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INVESTIGATION OF LOW SALINE WATER'S EFFECTS ON RELATIVE PERMEABILITY IN CARBONATE RESERVOIRS

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Abstract

Low Salinity Water flooding (LSW) is one of the favorable subsets of water flooding EOR methods due to its great advantages over normal water flooding; having a low cost of operation and being environmentally-friendly. LSW has been studied in mathematical, experimentally and practically point of view in numerous numbers of sandstone cases in the worldwide. Existing of giant carbonate reservoirs containing a great amount of petroleum in the regions of the North Sea and the Middle East have been turned into a motivation for the relevant experts to focuses on the possibility of running an LSW project in a carbonate reservoir. Accordingly, this paper aims to investigate this possibility through running two sets of flooding tests on selected cores from one of Iranian carbonate reservoirs. In more details, on each core two water flooding tests have been conducted in which the first test have been run by a sample of water from the Persian Gulf with high salinity and in the second one the injected water has been from Karoon River with a lower rate of salinity. Then, the recovery factor from both tests of a target core has been compared. The results indicate that running an LSW have been caused improvement in recovery factors which was approved by relative permeability curves analysis.

Keywords: Low saline water, Water flooding, Relative permeability, Carbonate reservoir

Abstrak

Pembanjiran Air Berkemasinan Rendah (LSW) adalah salah satu subset kegemaran daripada kaedah-kaedah pemulihan minyak tertingkat (EOR) secara Pembanjiran Air kerana besar kelebihannya ke atas Pembanjiran Air yang biasa; mempunyai kos operasi yang rendah dan mesra alam. LSW telah dikaji secara matematikal, eksperimen dan praktikal dengan sebilangan kes-kes batu pasir di seluruh dunia. Takungan batu karbonat gergasi yang mengandungi sejumlah besar petroleum di kawasan Laut Utara dan Timur Tengah telah mencetus motivasi kepada pakar-pakar yang berkaitan untuk memberi tumpuan kepada kemungkinan menjalankan projek LSW dalam takungan batu karbonat. Oleh itu, kertas kerja ini bertujuan untuk menyiasat kemungkinan ini dengan menjalankan dua kumpulan umum ujian pembanjiran pada teras-teras terpilih daripada satu takungan karbonat Iran yang terletak di bahagian barat daya. Untuk maklumat lanjut, pada setiap teras dua ujian pembanjiran air telah dijalankan di mana ujian pertama telah dikendalikan oleh sampel air dari Teluk Parsi dengan kemasinan yang tinggi dan yang kedua air telah disuntik dari Karoon River dengan kadar kemasinan yang lebih rendah. Kemudian, faktor pemulihan daripada kedua-dua ujian daripada teras sasaran telah dibandingkan. Keputusan menunjukkan bahawa menjalankan LSW telah menyebabkan peningkatan dalam faktor pemulihan yang mana telah dibuktikan oleh analisis lengkung kebolehtelapan relatif.

Kata kunci: Air Berkemasinan Rendah, Pembanjiran Air, Kebolehtelapan relative, Takungan batu karbonat

1.0 INTRODUCTION

According to statistical indices about energy consumption in the worldwide, there is a growing consensus that the demand fossil fuel energies are following a dramatic growing trend during next years. Hence, numerous numbers of researchers' attentions have been drawn towards proposing and implementing varieties of methods, generally known as Enhanced Oil Recovery (EOR) techniques, to increase the final oil recovery from target hydrocarbon reservoirs.

Water flooding has always been considered as one of the most economic, feasible and conventional types of referred techniques in which the seawater is injected into the porous media of the reservoir for pressure maintenance, and sweep oil towards the production well. In water flooding process, the availability of water resources plays the key role in real field's study. Generally there are three types of injection water in chemical analysis point of view: first, high salinity water such as connate water and formation water, second, moderate salinity water such as sea water and third, low salinity water such as river water and shallow-aquifer water. These types of injection water are different in divalent cations and anions and also in total dissolved solids. There are various interactions (chemical and physical) between injected water and reservoir fluid which affect microscopic displacement. For instance, interfacial tension between fluid, the wettability of the surface, miscibility of fluids are affecting parameters on displacement process [1]. Wettability is one of the most important parameters which depends on rock type and interaction between fluid and rock. Generally, carbonate rocks are classified as oil wet or intermediate wet and sand stones are classified as water wet rock [2].

