Oil Recovery by the New Incubated *Pseudomonas Aeruginosa* Bacteria Under Reservoir Conditions

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Abstract

Oil recovery experiments by using the bacteria of type *Pseudomonas aeruginosa* and a molasses base nutrient were performed, on a local manufacture model which simulates the reservoir conductions and packed with sandstone and Celica powder with permeability 800 mD. *Pseudomonas aeruginosa* bacteria is a surfactant producing microorganism, originally isolated from an Egyptian oil field, it was succeeded to increase the oil recovery by 20% when using this bacterium in the displacement run.

An examination of the literature shows that MEOR generally does not recover as much remaining oil in place in the field because of different reservoir conditions (temperature, salinity, lithology). Efforts to explain this limitation are severely encountered by the lack of quantitative measures of microbial performance (reaction of growth rates, stoichiometry, required metabolism product concentrations, etc.).

The aim of this paper is to study the effect of different reservoir conditions such as temperature, salinity, lithology and injection pressure on the performance of the used bacteria when it is injected in a linear model, saturated with the residual oil and the formation water to recover this residual oil. By the displacement process the effect of a new incubation technique, for the bacteria with the sea water outside the model, on the amount of oil recovered is also studied. Six displacement runs were performed, at different conditions, to study the effects of the above factors.

The results showed that when new incubation technique is used to incubate the used bacteria, it become able to give, at temperature up to 70 ^{O}C and salinity up to 150,000 ppm the same recovery as that was obtained by the used bacteria, when it was incubated by the conventional technique, at temperature of 50 ^{O}C and salinity of 100,000 ppm but the study showed also that there is no effect, on the recovery, for the presence of the dolomite and kaolinite inside the reservoir. An increase in the oil recovery by 2 % was obtained, when the injection pressure is increased from 10 psi to 30 psi. The new technique, of injecting the metabolism of the used bacteria, after incubation outside the model with sea water, give an increase in the oil recovery by around 5% more than its value when the bacteria is incubated inside the model.

Introduction

MEOR differs from other EOR processes only in the manner in which the chemicals are introduced into the reservoir, i.e. in situ generation, and therefore should be evaluated on the same basis as other EOR processes. It follows that any advantage of MEOR will arise only from being more efficient than another EOR process. In situ generation presents a potential advantage in logistics, especially if residual oil can be used as an in-situ carbon source for the nutrient of the bacteria. This is likely to be the most important, and possibility the only advantage over other processes. On the other hand, in situ generation introduces a new set of technical difficulties [(1)].

In addition to the challenges associated with in situ chemical generation, MEOR must overcome essentially the same technical problems and difficulties as other EOR processes, particularly the placement and propagation of recovery-enhancing chemicals. Indeed, decades of studies on chemical EOR underscore the importance of

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chemicals dissipation via dispersion and diffusion, and consumption or retention via interactions with the rock and with the oil. Similarly, propagation cannot be taken for granted in microbial treatments: injection of chemicals generated ex-situ recovered little or no oil, even through the same chemicals did lead to oil recovery when generated in situ [2]. Further, reservoir heterogeneity may severely reduce contact of the chemical slug with the oil contained in the reservoir rock, and fingering into the mobilized oil bank must be suppressed. Finally, the presence of recovery-enhancing chemicals in the produced oil may create processing problems.

Some recent studies [3-17], pilot tests and field trials, which were conducted during last ten years, were found that, the MEOR is a success process however it is limited to the conditions of using the bacteria at the low temperature and salinity.

The authors of the present study [18], in a pervious work, studied the isolation of indigenous bacteria, from three different Egyptian oil fields, and succeeded to isolate and identify three types which are *Pseudomonas aeruginosa, Pseudomonas fluerescens biotype G* and the *Celluiosimicrobium celluians*. The best type, suitable for MEOR from these three isolated types, was found to be the *Pseudomonas aeruginosa*. Nutrient with Molasses base was found to be the best type of nutrients for this bacterium, but its activity is largely affected by the increase in temperature and salinity [19]. In another study [20], a new technique was proposed for incubation of this bacteria and succeeded to increase its efficiency and make it able to stand with reservoir conditions of high temperature up to 70 ^{O}C and high salinity up to 150,000 ppm. A flooding run was performed, with the cyclic injection of the used bacteria, to explain the mechanism of increasing the oil production and the recovery factor by around 20% when using this bacterium which produce biosurfactant and gases [21].

