

**Chemical, Petroleum and Environmental Engineering**

**Enhanced Oil Recovery using Smart Water Injection**

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**ABSTRACT**

Smart water flooding (low salinity water flooding) was mainly invested in a sandstone reservoir. The main reasons for using low salinity water flooding are; to improve oil recovery and to give a support for the reservoir pressure.

In this study, two core plugs of sandstone were used with different permeability from south of Iraq to explain the effect of water injection with different ions concentration on the oil recovery. Water types that have been used are formation water, seawater, modified low salinity water, and deionized water.

The effects of water salinity, the flow rate of water injected, and the permeability of core plugs have been studied in order to summarize the best conditions of low salinity water flooding. The result of this experimental work shows that the water without any free ions (deionized water) and modified low salinity water have improved better oil recovery than the formation water and seawater as a secondary oil process. The increase in oil recovery factor related to the wettability alteration during low salinity water flooding which causes a decrease in the interfacial tension between the crude oil in porous media and the surface of reservoir rocks. As well as the dissolution of minerals such as calcite  $Ca^{+2}$  was observed in this work, which causes an increase in the pH value. All these factors led to change the wettability of rock to be more water-wet, so the oil recovery can be increased.

**Key Words:** Low salinity water, water concentration, oil recovery, breakthrough.

**زيادة استخلاص النفط باستخدام الماء الذكي**

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## الخلاصة

الغرض من استخدام الماء الذكي (الماء ذو الملوحة القليلة) في عملية الاستخلاص الثالثي هو ازالة اكبر كمية ممكنة من النفط الخام خلال عملية تغيير التبللية للصخرة بواسطة عدة تفاعلات تحدث بين سطح الصخرة والماء المحقون ذو الملوحة القليلة. بالإضافة الى دعم وزيادة الضغط المكمني لغرض منع انتاج الغاز (الحفاظ على ان يكون ضغط المكمن < من ضغط الفقاعة). في هذه الدراسة تم استخدام نموذجين صخرية رملية من جنوب العراق مع اختلاف النفاذية لكل نموذج لغرض دراسة تأثير حقن الماء ذو الملوحة المنخفضة على النفط المستخلص. انواع الماء المستخدم لعملية الحقن هي: ماء مكمني وماء بحر وماء ذو ملوحة منخفضة وماء خالي من اي املاح او ايونات بالإضافة الى دراسة العملية التي يتم بها زيادة النفط المستخلص والظواهر التي تحدث خلال عملية الحقن مثلاً: هجرة المواد الاسمنتية، ذوبان بعض معادن الصخرة والتغيير الحاصل في الشد السطحي بين النفط الخام والسطح الصخرة، كل هذه الظواهر تسبب تغيير التبللية للصخرة ( تغيير التبللية من صخرة محببة للنفط الى صخرة محببة للماء). تأثير الملوحة ومعدل الحقن والنفاذية للنماذج الصخرية قد تمت دراستها لغرض تلخيص تأثير حقن الماء منخفض الملوحة على النفط المستخلص. نتائج هذه الدراسة بينت ان الماء منخفض الملوحة والماء خالي من اي ملوحة قد تم استخلاص اكبر كمية للنفط الخام من خلالهما ذوبان بعض المعادن والمتمثلة بتركيز ايونات الكالسيوم Ca والمغنيسيوم Mg والكبريتات SO<sub>4</sub> بالإضافة الى ملاحظة زيادة الدالة القاعدية pH بمقدار يزيد كبير نسبياً.

**الكلمات الرئيسية:** الماء ذو الملوحة المنخفضة، تركيز الماء، معامل استخلاص النفط، جبهة الاختراق

## 1. INTRODUCTION

Water flooding is one of the secondary oil recovery methods because no special EOR-chemicals are injected. The purpose of EOR methods is to minimize residual oil saturation ( $S_{or}$ ), because a large volume of original oil in place remains in the reservoir rocks, so that, the oil will not be produced in large quantities. The secondary oil recovery process is usually used to increase oil recovery during the pressure maintenance by injecting a formation water. However, increasing oil recovery using low salinity water (LSW) is obtained by pressure maintenance and decreasing of interfacial tension (IFT) between the surface of the rock and crude oil, which means the wettability of the rock, will be changed from oil-wet to water-wet. Laboratory studies show that the water flooding can increase the oil recovery in carbonate reservoir after flooding several types of water such as brine, seawater, low salinity water with ion concentration approximately equal to 5,000 ppm and deionized water. The objective of this study is to improve oil recovery by using brine, seawater, low salinity water (modified seawater) and deionized water. Also, to explain the effect of injection of different water types in ion concentration on carbonate reservoir, the flow rate of injection water and explains the difference in the recovery factor when using a high and low permeability (in low permeability the areal and vertical sweep efficiency will be increased so that, the oil recovery is increased) and to compare the result of the secondary oil recovery and tertiary oil recovery.