Recently implementation of Low Salinity Water flooding (LSW) in various sandstone reservoirs becomes worldwide because it has experimentally been observed and proved that conduction of LSW, lowering the ionic strength of the injection brine, could magnificently improve oil recovery from sandstone reservoirs [3]. However, implementation of LSW leads to increasing pressure drop in core flooding due to fine migration which was observed by Zhang *et al*. [4]. In addition, being environmentally friendly and requiring the low rate of investment in different relevant facilities are other eye-catching advantages of an LSW operation. There are various mechanisms of LSW have been stated in the literature, for instance: fine migration [4], reduction of IFT due to increasing pH [5], double layer effect [6], wettability alteration [7]. In fact contacting low salinity water with clay leads to swelling and dehydrating of clay, consequently, fine migration occurs if there is poor cementing. Accordingly, this mechanism is not substantial in the carbonated reservoir. Reduction of water salinity cause increasing the pH of water due to interchange sodium ions with hydrogen ion in water [8]. The double layer effect is

According to statistical indices about energy consumption in the worldwide, there is a growing

defined by the force of charged surfaces in a liquid medium including Van Der Waals and electrostatic repulsion. Low salinity water makes water film more stable because of increasing in double layer effect [4]. It is strongly believed that the main mechanism which causes the LSW producing more oil from a sandstone reservoir is wettability alteration of clay minerals towards a more water-wet state. Wettability alteration could be the consequence of all others mechanisms [9]. In addition, this mechanism increases microscopic sweep by adjusting oil and water relative permeability [10]. Several studies showed that LSW could change wettability to more water wet even in carbonate rock. However there is growing interested towards LSW, the phenomena of wettability alteration are mute to some extent.

Besides, implementation of a LSW in hydrocarbon resources locating in the Middle East and North Sea where most of the petroleum reservoirs are carbonates have always been one of the most critical, important and vital topics of upstream connected industries. Typically, applying a normal water flooding project with seawater in carbonate reservoirs can result in improvement of recovery factor. Apparently, the main reason, which has been extracted after numerous numbers of laboratory investigations [11]–[13], to excuse the mentioned phenomena is that the existing sulfates in the seawater perform as catalysts in order to desorb the carboxylic substances from the carbonate surface. In terms of running an LSW operation in carbonates, it seems that lowering the amount of NaCl and spiking the sample water with sulfates can noticeably improve the oil recovery. The reason is that reducing the amount of NaCl causes better accessing of active ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} to the surface. Still, it is strongly believed that the main reason for effects of LSW on oil recovery in carbonate reservoirs is wettability alteration [10]. More well-documented information about applications and mechanisms of LSW in carbonates can be found in the previous literature [14]–[16].

Moreover, relative permeability curves in numerous numbers of LSW relevant studies have efficiently been gained as an advantageous tool in order to evaluate the quality of the run LSW tests [17]. In fact, it has been understood that the relative permeability model dependent upon wettability alteration and salinity could be constructive to picture the success of an LSW test. In another study, it has experimentally been concluded that those relative permeability curves derived from experiments based on secondary and tertiary tests can be implemented in a reservoir simulator. Also, endpoints of water and oil relative permeability are more sensitive to effects of LSW than other parameters, it must also be referred that oil endpoint is a stronger function of LSW effects that endpoint of water.

In this study, the possibility of running an LSW process in one the biggest carbonate reservoirs of

Middle East locating in south-west of Iran has been examined so that some candidate core has initially been sampled from the reservoir, and then they have alternatively been flooded with waters with different values of salinity. In more details, cores have firstly flooded with seawater and in the next step, they have been flooded with Karoon river water which has the much lower rate of salinity in comparison with the first sample. The results have been examined based on the effect of salinity on the shape of relative permeability curves as well as recovery factors. The inherent heterogeneity of carbonate cores has been channeled to deduce some results with different patterns which have been discussed in the next parts. The following parts of this study have been organized in the manner of the following structure: First of all the rock and fluid properties as well as apparatus description (experimental setup), have been introduced. After that experimental and mathematical methodology for both tests design and relative permeability, a determination has been presented. Next section contains the results and discussions of the performed tests and the evaluations done on relative permeability curves. At the last section, conclusions have been stated to clarify the effect of salinity on change of relative permeability shapes.

2.0 METHODOLOGY

2.1 Experimental Setup and Procedure

2.1.1 Fluid Properties

In this study, a light oil (regarding the API gravity) sample from one of the oil reservoir from the south-western part of Iran was used. Two different sources of injection water are employed to conduct water flooding; one is sea water with moderate salinity and other is Karoon river water with low salinity. Fluid properties in reservoir condition are illustrated in Table 1.

