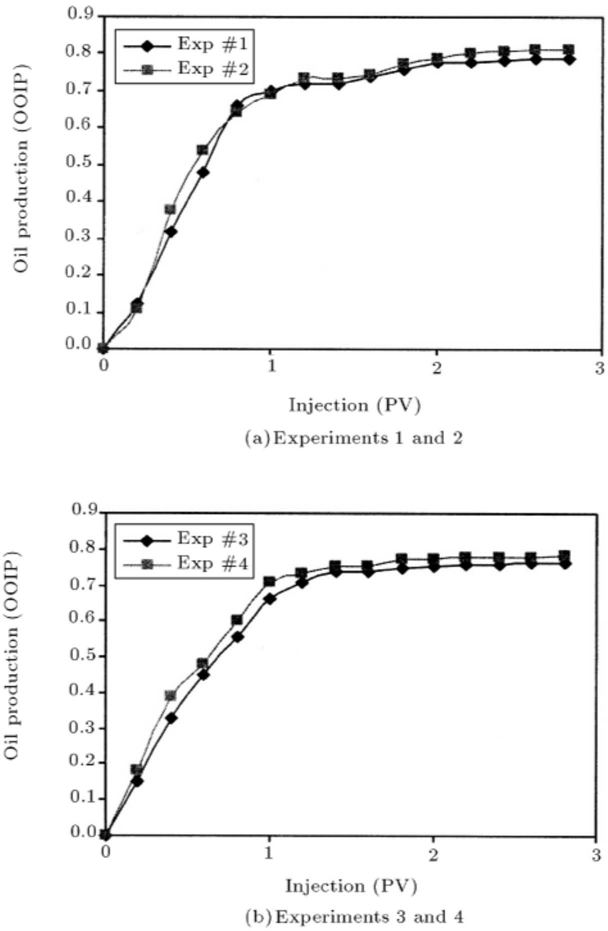

Figure 4. Effect of flow rate.

production of the crude at different flow rates hardly differs. Consequently, it may be deduced that the effect of the flow rate of the displacing brine on the two specified parameters is not very significant. This observation may be attributed to the relatively short length of the core samples and the fixed value of the back pressure. This condition may lead to a high and, probably, complete sweep efficiency, independent of the flow rate of the displacing brine in the simulated "reservoir system". Obviously, such a high sweep efficiency may not prevail in a real reservoir and, hence, a field optimization campaign should be carried out to determine the proper injection rate in a natural system. The proper injection rate, of course, may not exceed an upper limit to avoid the well known fingering effect and should be optimized with rate of production and incubation time.

Effect of Incubation Time

Out of the 6 experimental runs, run No. 1 and No. 3 have the same flow rate of 0.1 ml/min, but two different incubation times of 7 and 14 days. Similarly, Experiments 2 and 4 have the same flow rate of 0.2 ml/min and, again, two different incubation times of 7 and 14 days, respectively. It may be expected that the shorter the incubation time, the less will be the capillary number increase and, hence, the less will be the oil production. To examine this expectation experimentally, results of these four experiments were shown in Figure 5. The average rate and final production of the crude in Experiment 1 are 0.034 and 79% as compared to 0.017 and 76% respectively, of Experiment 3. Similar features of Experiment 2 are 0.058 and 81%, in comparison to 0.017 and 77%, respectively, in Experiment 4. It seems that there is a direct correlation between incubation time and oil production and this can be observed in the results of Experiments 1 and 2, which have a longer period of incubation but also have higher cumulative crude production values. A 100% increase in incubation time from 7 to 14 days results in an increase from 3% to 4% and 0.017 to 0.041 in the two parameters of total cumulative production and average rate of oil production, respectively. This clearly certifies the noticeable effect of incubation time on the overall success of the MEOR practice.