## 2. LITERATURE REVIEW

The idea of low salinity water (smart water) flooding has been addressed since 1960 by Jadhunandan on a sandstone reservoir rocks. The result of experimental work shows that the oil recovery was increased by using low salinity water. Extensive research works, **Yildiz, and Morrow, 1997, Zhang, and Morrow, 2006, and Lager, et al., 2007**, and others have confirmed and validated the new-trend through reservoir conditions core-flood experiments as well as reported that the average increase in oil recovery from more than 16 reservoir core-flood



experiments was around 14 % from OOIP. The increase in oil recovery was proved in both secondary and tertiary oil recovery. They discussed the increase in oil recovery using low salinity water flooding is caused by wettability alteration, that's mean the rock will change from oil wet to water wet by several mechanisms such as; fine migration and pH increasing. The increase in pH value is induced by  $\text{Ca}^{+2}$  dissolution and cation exchange when low salinity water is injected. Moreover, the fine mobilization can be detected from pressure stability.

### 3. EXPERIMENTAL WORK:

#### 3.1 Experimental materials:

3.1.1 Core samples: The sandstone cores samples have been taken from the Nhrumr reservoir, well No.10, Amara oil field. The minerals composition is detected by using X-Ray Diffraction (XRD), as shown in **Table 1**.

3.1.2 Crude oil: Dead oil from the south of Iraq, was used in these experiments work. The oil sample was centrifuged at 5000 rpm, then filtered until no precipitation of any asphaltenes were observed during storage to avoid any solids plugging or emulsion problems. This oil has been provided by Al-Dura-refinery. The acid number, the base number, the viscosity, and the density of crude oil are illustrated in **Table 2**.

3.1.3 Brine: Four types of water are used in smart water flooding; formation water, seawater, modified low salinity water, and deionized water. Sodium chloride ( $\text{NaCl}$ ), Magnesium-chloride ( $\text{MgCl}_2(\text{H}_2\text{O})$ ), Potassium chloride ( $\text{KCl}$ ), Calcium chloride ( $\text{CaCl}_2$ ), Calcium carbonate ( $\text{CaCO}_3$ ) and Sodium sulphate, also known as sulphate of soda ( $\text{Na}_2\text{SO}_4$ ) was used to prepare synthetic formation water. All these salts are soluble in the water. These salts were mixed with deionized water in order to obtain a synthetic formation water with ion concentration similar to the formation water of Mishrif formation/ Eridu oil field. After mixing the deionized water with salts, in spite of all salts, which has been used, are soluble in water the mixture must be filtered to remove any contamination because of the water will reach the saturated state. The ions concentration and physical properties of water types are shown in **Table 3, 4 and 5**

#### 3.2 Experiment Steps

Two carbonate core plugs are used to investigate the effects of altering the ion concentration of injection water on oil recovery process.

3.2.1 Core plugs: have been cut by using a milling device.

3.2.2 Core cleaning: Distillation-Extraction (Dean-Stark and Soxhlet) has been used for core cleaning. The main components are a volumetric flask containing the solvents, a heating mantle to heat the solvents in the volumetric flask, a reflux core chamber where the core is exposed to the boiling solvent, and a condenser to condense the solvent. Solvents (toluene  $\text{C}_7\text{H}_8$  and methanol  $\text{CH}_4\text{O}$ ), are evaporated and flowed through the core plugs to remove the crude oil and salts from the porous media. The toluene  $\text{C}_7\text{H}_8$  is used to remove contaminats (oils) and the methanol  $\text{CH}_4\text{O}$  can be removing the salt.



3.2.3 Core drying: After the color of the mixture (toluene and methanol), have not any color of crude oil and the concentration of methanol reach to a constant value, the core will be placed in a heating cabinet at 80°C for 4 hours to evaporate the remaining liquid inside the pore space. This operation can reach to end when the weight of core sample becomes constant.

3.2.4 Porosity and pore volume Measurement: The pore volume and porosity measured using Helium Porosimeter: the principle of "Helium Porosimeter" is Boyle's law ( $P_1V_1 = P_2V_2$ ). After the plugs have been dried, the air inside the porous media is evacuated by using vacuum machine. From grain volume ( $V_g$ ) data if an accurate bulk volume ( $V_b$ ) measurement of the core sample is available (by using Vernier caliper), the pore volume can be calculated by subtracting the  $V_g$  from  $V_b$ .

3.2.5 Core plugs saturation: The MS-535 Manual Saturator has been used to saturate the core plugs. After the core plugs have been dried, the core plugs were put in marbles (to be sure that, there is no wetness in the core samples). Then, the samples were put in the container of manual saturator to evacuate it from any air that may be in porous media.