Table 1 Fluid properties in reservoir condition

Parameter		**Value at Reservoir condition (5000 Psia & 121.95°c)**
Density, ρ_l	Kg/m3	615.4
Gravity	API	38
Viscosity, μ_o	C.P	0.28
C7+ molecular weight,	kg/mole	242.7
Water Salinity	p.p.m	Formation: 152500
		Sea: 40000
		Karoon: 4000
Water Viscosity, μ_w	C.P	Formation: 0.3876
		Sea: 0.5164
		Karoon: 0.2483
Water density, ρ_w	Kg/m3	Formation: 1121
		Sea: 1019
		Karoon: 1001

2.1.2 Core Sample Properties

During the experiment, two candidates carbonated core samples were used. These two samples have almost same physical properties, both are tight rocks with low permeability. However, there is the small difference in porosity and permeability. The properties of the core samples are given in Table 2.

Table 2 Physical properties of core samples

Parameters		Carbonate A	Carbonate B
Diameter	mm	38.52	38.53
Length	mm	48.21	51.41
Area, A	cm2	11.65	11.66
Pore volume, PV	cc	7.87	10.79
Porosity, φ	fraction	0.14	0.18
Absolute Permeability, K	mD	0.55	0.60

2.1.3 Apparatus

Generally, there are two approaches to conducting core flooding experiments: Steady state and Unsteady state experiments. The main advantage of unsteady state approach is the fast implementation compare with steady state. Apparatus design for both approaches are not far off each other, the only substantial difference is that in steady state experiments a system for tracking of the saturation profile through the core is required, a system such as a gamma ray to measure the water saturation throughout the flooding process. In this experimental work, due to fast implementation, the unsteady state displacement approach was applied. A schematic diagram of the connections in the displacement apparatus is illustrated in Figure 1.

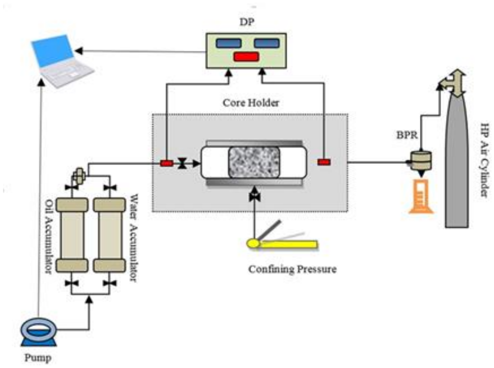

Figure 1 Core flooding apparatus

As it has been illustrated in Figure 1, the implemented setup consists of an injection system, two piston accumulators, a core-holder, a back pressure regulator, an overburden pressure system pressure differential measurement system and the computer system for data acquisition and process control. The gained syringe pump injects the distilled water below the pictured fluid vessels in order to supply the desired fluid, the recombined oil, and the injected water, with the required pressures and rates. Then, the target fluid in one of the supposed vessels is flooded into the core which has already been located in the core holder and confined with a rubber sleeve. It is highly vital that the thermos dynamical reservoir conditions, temperature, and pressure, be simulated, so a hydraulic pump is conducted to compress the core and an oven is surrounded the core holder to establish the reservoir temperature. The outlet of the core holder has been connected to a back pressure which controls the discharging of the effluent fluid. Passing the back pressure system is continued by a collector showing the amount of the produced fluids. To measure the differential pressure, and also observe the pressure conditions of the system, two pressure transducers are located before and after of the core holder which their measurements and differences are directly recorded and supported by a backup computer.

2.1.4 Test Procedure

Initially, the selected clean dry cores are weighted and after running the procedure of evacuation, they turned into the saturated mode by using the formation water. Next, the saturated cores are weighted again and their new weights are recorded as the wet ones. After determining the pore volume of each core through having information about both weights and density of the formation water, the target core is set into the core holder under the overburden pressure. Subsequently, the thermo dynamical conditions of temperature and pressure are prepared. In the next step, the oil sample is injected into the core for enough numbers of pore volumes in order to reach the core to the critical water saturation. After aging procedure, laying the core in reservoir temperature for one week, the saturated core is flooded with the sample water with a corresponding salinity, under reservoir conditions; overburden pressure of 5000 psi and temperature of 136°C. In more details, the core is firstly flooded with the sea water by a constant rate of 9 ml/hr, in the meanwhile, the recovery results data which are required for the calculation of relative permeability are recorded. The next test is exactly the same as what has just been described, but the difference is that the salinity of the flooding water has been changed. In fact, the same core of the previous test follows the same preparation procedures in order to become ready for water flooding. In this step, instead of gaining from sea water, the sample water, river water, with lower salinity is utilized. The entire mentioned procedure is performed for both core samples A and B.

