

Relative Flow of Bacteria and Oil in Porous Media

Abdulrazag Y. Zekri, Mohmed Nasr, and Amer M. Aborig

Abstract—The relative permeability of porous media has been shown by a number of investigators to play a big factor in determining the recoveries resulting from both water floods and tertiary floods. Solutions of bacilli strains of bacteria in water, Bacterial Enhanced Oil Recovery (BEOR) have previously been shown to be effective in improving oil recoveries from Carbonates using laboratory core-flooding experiments. One of the mechanisms indicated was a change in rock relative permeability due to changes in wettability of the flooded system from oil-wet to more water-wet conditions. The causes of these changes are the interaction of bacteria with crude oil *in situ* producing gases, surfactants, other chemicals like acids and mild organic polymers. This wettability alteration increases the oil relative permeability, decreases the water relative permeability, and reduces the residual oil saturation (ROS). These factors and others, in turn, result in an improvement in the bacterial flood recovery over recoveries obtained by water flooding alone. The objectives of this work are to describe and quantify the relative permeability alteration occurring in BEOR processes and the study the factors that would enhance such alteration and improve oil recovery.

Index Terms— Bacteria, flow, porous media, bacilli-strains.

I. INTRODUCTION

Laboratory research has shown that microbial products can change the chemical and physical properties of oil, selectively plug high permeability zones, which results in improvement in volumetric sweep efficiency Crawford¹.

Once the bacteria are in place, a designed volume of nutrients may be injected into the reservoir to support *in situ* metabolism of the bacteria. The result of this metabolism is the production of cellular mass capable of initiating physical plugging. The physical plugging results in a reduction of the original permeability and can be expressed as the ratio of impaired to original permeability. Continuous injection will result in a diversion of the injected fluid from closed high permeability zones to upswept zones and significant improvement in overall sweep efficiency. Microorganisms that produce gases such as CO₂, N₂, H₂, and CH₄ can improve oil recovery by increasing reservoir pressure and by swelling individual trapped oil droplets and reducing oil viscosity due to the dissolution of above gases in the oil. Three phase relative permeability studies have shown that the residual oil saturation can be reduced by the presence of a gas in water-wet stems Crawford¹.

Another mechanism microorganisms have shown is emulsification of crude oil during flow in a porous medium. The solvents that microorganism produce is typically low molecular weight alcohols.

These compounds promote emulsification. Microbes also produce surfactants that can lower oil-water interfacial tension (IFT) thus causing emulsification. A natural lipid bio-surfactant isolated Cooper² from the anaerobic *Clostridium Posteurianum*, and anaerobic bio-surfactant produced from *Bacillus*. *Bacillus Licheniformis* also produce a surfactant under anaerobic conditions. An increase in actual fluid velocity within porous media results from fluid being diverted into smaller pores due to bacterial plugging. The drop in interfacial tension and increase in fluid velocity combine to increase the capillary number. Increased capillary numbers are associated with reduction of residual oil saturation. Some microbial species can also significantly improve oil production by helping to remove suspended debris and paraffin from near-well bore region (Al-Magrabi ref. 3). In carbonate formations or sand stone rocks with carbonaceous cementing materials, acid-producing microbes can increase permeability of rocks and thereby improve oil recovery.

Rouse et al.⁴, concluded that there is no experimental evidence that the MEOR process using powdered microbes and starch consisting of *acinetobacter venospecre* group II and *coryneform* results in oil production in excess of that provided by water flooding due to the absence of enough oxygen required to generate either surfactant and or polymer *in situ*. Other investigators, however, have concluded that viable microorganisms can penetrate porous media, produce chemicals and gases and preferentially plug high permeability zones, which improve oil recovery significantly. Chisholm et al.⁵, Yonebayashi et al.⁶, Myers and Samiroden⁷, Jenneman et al.^{8&9}, Torbati, et al.¹⁰, Jack et al.¹¹, Bryan and Douglas¹², and Raiders et al.¹³ studied the effects of viable microbial in the porous media. Coa et al. presented an extensive review of microbial EOR^{14,15}. Zekri et al studied the possibility of contact angle alteration by microbial flooding¹⁶.