When the core plugs become emerge in the formation water by vacuum pressure (reaching up to 30 psi), the brine is pumped into the smalls porous media by Pneumatic pump, under pressure up to 2000 psi, to be sure that the core samples reach to 100% saturation state.

3.2.6 Permeability measurement: by using the BPS-805 Benchtop Liquid Permeability System, the formation water was injected at different flow rates inside the core sample, the pressure drops were recorded, and then the relationship between flow rates ( $Q$ ) and pressure drops were plotted as shown in **Fig. 1**.

The liquid permeability of core plug was calculated by using Darcy's law:

$$K = \frac{Q\mu L}{A\Delta P} \tag{1}$$

Where:

K = Permeability, Darcy

Q = Flow-rate, cc/Sec

L = Length of core plug, cm

$\mu$  = Water viscosity, cp

A= Cross section area of core plug, cm<sup>2</sup>

$\Delta p$  = differential pressure, atm



$K = 572 \text{ md}$ .

### 3.2.7 Oil saturation:

After the core saturation has been done, and the physical properties are calculated. The next step is the saturation of core plugs by crude oil using the core-flood system. When the oil is injected to the core plug, the flow rate is increased to displace the formation water and to be sure that the remaining formation water represents of irreducible water saturation. The outlet of formation water must be collected to calculate the irreducible water saturation ( $S_{wi}$ ) and original oil in place (OOIP) as follows:

- The outlet of formation water = oil entered to the core sample (OOIP)
- $(P_v \text{ of core plugs} - \text{the outlet of formation water}) / P_v = S_{wi} \%$

## 4. OIL RECOVERY PROCESS

When the core plugs are completely saturated with formation water and original oil in place, the oil recovery process can be started by injection of different water types to displace crude oil from the core plugs. Low salinity water flooding in this experimental work is used as a secondary oil recovery. Different flow rate was used in this work to obtain an optimum flow rate (maximum oil recovery and longer time to get a breakthrough. The main parameters that must be recorded are; pressure drop across the core holder to study the effect of injecting different ions concentration of water. The damage that may occur during water flooding can be explained by fine migration that leads to close the porous media, water-cut, and oil recovery. All these parameters will be discussed.

### 4.1 Effect of flow rate

The first parameter that was studied in this laboratory test is the flow rate. These tests were done at ambient temperature is  $23^\circ\text{C}$  on core sample #1 that have permeability =572 md and crude oil viscosity equals 16 cp (considered intermediate viscosity).

The values of flow rate were ( $Q = 0.7, 0.4, 0.2,$  and  $0.1 \text{ cc/min}$ ), seawater is used to investigate the effects of injection rate on oil recovery factor.

The results of this test, which aim to determine the optimum injection rate that gives the highest oil recovery, (ultimate oil recovery), indicate that as water injection rate increases, the oil recovery and time to reach breakthrough decrease.

In addition, the water cut reaches the maximum value.

The fingering phenomena caused early breakthrough and as a result, the water-cut increases.

High values of injected pore volume are needed in case of using a high flow rate of water injection as shown in **Fig. 2**. It can be concluded that:

- Maximum oil recovery is obtained when the flow rate was minimized
- The time of breakthrough is the maximum in a state of low flow rate ( $Q = 0.1 \text{ cc/min}$ ).



- Oil recovery and the time of breakthrough are approximately equal in case of  $Q = 0.1$ , and  $0.2$  cc/min.

- The optimum flow rate is  $Q = 0.2$  cc/min.

The effect of capillary pressure was a reason for increasing the oil recovery after the water breakthrough.

**Fig. 3** illustrates the effect of flow rate on the oil recovery factor and the time of breakthrough.

As shown in **Fig. 3**, when water injection rate increases, the recovery factor at breakthrough decreases. The cause of decreasing the oil recovery as water flow rate increased is the effect of the fingering phenomena, so that, the time of breakthrough was small.

#### 4.2 Effect of ions concentration on oil recovery factor

In these tests, four ion concentrations of water were used to investigate the effect of different water ion concentration on oil recovery for a sandstone core plug, which is saturated with formation water at connate water saturation, and the remaining pore volume has been saturated with crude oil. The tests were done at the same conditions, which are; overburden pressure = 500 psi, temperature =  $23^{\circ}\text{C}$  and optimum flow rate =  $0.2$  cc/min.

A wide range of ions concentration (salinity) was investigated as follows:

The first test was done by preparing a synthetic formation water where the analysis of a sample of a formation water that was taken from one of the Iraqi southern fields. This preparation was done in the Laboratory of Petroleum Research and Development Center. After the core sample has been saturated, the crude oil was injected in order to estimate the irreducible water saturation which was  $22.54\%$  at  $23^{\circ}\text{C}$  for plugs 1 and 2.