The objectives of this paper are: 1) to study the effect of different reservoir conditions such as lithology, injection pressure, temperature and salinity on the performance of this bacteria, 2) to study the effect of using a new displacement technique in which the used bacteria is incubated outside the model with the sea water then flood the model with this solution (sea water + bacteria and its metabolisms).

Experimental work

Materials used

Bacteria

The bacteria of type *Pseudomonas aeruginosa* bacteria, which was isolated (in the pervious study of the authors) from an Egyptian crude oil, is used to perform the different displacement runs that were carried out in the present study [18]. This bacteria has the following characterization: round, granular, entire, flat, colorless, translucent, an aerobic, gram-negative, short rods, no spore was performed and not resist to acid [18].

Media

One media that is called a "modified media"[22] was selected to incubate the used bacteria. This media was selected specially for the bacteria *Pseudomonas aeruginosa* to make it give a higher growth rate. The composition of this modified type is given in table 1.

Nutrients

As proved before (in the pervious study of the authors) the best nutrient type for the used bacteria was found to be the nutrient which has the following composition [19]: Molasses (2 gm/lit), NaCl (5 gm/lit) and KNO_3 (10 gm/lit).

Brine water

Two brine solutions were used the first is the formation water (with salinity of 100,000 ppm) and the second one is the sea water (with salinity of 40,000 ppm). Both of them obtained from an oil field, that is differed from the field from which the used bacteria is isolated from its crude, this field is located in the Gulf of Suez area, Egypt. The compositions of these two brine solutions are given in table 2.

Oil

The crude oil that is used in the present study to saturate the model was obtained from the same field from which the brine solution was collected. This crude was tested to be sure that it is free from any indigenous bacteria and it was found to have the characteristics as shown in table 3.

Sandstone and Celica powder

Two types of sand and Celica with different size were used to fill the model with percentage of 75% of sand and 25% of Celica to give an overall permeability value to 800 md, which simulate the value of the reservoir permeability.

Displacement model

In order to perform the displacement tests a linear model is designed by using suitable dimensions [23](length of 2 ft and radius of 2 inch). In order to keep a constant temperature inside the model, worm water was surrounding the model through the external cylinder with an inlet and an outlet for the water which connected to a water path having a heater with a thermostat to control the designed temperature similar to reservoir temperature. To carry out the displacement process inside the model, 4 tanks were designed to store the fluids that will used in the displacement tests (oil, brine water, nutrient, …) the volume of every tank is around six liters.

In order to evacuate the model before saturating it by the formation water a vacuum pump (EDWARDS model No. ES75) was connected to the model.

All the designed components mentioned above was connected together with the pressure control panel of the oil-water relative permeability apparatus, to maintain a constant pressure during the displacement tests as shown in figure 1.

Experimental Procedure

In a previous work for the authors[21], a displacement run was performed in which one pore volume of the bacteria is injected in the model when the oil saturation inside the model was equal to the residual saturation value i.e. at Sor, in this basic run the residual saturation was reached after flooding the model with 5 PV and at that time no more oil come out of the model. After the injection of this one PV of bacteria, the model was left for incubation for 1 week. After that the residual oil is displaced by the injection of 3 PV of sea water and it was found that, the oil recovery is increased by about 12% of OOIP. The procedure of this run will be used as a base for the different experimental runs of the present study and its results will be used for the comparison with the results of the different six run that will performed during this research. In the following a detailed description for the procedure of the first run. In the other 5 runs (from 2 to 6) the same procedures and conditions will be followed except the value of the parameter under study which will be changed in each run to study its effect. Table 4 gives the conditions of the first run, and table 5 gives conditions of the other 5 runs that were performed in comparison with the conditions of the first run.