The relative permeability of bacteria/oil/water mixtures is the single most critical factor in determining the success of a microbial flood. Many papers focused and described the relative permeability behavior between oil/water and surfactant, CO₂ or condensate yet not much work has been conducted to evaluate and assess the relative permeability of bacteria/oil/water mixtures. Study of the relative permeability will assist in developing and optimizing of microbial systems for enhanced oil recovery. In this project the relative permeability behavior of bacteria solution using different carbonate core samples and bacteria concentrations was investigated.

This study presents the results of relative permeability of Bacteria/brine/ oil systems. In addition to that the interfacial tension of microbial system was also measured using four

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different types of crude oils obtained from UAE reservoirs¹⁸. A test core flooding run was conducted to confirm that microbial system used in this study can lower IFT inside the porous media (carbonate rocks). The goal of this study is to expand the current knowledge on the microbial mechanisms involved in the MEOR process.

II. APPARATUS AND MATERIAL

A. Bioreactor

This reactor is an air curtain driven fluidized bed reactor. It is used to generate the live bacteria solution for injection experiments. Compressed air is injected into the reactor through a series of perforations in a transverse tube in order to create fluid circulation with an air curtain. This system provides for bacteria an efficient aeration technique that is non-intrusive and is particularly helpful for growing filamentous bacteria. The location of the air curtain, as well as the flow of the compressed air, was optimized. Air was supplied to the reactor through a transverse tube with equally spaced 16 perforations of 1.6 mm diameter each, placed in a single row. The tube was placed centrally across the bottom

of the bioreactor.

B. Bacteria

Two strains of bacteria rounded and rod shape type, both belonging to the *Bacillus* family, were obtained from the UAE local hot water streams. These bacteria were unique in their tolerance of the high temperature and salinity conditions prevailing in the UAE environment. Prior to injection in the cores, an inorganic powder nutrient (containing beef extract and yeast) was added to live bacteria and mixed together in the bioreactor. This had the effect of increasing the bacterial concentration to around 30×10^3 cells/ml in the water solution, which was then used in the flooding experiments.

C. Computerized Image Analyzer

A computerized image analysis system was used to measure concentrations of bacteria in the culture for both the injected and the effluent water samples. The basic system consists of a high-resolution video camera on an optical microscope, an image processor, a Pentium PC, a high-resolution image monitor, and a high-resolution text monitor.

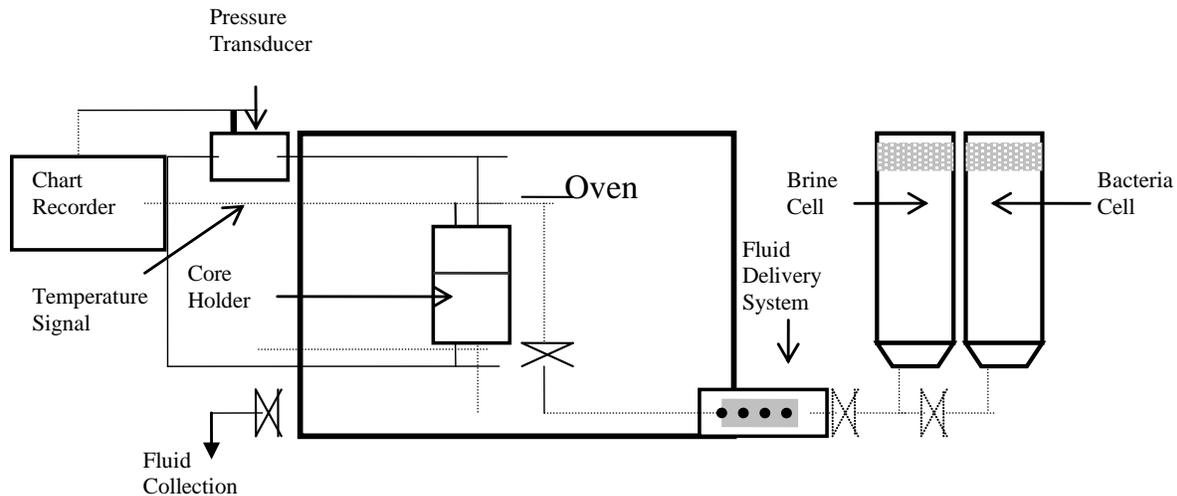


Fig. 1 – Core Flooding Apparatus.

The image is visualized with the video camera through a microscope lens. As soon as binary images are produced from an accepted microphotograph, a feature count can be performed. This is accomplished simply by selecting the desired bit plane and activating the count option.