The effects of pore volume injected and pressure drop on oil recovery for the four types of water are shown in the **Fig. 4, 5**.

Injection of formation water was stopped when no more oil recovery was produced from the core plug.

The recovery factor that has been obtained by injecting a brine is equal to  $45.55\%$  of initial oil in place (IOIP) after injection about  $0.6 P_v$ . The amount of oil recovery from formation water is considered high, so this type of sandstone may be a water-wet rock.

When the seawater was injected, the oil recovery that obtained reach to  $52.22\%$  of IOIP after injection about  $2.33 P_v$ . The difference between a high salinity water flooding (formation water) and seawater was clear noticing that, no oil recovery was obtained at  $0.6 P_v$ , contrariwise the seawater continues improving oil recovery until injection  $4.12 P_v$ .

This gives an indication that the seawater has the ability to minimize the interfacial tension between the crude oil and the surface of the plug. As well as many phenomena can be noticed by injection water that has a salinity less than formation water, which will be explained in the next tests such as; fine migration, and clay swelling.

Modified low salinity water has been investigated in order to explain the effect of low salinity water flooding on oil recovery, as well as the water-cut. The oil recovery obtained from injecting modified low salinity water was  $71.11\%$ . The difference between oil recoveries by formation



brine and seawater as compared with LSM, where the LSM was more oil recovery as well as more time of breakthrough. This type of water will give a less water-cut so, it is preferred in enhanced oil recovery process. The producing of oil was continued until injection about 4.9 P<sub>v</sub>. The reducing of interfacial tension in this type of water was better than the use of seawater.

The last type of water injected was Deionized water. Most of swelling shale is caused by this type. The presence of shale is important to enhance oil recovery, the reason for the increase in oil recovery in the presence of shale and fine migration will occur. Fine migration is resulted from hydration of shale by freshwater flooding when the shale is swelling; the pore space will decrease, so the water in this case, can produce more oil by the effect of low permeability, which will be explained in the next experiments.

#### 4.3 Effect of Pressure drop

**Fig.5** shows the effect of water salinity on the pressure drop when the formation water has been injected into the core plug, the pressure reached to 6.4 Psi and stabilized on the 3.8 Psi. This indicates that neither shale swelling happened nor fine migration resulted from formation water.

When comparing the pressure drop of injection formation water with the pressure drop that is caused by injecting deionized water, there is a clear and wide difference in the two cases. As shown in the **Fig.5** after deionized water was injected with the pressure drop reaching to the maximum value 3.45 Psi (less than the maximum pressure of brine because of the viscosity difference ) and the pressure has not reached to stabilized state after no more oil recovery observed. The increase and decrease in the pressure drop is an indication of the clay swelling and the pore size will be affected by these swelling of shale so, the pore size will become smaller than the pore size before a start of the water flooding process.

#### 4.4 Effect of permeability on water flooding

The effect of permeability on the water flooding can be explained for the different types of water salinity by comparing the previous experimental work of core plug #1 with tests of core plug #2 as shown in **Fig.6**. It is clear that the recovery factor of low permeability core plug for all types of water is increased, and the time of breakthrough is delayed by comparing these results with core plug #2 as illustrated in the **Fig. 4, 6**. Because of the water in the case of low permeability can improve more oil recovery by the effect of fluid-rock / fluid-fluid reaction (the region of contact between the crude oil inside the pore space and the low salinity water injection more effective and more reaction can happen between them).

#### 4.5 Effect of IFT

Interfacial tension of the oil-water types is measured using an optical tensiometer. As the concentration of injected water decrease, the IFT of oil-surface of rock decrease and crude oil in water emulsification, so the residual oil saturation decreases, therefore the oil recovery increases as shown in **Fig. 7**



## 5. RESULTS

The Results indicated that the oil recovery was increased as the ion concentration of injected water decreases.

Low salinity water flooding gives more oil recovery in low rock permeability. Interfacial tension between oil and water is decreased as the ion concentration decreased. Fine migration and dissolution of minerals such as calcite ( $\text{Ca}^{+2}$ ) can be detected from pressure stability (when the pressure reaches a constant value, then increases; this is an indication of fine migration and the pore space will be blocked in this case which causes a permeability reduction).

## 6. CONCLUSIONS

- 1- Ion concentration in the water injection has significant effects on the oil recovery factor in sandstone reservoir rocks at room temperature but the effect becomes greater in high temperature.
- 2- Injection of low salinity water/ fresh water will cause a formation damage because of the swelling of clay minerals. The formation damage was detected by pressure observation which has significantly increased when the fresh water was injected, as well as the permeability of core plug was decreased after low salinity water-flooding.
- 3- The mechanism of smart water flooding confirmed that the alteration of ions concentration of water injected is able to change the wettability of rock in sandstone rock from oil-wet to water-wet system.
- 4- Alteration of ion concentration has an effect on the interfacial tension IFT of fluid- fluid, and solid-fluid interaction, which causes the reducing of adhesion a crude oil on the surface of the rock; this led to increasing the oil recovery.