The same procedures of the basic run, which mentioned above, will be used in this first run with the same conditions except that, the time of the bacteria injection in this first run will be just after flooding the model with only 1 P.V. of sea water instead of

5 P.V. in the basic run. This means that, when the bacteria injected in the model, in the first run, the value of the oil saturation in the model is higher than its value in the basic run.

The following procedure were used to perform the first run:

1- Fill the model with the selected rock which is composed of the mixture of sandstone and silica powder as given above.
2- Use the heater of the water path to adapt control the required temperature around the model (50 ^{O}C).
3- Evacuate the model by using the vacuum pump.
4- Fill the model with the formation water (100,000 ppm) and calculate the porosity then measure the absolute permeability.
5- Flood the model with the oil until no more water come out then calculate the connate water saturation and Ko at Swi.
6- Flood the model with the sea water of 40,000 ppm by one pore volume.
7- Inject one PV of bacteria solution (bacteria and its nutrient 8).
8- Lift the model for one week for incubation.
9- Flood the model with sea water (40,000 ppm) until no more oil come out (5 PV) using injection pressure 30 psi.
10- Calculate the Kw at Sor.

The effluent fluid from the model was collected in a test tubes having a volume of 50 cm to record the changes in the aqueous phased and the oleic phase volume while flooding.

Fig. 2 shows the type, the amount and the sequence of fluids injected inside model Vs the total number of pore volume injected during the first run (Run-1).

Repeat the steps that were mentioned above in run-1 except that for the value of the injection pressure, in step number 9, it will be 10 psi in this second run instead of 30 psi as in the first run (Run-2).

The steps of run-1 were repeated, except that for the composition of sand that will be used to fill the model, it will be changed to 75% by weight of sandstone, 20 % by weight of silica and 5% by weight of Dolomite and Kaolinite (Run-3).

Repeat the steps of the first run except that instead of lifting the bacteria for one week for the incubation inside the model, the bacteria are incubated for one week also but outside the model, in a tank with the sea water and the same nutrient 8. After the time of incubation, start injecting the bacteria solution and its metabolism inside the model for 6 PV (i.e. until no more oil recovered from the model) (Run-4).

The steps above of run-1 were repeated, the only parameter that will be changed in this first run, is the temperature inside the model during the incubation period, it will be changed to 70^{O}C instead of 50 ^{O}C (Run-5).

Use all the steps and the conditions of run-5, the only parameter that will be changed in this sixth run is the salinity of the formation water which will be increase to a value of 150,000 ppm instead of 100,000 ppm (Run-6).

Result and discussion

Table 6 shows the result of the basic physical properties that were measured in each run, before the starting of injection of the one pore volume of the bacteria solution. It is noticed that the values of the porosity, the absolute permeability, the oil permeability at Swi and the OOIP have a very narrow range of variation which give a self confidence for the reproducibility of the different runs and confirm the validity of the comparison between the results obtained after each run when assuming that the difference in the obtained results, if present, will be only due to the variation of the

parameters under study. The only large variation in these properties could be observed in the value of the permeability for the third run, and this is due to presence of Kaolinite and Dolomite in the sand pack of the model.

Effect of initial oil saturation before start injection (Run-1)

Fig. 3 shows the volume of oil produced and the recovery factor VS the pore volume injected for the two comparative runs, the basic run which was performed in the previous work [22], and the first run of the present study.

The results of this comparison showed that, there is an increase in the ultimate oil recovery by about 12 %, when injecting the bacteria after only one pore volume of sea water injection as made in the first run, instead of its injection after the flooding of the model with five pore volume of the sea water as done in the basic run, this means that it is better to start the MEOR project as early as possible as in this case the amount of oil recovered increases and the total number of pore volume of sea water which needed to be injected in the model decreases and this increase the economics of the process.

Effect of injection pressure (Run-2)

The volume of oil produced and recovery factor VS the pore volume injected for the two comparative runs (1 & 2) is shown in Fig. 4.