D. Interfacial Tension Apparatus

The spinning drop of Core Lab Model 500 interfacial tensiometer was used in this project. The apparatus includes a variable temperature air bath so that reservoir temperatures can be simulated.

E. Core Flooding Apparatus

The schematic diagram of the core flooding apparatus is shown in Fig. 1. Two fluid accumulators are connected to a variable rate injection pump. The core holder is placed in a variable temperature oven. Pressure and temperature transducers are connected at both ends of the core inside the

core holder. A chart recorder and a digital pressure recorder are connected to the temperature transducer and pressure transducer respectively

F. Fluids

Crude oil obtained from the United Arab Emirates oil field (AH) was used to study the changes in interfacial tension between microbial solution and oil. All IFT, contact angle, and relative permeability measurements were conducted using one type of crude (AH crude). Table 1 presents the composition of the used crude oil.

TABLE I
AH CRUDE OIL COMPOSITION

Component	Mol%	Wt %
Hydrogen Sulphide	trace	Trace
Carbon dioxide	2.71	1.2
Nitrogen	0.06	0.02
Methane	34.66	5.59
Ethane	6.96	2.10
Propane	6.46	2.87
i-Butane	1.54	0.90
n-Butane	4.09	2.39
I-Pentane	1.87	1.36
n-Pentane	2.57	1.87
Hexane	3.58	3.10
Heptanes plus	35.5	78.60

III. EXPERIMENTAL PROCEDURE

Initial tests involved the growth of bacteria in the air curtain bioreactor under 22°C room temperature. A 10mg/4000 ml of the Nutrient is added to the Bacteria solution. The next step is to estimate observe the bacteria growth as a function of time. To determine if the bacteria are aerobic or anaerobic, a sample of bacteria solution is placed in smaller bioreactor and N₂ is bubbled through the bacteria solution. The bacteria remained alive in the absence of O₂ which indicate that the employed bacteria are anaerobic bacteria.

The spinning drop apparatus was used to study the interfacial tension of the used crude oil sample and nutrient-rich brine containing bacteria. The spinning drop apparatus includes a capillary tube, into which an aqueous bacteria solution is injected, followed by a small drop of oil. The oil and nutrient-rich brine bacteria solution are mixed together in a cylindrical tube and shaken well. The mixed fluids are then kept for 48 hours to reach equilibrium before using them in IFT measurements.

The limestone cores were dried at 80°C for 72 hours. Each core was evacuated for 12 hours and saturated with 7% (by weight) brine solution. During this step, we measured the volume of water required to completely saturate the core in order to determine its pore volume and porosity. The core was then flooded at a high rate with the AH crude until no further brine was produced. The residual brine saturation was calculated from the recovered effluent brine volumes. The core was flooded continuously at a constant pressure with the rich nutrient bacteria solution until a water cut of 100% was reached. All produced fluids are collected and bacteria concentrations were measured as function of pore volume injected to evaluate the relative permeability and growth of microorganisms of the studied system.

Contact angles are measured using the sessile drop method. The device consists of a box made of Pyrex with dimensions of 10 cm × 10 cm × 13.5 cm. A circular limestone disk (Diameter 3.6 cm) is placed on the top of the open side of the table as shown in the schematic diagram. The box is filled with the specified bacteria solution. Then a small drop of oil is placed at the bottom of the limestone disk and given a dynamic water receding condition. The changes in the drop size as function of time were monitored using a digital camera. Runs were performed to assess the effect of bacteria concentration on the contact angle of the studied system.

IV. RESULTS AND DISCUSSION

A. Interfacial Tension Measurements

The AH crude oil was used to investigate interfacial activity of the microorganism at different temperatures. All measurements were carried out at temperatures between 35-90 °C and the salinity was kept constant through out at 10% by weight. Bacteria concentration used for all IFT measurements was equal to 30×10³ cells/ml. **Fig. 2** shows the effect of temperature on the IFT of AH crude. Two systems were tested, bacteria- free solution consist of a 10% NaCl solution only and a bacteria concentrated solution of 30 ×10³/ml. As shown in fig. 2, results clearly demonstrate that bacteria metabolism is essential in reduction of IFT at relatively high temperature of around 60°C. Increasing temperature from 30 to 90 °C resulted in reduction of IFT from 46 dyne/cm to 1.6 dyne/cm, Meanwhile, the bacteria free solution exhibit no significant changes in the interfacial tension between AH crude oil and the saline solution. To demonstrate that bacteria consumes hydrocarbons, a small drop of the AH crude was added to the bacteria solution and kept for one day. After one day, the drop disappeared completely. The reduction of IFT and reduction of drop size with time and temperature indicate that bacteria activity is increasing with temperature and at high temperature bacteria metabolize producing surfactant and the density of bacteria increase by consummation of the AH crude oil.