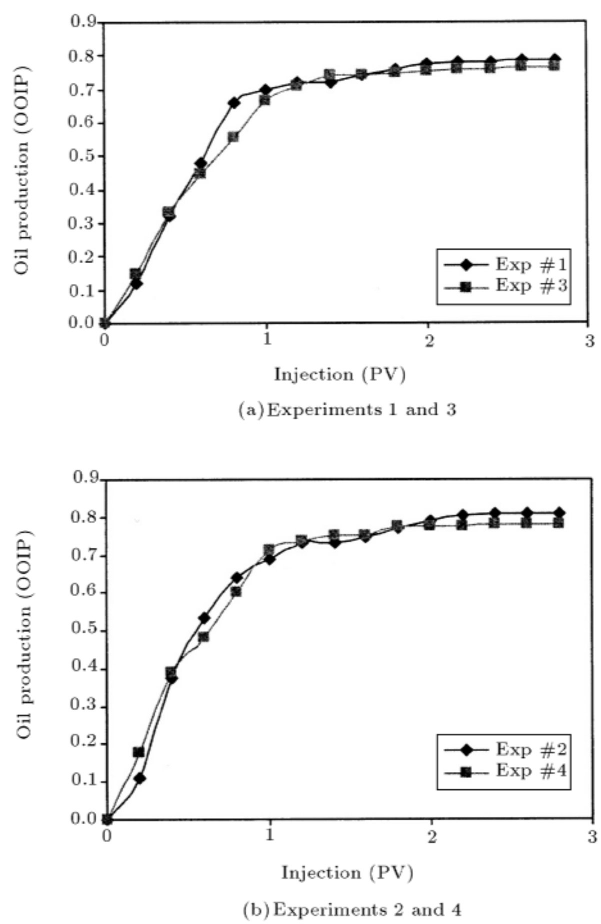

Figure 5. Effect of incubation time.

Probing the Trajectory of Microbial Performance Activity

Although a direct relationship between incubation time and cumulative crude production was documented from the experimental results, it may be speculated that this relationship will be up to a specific time, beyond which a longer time of incubation would not result in any useful result. This idea is based on the fact that the oil reservoir, in general, and the core in the core flooding experiments are, in fact, batch bioreactors. In the batch mode of operations, a longer period of incubation accommodates bacteria with more time to produce effective metabolites, including biosurfactants. However, it is well known that accumulation of biological toxins and/or depletion of nutrients hinders bacterial growth and metabolite production after a specific period of time in all batch fermentations. This time, of course, is a function of so many parameters, including the genus of bacteria, type of nutritious media, fermentation conditions, etc. Beyond this critical time, the rate of production of useful metabolites diminishes gradually and comes to a standstill at the end. Obviously, extension of the MEOR protocol would not result in any proper effect after this time.

To investigate these speculations, a new experiment (Exp # 5) was designed and carried out in similar conditions to Exp # 2, except that, in this new experiment, the core sample was incubated for an extra incubation time of 5 days and waterflooding was conducted only at the end of 19 days. The produced oil in this run was hardly more than the result of Exp # 2 and little amount of extra oil was produced. This observation not only supports the above considerations, but also, gives an estimation of about two weeks for the critical time span in this system.

Based on the available experience of working with batch bioreactors and in lieu of the above considerations, a cyclic mode of operation could be beneficial to the overall effectivity of MEOR operations. In this case, the total time of protocol could be split into a number of incubation and water flooding operations. Therefore, accumulated biotoxins could be washed away intermittently, leaving a "cleaner" environment for the bacterial activity and the hindrance effect of batch operation would be eliminated. This idea was examined through another experiment (Exp # 6). The core sample of Exp # 4 was used for this new experiment immediately after finishing Exp # 4. This core was incubated for an extra week and then flooded at a flow rate of 0.2 ml/min. As large as 2% of Original Oil in Place (OOIP) was produced and a 1.7% decrease in the residual oil was achieved. However, the sum of the oil produced in these two cycles was less than that of Exp # 2, which had similar conditions, except that its incubation time was continuous. The results of these two cases are shown in Figure 6. This observation may be explained, based on two possible effects, as follows:

- Upon flooding the system after one week, not only are the toxic metabolites washed away from the system, but also, valuable metabolites, including biosurfactants, are removed from the core. This, obviously, would have a negative effect on the overall function of the MEOR process;
- By flooding the system, the miniature environment of the bacteria changes in terms of composition. This would result in a lag phase in the biokinetics of the cell culture and, hence, biosurfactant synthesis could be stopped for a while and resumed again at a lower rate. In this case, the average concentration of biosurfactant during the whole period of operation would be lower and, again, the overall production would suffer in this mode of operation.