## NOMENCLATURE

A = cross section area,  $\text{cm}^2$

L= length, cm

Vb= bulk volume, cc

Vp= pore volume ,cc

VG= grain volume, cc

$\Phi$ = porosity, fraction

$\mu_o$ = oil viscosity, cp

$\mu_w$ = water viscosity, cp

Swi= irreducible water saturation, fraction

Sor= residual oil saturation, fraction

Q= flow rate, cc/min.

CBR= crude oil, brine, rock system

AN= acid number, mg KOH/g

BA= base number, mg KOH/g

OOIP= original oil in place

md= milliDarcy

Ppm= part per million





TDs= total dissolved solids  
 SW= seawater  
 DI= deionized water  
 LSM= modified low salinity water  
 pH= alkalinity-acidity

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**Table 1.** Mineral composition of carbonate cores.

Minerals	Concentration %
Calcite (cementation materials)	1
Quartz	95
Dolomite	4% clay(illite or kaolinite)
Feldspar	-



**Table 2.** Physical properties of crude oil.

<b>Density</b>	<b>0.863 g/cm<sup>3</sup></b>
<b>Viscosity @23 °C</b>	16 cp
<b>Acid number</b>	1.2 mg KOH/g oil
<b>Base number</b>	0.321mg KOH/g oil

**Table 3.** Chemical analysis of formation water /Mishrif reservoir.

<b>Type of ions</b>	<b>Ions concentration mg/l</b>
<b>Na<sup>+</sup></b>	69915.17
<b>Cl<sup>-</sup></b>	144880.0
<b>Hco<sub>3</sub><sup>-</sup></b>	63.44
<b>So<sub>4</sub><sup>-2</sup></b>	590
<b>Ca<sup>+2</sup></b>	14000.0
<b>Mg<sup>+2</sup></b>	3888.0
<b>K<sup>+</sup></b>	610.4
<b>TDs, mg/l</b>	233336.661

**Table 4.** Seawater and modified low salinity water (LSM).

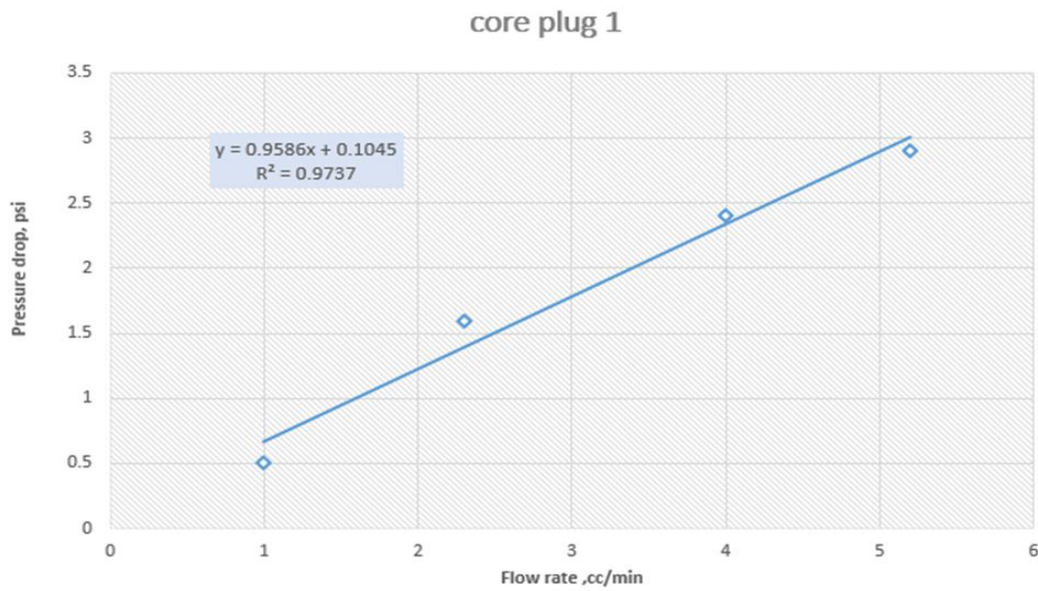
	<b>seawater</b>	<b>LSM</b>	<b>Deionized</b>
<b>Type of ions</b>	Ions concentration mg/l	Ions concentration mg/l	Ions concentration mg/l
<b>Na<sup>+</sup></b>	15105	1488	-
<b>Cl<sup>-</sup></b>	29212	2605	-
<b>Hco<sub>3</sub><sup>-</sup></b>	141	175	-