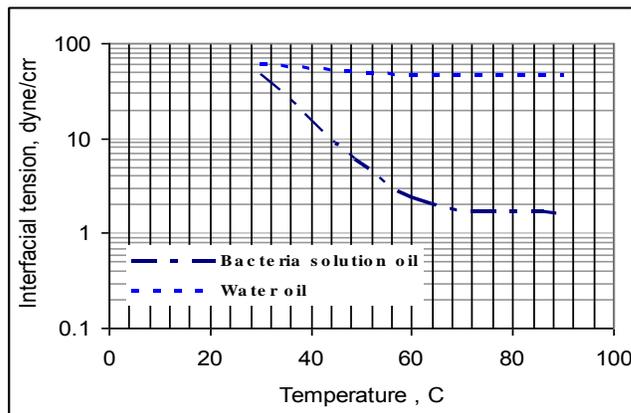


Fig. 2 Effect of bacteria solution on interfacial tension

B. Microbial Solution-Oil Contact Angle

Fig. 3 presents the effect of bacteria concentration on the contact angle and indicates that increasing microbial concentration results in a reduction of contact angle up to a certain concentration, beyond which the bacteria concentration exhibit no effect on the contact angle. This is probably due to the fact some microbes tend to partition into the oil phase, contact each other (forming a ring shape) and then adsorb on the rock surface as reported by Zekri and Almehaideb¹⁸, who observed that bacteria have affinity for the carbonate rock. As a result of the partition into oil and adsorption on rock surface,

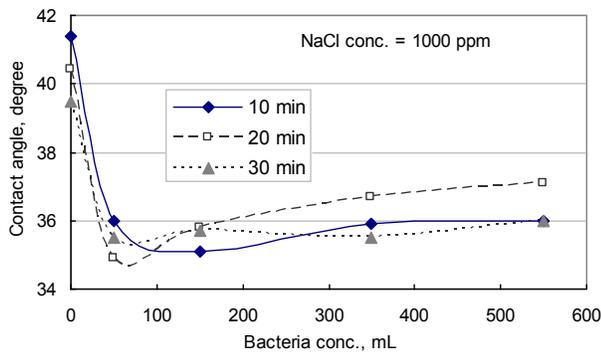


Fig. 3 Bacteria concentration versus the contact angle.

Changes in contact angle are observed with changes in microbial concentration. At saturation, i.e. when the drop of oil is completely ringed with microbes and the rock surface covered with microbes; addition of new microbes to the system will produce no effect on the behavior of the system. The microbes interact with the system rather quickly as we observed a sudden reduction of contact angle (from around $41-39.5^\circ$ to around $37-36^\circ$) as we increase bacteria concentration from 0 cells/mL to 60×10^3 cells/mL.

C. Microbial Solution-Oil Relative permeability

Water wet systems

Two tests of oil-water relative permeability measurements were conducted at the same conditions to assess the reproducibility of the data. The results showed identical relative permeability curves which give us confidence in the generated relative permeability data during microbial flooding.