2.2 Calculation

To extract the relative permeability curve, commercial software was employed in which inverse modeling (i.e. history matching technique) was applied to extract the relative permeability curves implicitly. In this approach, the value as an initial guess is required, therefore, an analytical method such as JBN method [18] has been utilized to calculate the relative permeability as an initial guess (solving flow equations by IMPES method). Then, the production results from the simulator were compared with the experimental results. Eventually, the difference between the experimental production results and simulation results would be minimized using a suitable optimization algorithm. There are enormous optimization algorithms in the oil industry, however, the common and suitable one for relative permeability studies are Genetic Algorithm (MATLAB's tool box). The optimization procedure has been performed by minimizing the error function as the objective function. The results of relative permeability obtained from the last step of optimization process would be defined as the implicit values.

3.0 RESULTS AND DISCUSSION

To find the dominant mechanism of low salinity water flooding as well as its effect on relative permeability curves, two categories of water flooding have been done; firstly low saline water flood, secondly high saline water flood after core preparation on the same core sample. The same procedure was done on another core sample with rather different rock characteristic but from the same reservoir in order to validate the trend of change.

As mentioned in the methodology section, history matching technique was used to extract relative permeability curves. Figure 2 shows the input data for commercial software to do the fluid flow simulation and successively history matching in imbibition process of low saline water flooding in core sample A and also Figure 3 shows the history matched results of production for this case.

SCAL project: XXX
Core ID: XXX
Core length: 48.21 mm
Core diameter: 38.52 mm
Core porosity: 0.1403 frac.
Core base permeability: 0.96 mD
Fluid system: Water-Oil
Process: Imbibition
Scenario: Unsteady state
Flow direction: Horizontal
Water viscosity: 0.2483 cP
Oil viscosity: 0.28 cP
Initial water saturation: 0.49 frac.

Figure 2 input data for simulation software

(a)

(b)

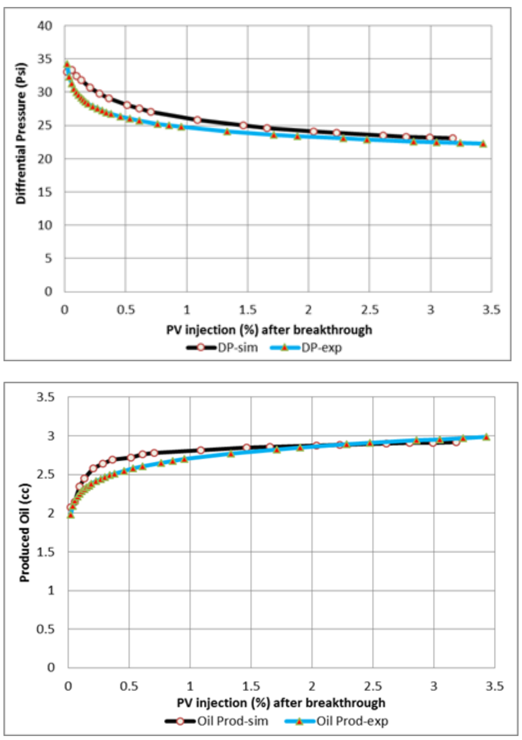

Figure 3 The result of history matching for pressure and recovery of case 1

Figure 3 depicts that utilizing of the optimization method for history matching leads to the acceptable matching of oil recovery and pressure data.

The explained procedure was done for all other tests (high saline water flooding on core sample A and high/low saline flooding on core sample B). Figure 4 and 5 show the comparison of relative permeability curves between high and low saline flooding for all four tests.

As observed in Figure 4 and 5, in the case of low saline water flood, the oil relative permeability increases, and water relative permeability decreases. This phenomenon reflects the wettability change mechanism in which the wettability become more water wet and decreasing contact angle [12] due to exchanging ion on the rock surface and double layer effect. These results are definitely in line with previous studies [19]. Although both core samples were affected by low saline water, but this effect is quite obvious in core A compare with a sample B. Since these two cores have taken from same carbonate reservoir but in different depths, the lithology of these two might be different to some extent.