<b>So<sub>4</sub><sup>-2</sup></b>	398	698	-
<b>Ca<sup>+2</sup></b>	650	372	-
<b>Mg<sup>+2</sup></b>	1592	58	-
<b>K<sup>+</sup></b>	123	16	-
<b>TDS</b>	47221	5412	-

**Table 5.** Physical properties of water types.

Type of water	Density, gm/cm3	Viscosity, cp	PH	TDS mg/l
<b>Brine</b>	<b>1.168</b>	<b>1.168</b>	<b>6.19</b>	<b>233336.661</b>
<b>seawater</b>	<b>1.1075</b>	<b>0.984</b>	<b>6.5</b>	<b>47221</b>
<b>LSM</b>	<b>1.0155</b>	<b>0.875</b>	<b>6.35</b>	<b>5412</b>
<b>Deionized</b>	<b>1.010</b>	<b>0.609</b>	<b>6.97</b>	<b>-</b>



**Figure 1.** Q vs. P – of formation water injection.

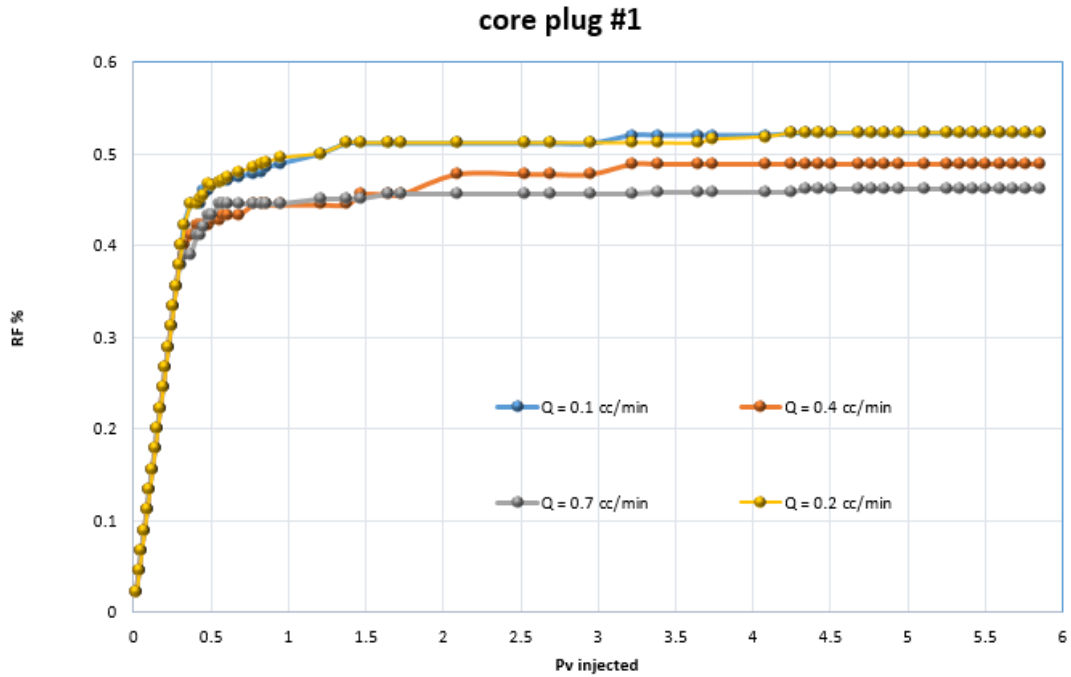


Figure 2. The effect of flow rate on the recovery factor.

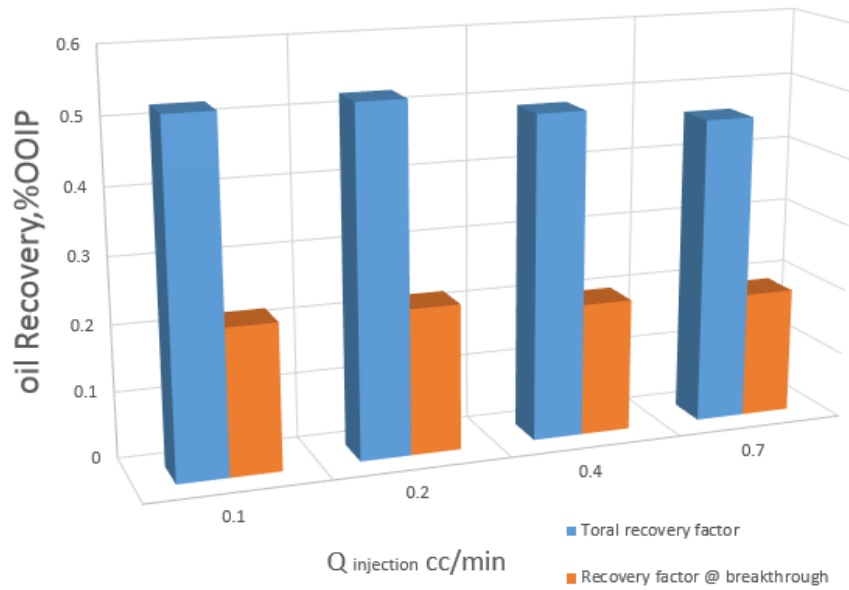


Figure 3. Oil recovery factor at breakthrough.