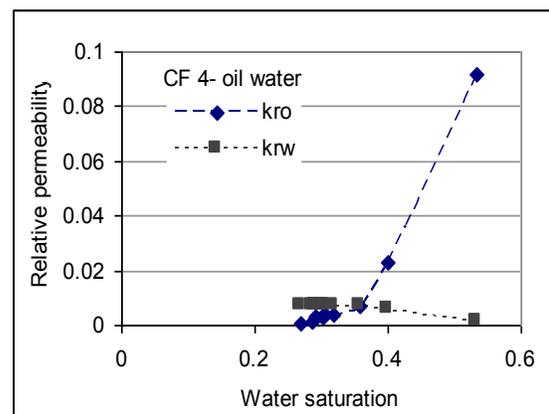
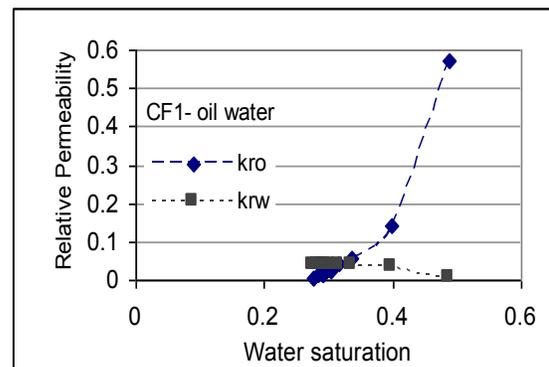
Figs. 4 show the oil-water relative permeability for cores CF1, CF4 and CF5 respectively. All measurements were conducted at the same injection pressure 500 psia, using AH crude, and 10% NaCl water salinity. The three figures exhibit a water wet behavior of the studied systems. The crossover point of the oil-water relative permeability for the cores CF1, CF4, and CF5 located at the water saturation of 0.32, 0.35, and 0.35 respectively which indicating that system is water wet system.

Relative permeability measurements were conducted on the cores CF1, CF4 and CF5 after flooding the cores with microbial solution having bacteria concentration of 30×10^3 cells/mL.

Note all the cores have similar permeability to mask the effect of variation of permeability on the studied system. Fig. 5 shows the microbial-oil relative permeability curves for cores CF1, CF4, and CF5. Significant change in the characteristics of the relative permeability was observed after microbial flooding for all used cores, CF1, CF4, and CF5. The crossover point changed from water saturation of 0.32 to 0.83 for core CF1, from 0.35 to 0.86 for core CF4, and from 0.35 to 0.67 for core no. CF5. The irreducible water saturation changed from 0.28, 0.27, and 0.33 for oil-water system to 0.45, 0.44 and 0.33 for microbial-oil system, for cores CF1, CF4, and CF5 respectively. Meanwhile, the residual oil saturation changed from 0.51, 47, and 62 for the oil-water

system to 0.05, 0.02, and 0.24 for microbial oil system. The change in the characteristics of relative permeability curves as a result of microbial flooding indicating that the system became oil wet as a result of microbial activities. This change will hinder the performance of the system. As oil wets the rock, it will be more difficult to move, and oil tends to stick to the rock surface. It is clear from the IFT measurements shown in Fig. 2; microbial solution reduces the interfacial tension between oil-microbial solutions as a result of metabolism of the bacteria. Reduction of interfacial tension between oil-microbial solution lead to a substantial reduction in the residual oil saturation after microbial flooding as reported in this study. This clearly indicates that the bacteria used in this study is capable in removing oil with much higher displacement efficiency than saline water at the same operating conditions of pressure and temperature.

The changes in the system wettability due to microbial flooding were confirmed by the observed changes in the contact angle between microbial solution and oil system. As shown in Fig. 3, the contact angle changes drastically as oil exposed to higher bacteria concentration with time. A spreading of oil on the rock surface was observed as we move an oil drop from oil-water system to microbial oil system Oil spreads on the rock surface due to changes in the system wettability, indicating that the system became oil wet system This phenomenon supports the conclusion drawn previously from the measurements of microbial solution-oil relative permeability curves which stated that for a water wet system microbial flooding tends to change the system wettability to an oil wet system. The changes in the system wettability brought about by different microbial activity in the presence of AH oil.