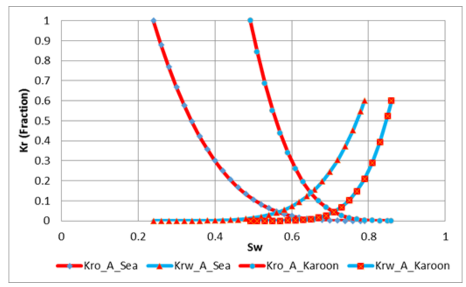

Figure 4 Relative permeability curves for sample A in both low and high saline water injection scenarios

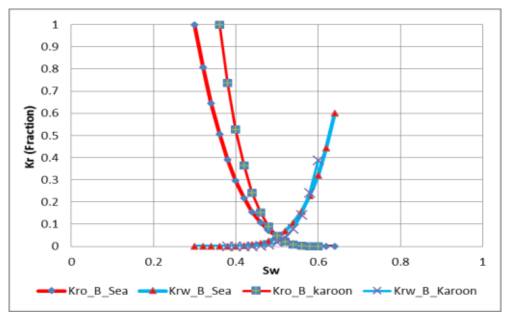

Figure 5 Relative permeability curves for sample B

In both low and high saline water injection scenarios.

The dissimilarity in wettability of core samples during sea water flooding proves the dissimilarity in lithology; sample A is more water wet compare with sample B during sea water flooding. The existence of the little amount of clay in the core may result in significant changing in relative permeability due to fine migration and double layer effect. Therefore, it can be concluded that difference in lithology is the reason for this behavior.

As a consequence of increasing the oil relative permeability due to low saline water injection, oil recovery should be increased. This accretion of oil recovery has been asserted in previous studies [9], [13].

The other consequence and indicator of wettability alteration mechanism can be observed as higher oil recovery in case of low saline water flooding compared to higher saline water which is shown in Figure 6 and Figure 7.

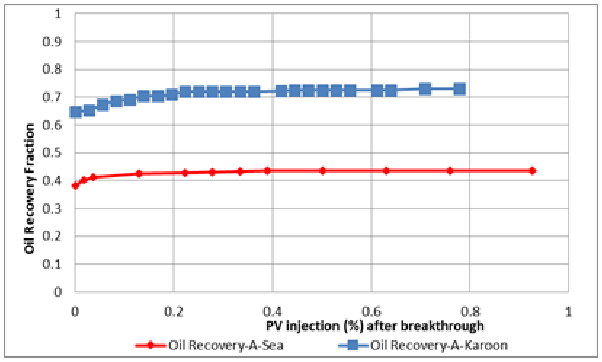

Figure 6 Recovery fraction of sample A

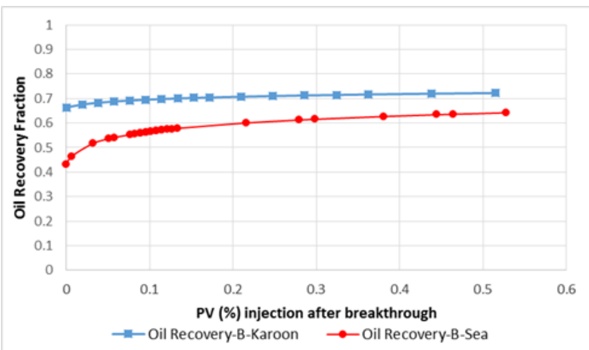

Figure 7 Recovery fraction of sample B

The active mechanism in low saline water flooding is stronger in the case of core sample A compared to core sample B. The main reason is related to rock characteristics and lithology of rocks. As mentioned before core A is more water wet compare with core B, therefore, low saline water has more effect on relative permeability curves, consequently, on recovery factor of core A compare with core B.

4.0 CONCLUSION

According to presented study, it may be concluded that the low saline water injection obviously improves the recovery factor even in carbonate rocks due to increasing relative permeability of oil and decreasing the relative permeability of water.

There are several mechanisms behind relative permeability changes which each of them might be the dominant mechanism in the different condition. However among these mechanisms, wettability alteration is cardinal one in all conditions. Moreover, the results show that the LSW performance is affected by wettability. In another word, LSW wettability changing mechanism is more significant in water wet rock rather than mixed-wet rocks. The fundamental study on wettability alteration process due to LSW in carbonate reservoir is an open opportunity for future work. Moreover, the feasibility of LSW field application is one of the challenging topics which needs more studies.

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