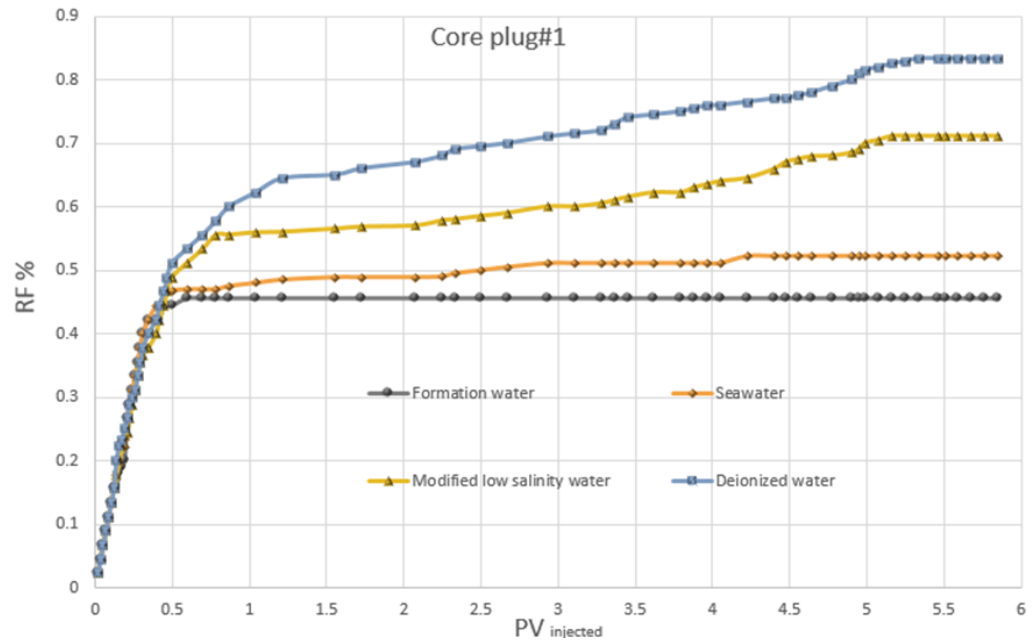


Figure 4. Effect of ions concentration on oil recovery.

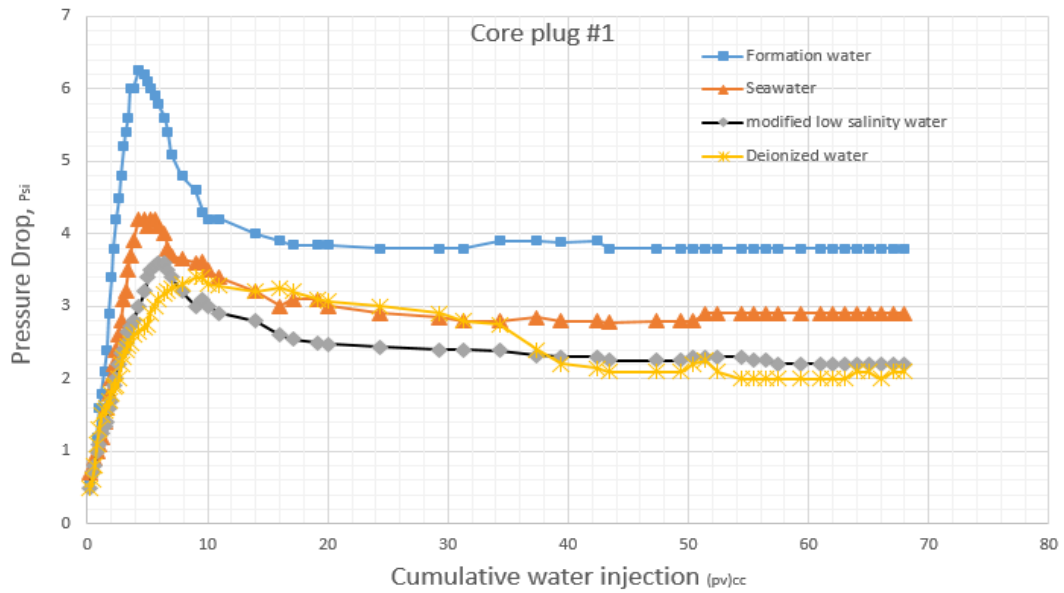


Figure 5. Pressure drop throughout the core while injection different water concentration.