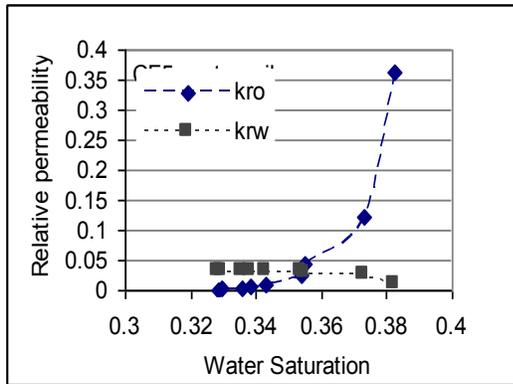


Fig. 4 Oil-water relative permeability, cores CF1, CF4, and CF5

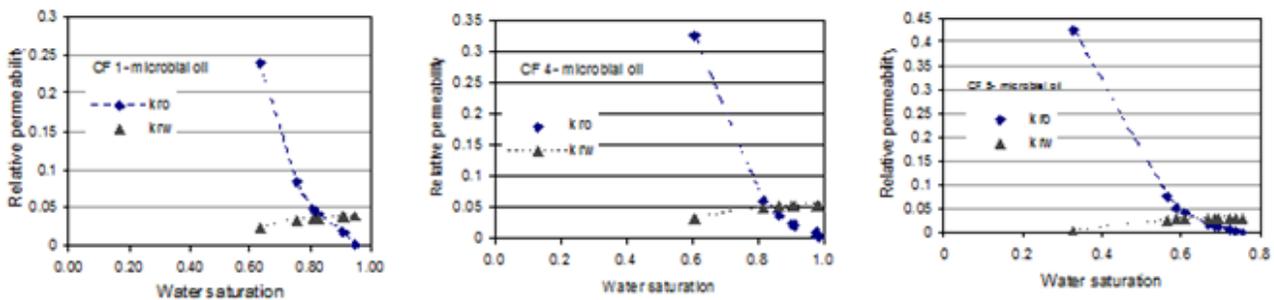


Fig. 5- Microbial solution-oil relative permeability. CF1, CF4, and CF 5.

As bacterial contacts oil, it metabolize producing surfactant, surface active agent which in turn act on the surfaces reducing the forces between oil and microbial solution, in addition to that, microbial tends to partition into the oil phase as the time passes and the microbes gets adopted to the new environment. Coupled with that, the dead bacteria cells tend to stick to the rock surfaces and resulting in wettability alteration. Chrisholm et al.⁵ concluded in their study that microbial processes result in a change in the relative permeability relationship by the presence of biogenetic gas. A free gas phase has been found to decrease residual oil saturation⁵. In our experimental study, no free gas phase expected to take place due to high pressure used in the studied system, which suppress the gas and keeps the gas in solution. In addition to that as reported by Bryant and Lockhart¹³, to generate a reasonable quantity of free CO₂ would require impractical oil and water volumes in addition to oxygen. They indicated that, practically in-situ generation of CO₂ requires an alternative ex-situ oxygen source¹³. Meanwhile, in situ generation of methane in principle requires no external sources¹³. Bryant and Lockhart¹³ reported that a significant amount of methane could be produced only in low pressure reservoirs. In a small core flooding experiments at high pressure flooding system, miscible gas displacement is unlikely to contribute to microbial production mechanism. Any free gas generation due to microbial activity that produces an increase in reservoir pressure is likely to be

relevant to well stimulation and not for microbial enhanced oil recovery¹³.

Oil Wet System

Figs. 6 show the oil-water relative permeability for cores CF2, and CF3 respectively. All measurements were conducted at the same injection pressure of 500 psia, using AH crude, and 10% NaCl water salinity. The three figures exhibit an oil wet behavior of the studied systems. The crossover point of the oil-water relative permeability for the cores CF2, and CF3, located at the water saturation of 0.70 and 0.53 respectively which indicating that both systems are an oil wet systems.

Microbial-oil relative permeability measurements were conducted on cores, CF2, and CF3 after flooding the cores with microbial solution having bacteria concentration of 30×10^3 cells/ml, at the same conditions of pressure and temperatures used to measure oil-water relative permeability and using the same type of crude oil AH crude. Note that both cores have almost the same permeability to mask the effect of permeability variation on the studied system. **Fig. 7** shows the microbial-oil relative permeability curves for cores CF2, and CF3. Significant change in the characteristics of the relative permeability was observed after microbial flooding for used cores, CF2, and CF3. The crossover point changed from water saturation of 0.70 to 0.81 for core CF2, from 0.53 to 0.62 for core CF3. The irreducible water saturation changed from 0.51 and 0.48 for oil-water system to 0.45, and 0.35 for microbial-oil system, for cores CF2, and CF3 respectively. The observed reduction of irreducible water saturation as a

result of microbial flooding, indicating that the system became more oil wet system and represents a shift of the system wettability toward more oil wet system. Meanwhile, the residual oil saturation changed from 0.19 and 28 for the oil-water system to 0.05, and 0.21, for microbial oil system for cores CF2, and CF3 respectively.