Whatever the reason, experimental findings suggest that cyclic operation, at least in this schedule, is not effective in promoting the efficiency of the operation. A modified schedule to reveal the potential application of the cyclic operation could be applied, after getting to the normal time span of the logarithmic growth phase and upon entering the stationary phase in this "batch bioreactor", and is to be examined experimentally.

Wettability and Capillary Number in MEOR

In internal biosurfactant flooding, it is believed that reduction of oil and water interfacial tension (IFT) and alteration of the wetting preference of the rock surface are the two main mechanisms working together to increase the production in MEOR [17]. Both of these mechanisms affect oil recovery but their contribution in the final result may differ from case to case. IFT reduction facilitates the flow of the trapped oil in the porous media by reducing the coherent energy barrier at the

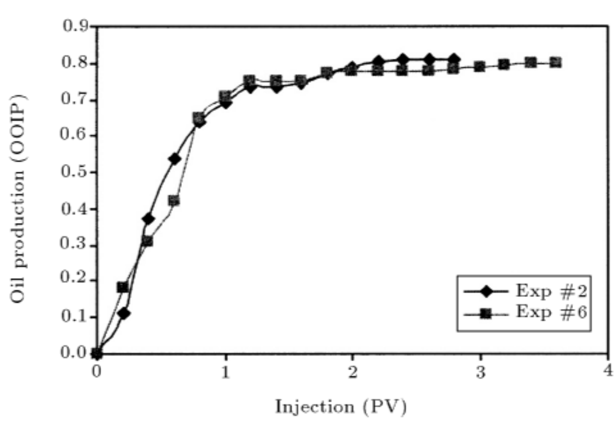

Figure 6. Results of cyclic versus continuous modes of operation in MEOR process.

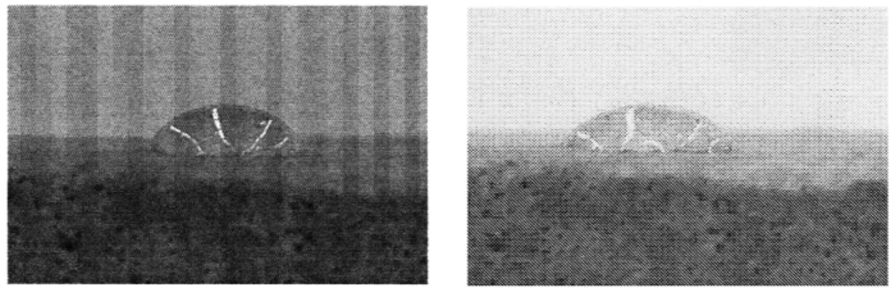

Figure 7. Contact angle of water droplet on the core sample before (left) and after (right) microbial treatment.

elastic interface layer of the two phases. Chemical components of the crude, lithology of the reservoir rock and chemical structure of biosurfactant are some of the important parameters in the wettability alteration mechanism [18]. In theories describing the evolution of the crude, the wetting preference of the rock is assumed to be neutral before contacting the reservoir fluids. Chemical reactions between the active sites in some of the crude components, such as resins or asphaltene, develop conditions in which the rock is converted to an oil wet substrate. The presence of some metal ions, such as calcium and magnesium enhances the occurrence of these reactions. Biosurfactant molecules can change this state in two ways. In the first one, they may attack and break these chemical bonds through their active sites and establish new bonds to the rock. In this case, wettability would be altered irreversibly. In the second way, the pore surface of the rock may be shielded by a thin layer of biosurfactant molecules and the wettability would be altered reversibly. In these experiments, the wetting preference of the core samples altered, to some extent, in favor of water after microbial treatment.

The relative importance of these two effects was checked in this study. A change in wettability was detected qualitatively by means of measuring the fluid-rock contact angle via digital photography, a typical view of which is shown in Figure 7. This figure shows the contact angle alteration for a drop of water on the core sample before and after microbial treatment. Measurements in this study do not show a strong change in contact angle when treated by the bacteria. On the other hand, results of experimental runs show that a strong change in capillary number occurred in this treatment. As shown in Table 5, an increase as large as 468% in capillary number was achieved in microbial treatment of the core system and the minimum capillary number increase, due to IFT reduction, was 307% in Exp # 3. These data imply that reduction of interfacial tension has been the stronger mechanism of oil recovery in this work.

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