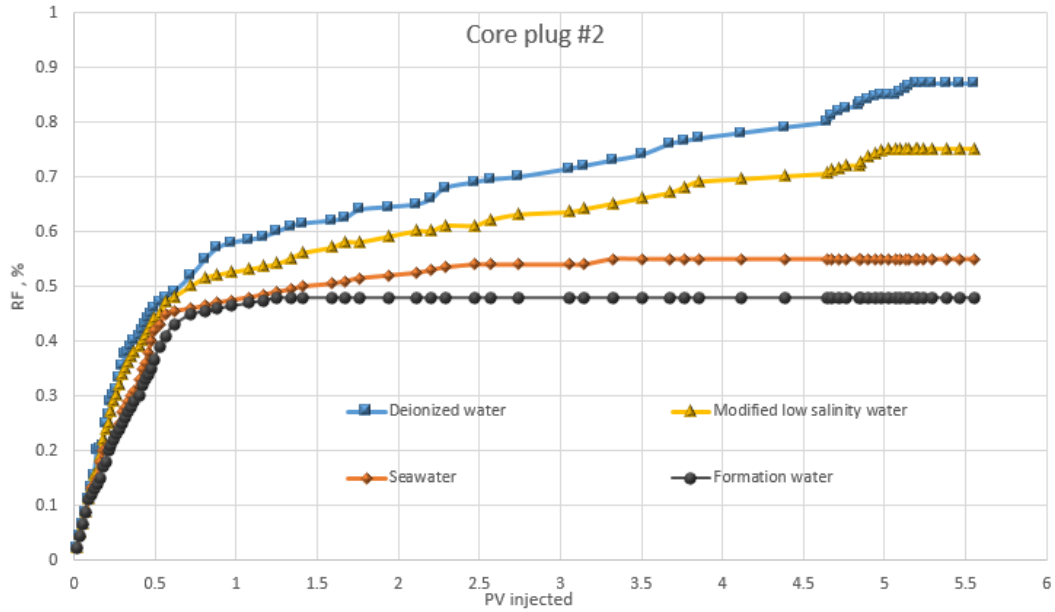


Figure 6. Effect of different water types on oil recovery and time of breakthrough of core plug #2.

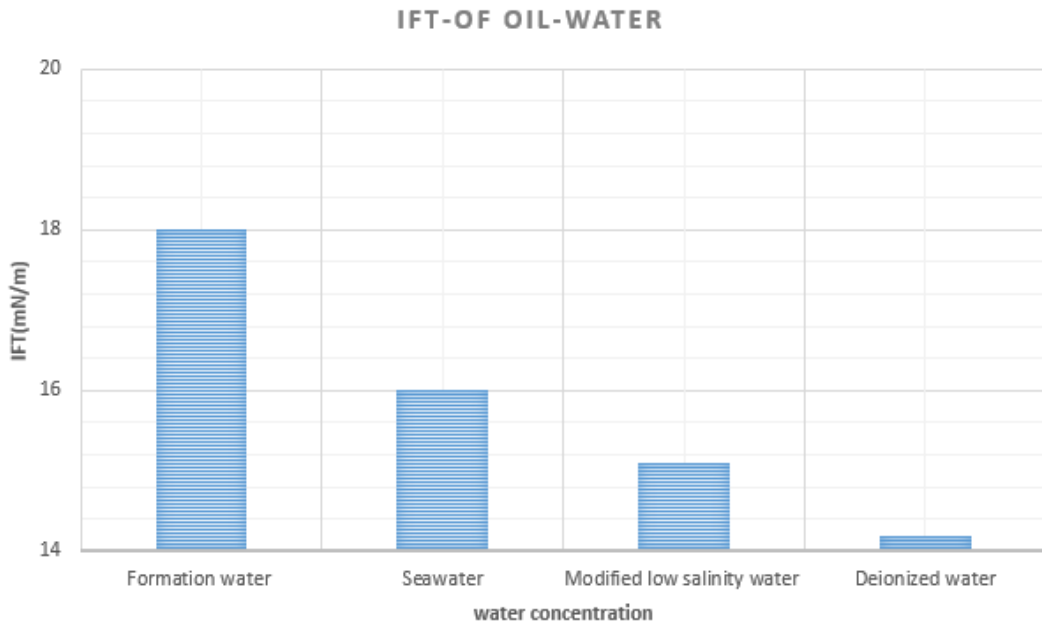


Figure 7. Interfacial tension of oil-water system at room temperature.



Figure 8. Core-flood system.