As bacteria get adapted to its new environment, oil and rock system, it moves toward the oil which mostly surrounds the rock surface. Again bacteria metabolize producing chemical, in our case surfactant which alters the surface forces of the oil resulting in more spreading of oil on the rock surface, i.e. more oil wet system. Data indicates that the more oil wet the system the higher the shift in the wettability toward more oil wet associated with higher reduction of residual oil saturation which contradicted what reported in the literature regarding reduction of oil recovery associated with an oil wet system compared to a water wet system. In the case of core CF2, an improvement of 73% in oil recovery by microbial over water flooding compared to an improvement of 25% in the oil recovery by microbial over water flooding for core CF3, although CF2 became more oil wet compare to CF3. This phenomenon can simply be explained by pointing out that negative effect of wettability changes toward more oil wet system masked by the positive effect of more surfactant produced during the big shift in wettability as result of more metabolism by bacteria. A higher concentration of surfactant will lead to more reduction in interfacial forces and consequently higher displacement efficiency and hinder oil

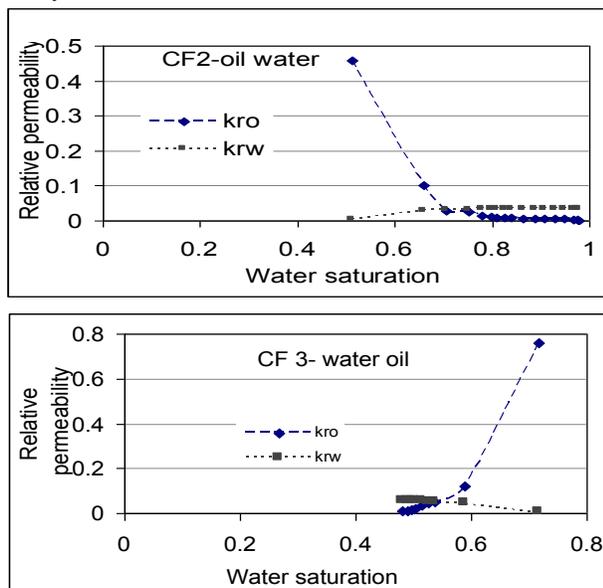


Fig. 6 Relative permeability of oil-water, CF2, CF3.

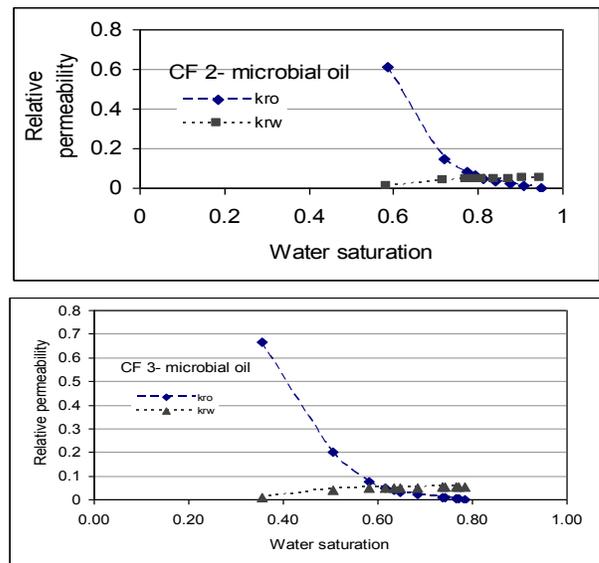


Fig. 7 Relative permeability of microbial solution-water, CF2, CF3.

recovery i.e. lower residual oil saturation. Microbes seems to have a certain degree of affinity toward the rock surfaces in this studied system, therefore will contact more oil in the case of an oil wet system resulting in more metabolism and more shift in the wettability of the system toward more oil wet system.

V. CONCLUSIONS

Based on the experimental conditions employed in this project the following conclusions can be obtained:

1. Microbial flooding alters the relative permeability characterizes of the limestone rocks.
2. The relative permeability of limestone rock water wet system will be changed to an oil wet systems as a result of microbial flooding of that system.
3. The relative permeability of an oil wet limestone rock will be shifted toward more oil wet by microbial flooding.
4. Higher oil recovery obtained in the case of higher wettability shift toward more oil wet system due to higher microbial activities resulting in more metabolisms of surfactant and consequently lower displacement efficiency.

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