It is clear from Fig. 4 that, there is an increase in the ultimate oil recovery by 2 % when the injection pressure is increased to 30 psi.

Figures 5, 6 give a matching in the physical properties (conductivity and pH) of the two runs. It is clear from these figures that the increase in the oil recovery is accompanied by a decrease in the pH value and the conductivity. This confirm the same observation that was noticed before in the previous work of the authors while interpreting the results of the basic run [21].

Effect of different lithology (Run-3)

Fig. 7 shows the variation in volume of oil produced and recovery factor as a function of the pore volume injected during the two comparative runs, the first and the third run. The comparison between the two curves of the recovery factor, for the two runs, shows that there is no big change in the final recovery due to the presence of Kailinite and Dolomite, the only difference between the two curves is that the final value of the recovery factor is reached faster in the third run (after 4.5 PV), while in the first run it is reached after 6 PV, this may be due the relating change of permeability.

Effect of incubation the bacteria outside model (Run-4)

The effect of changing the place of incubation of the used bacteria, on the oil rate and the oil recovery factor is shown in Fig. 8. It is clear from this figure that the value of the oil recovery factor in case of incubated the bacteria outside the model is greater than its value in case of incubation inside the model by about 5%.

Effect of temperature change (Run-5)

The effect of increasing the temperature of incubation, on the performance of the used bacteria and its activity can be observed from figures 9,10 and 11. it is clear from Fig. 9 that there is an increase in the ultimate value of the oil recovery factor, by about 2% due to the increase in the temperature from 50^{O}C to 70 ^{O}C. This small increase in the oil recovery does not refer to an important increase in the activity of the used bacteria at the higher temperature but it is due to the fact that the viscosity of the residual oil in the model decreasing as the temperature inside the model increasing from 50 ^{O}C to 70 ^{O}C and this increase the relative movement of the oil and hence increase the amount of oil recovered by displacement. This is also confirmed from the observation of figures 10 and 11 which indicates that the curves of the pH value and conductivity of the effluent solutions, of the two runs, are nearly identical which means that the

activity and the performance of the used bacteria at 70 ^{O}C, i.e. its capability to produce the bioproducts, are the same as its activity and performance at the lower temperature of 50 ^{O}C. This result represents a good prove to the validity of the new technique of incubation, that developed by the authors in a previous work [20], to increase the capability of the used bacteria to stand with the high temperature conditions of the reservoir.

Effect of Salinity change (Run-6)

Fig. 12 represent a comparison between the two curves of the oil recovery factor, for the run number 5 and run number 6, as a function of the pore volume injected. It is clear from this figure that there is a small decrease in the recovery factor by about 4% due to the increase of the salinity from 100,000 ppm to 150,000 ppm both at temperature 70 ^{O}C. This small difference in the value of the ultimate recovery factor between the two runs mean that the used bacteria still have a good activity and give a relatively good performance, for the MEOR propose, even at hazard reservoir conditions of high salinity and high temperature, as it gives at temperature of 70 ^{O}C and salinity of 150,000 ppm an oil recovery factor of 82%. Figures 13 and 14 confirm this conclusion as the performance of the pH and conductivity of the effluent solutions are nearly similar to each other, that is means that, the activity of the bacteria is the same of the two runs. And as the results of the basic run shows that the ultimate oil recovery factor by water flooding, without bacteria is about 60%. So, the results of run number 6 means also that the used bacteria, can increase the oil recovery by about 22% in spite of the high salinity of the formation water 150,000 ppm and the high reservoir temperature of 70 ^{O}C. Such that it must be incubated by the new technique that was developed by the authors [20].

Overall comparison

Table-7 shows the results of measuring of the water relative permeability Krw at Sor, the residual oil in place Sor and the final recovery factors for all the runs that were made above. It is clear that the Krw increases when the Sor decreases. The highest recovery factor was obtained when incubating the bacteria outside model, in run number 4, as it gives a final recovery factor around 89%, this result confirmed by Figures 15 and 16 as this run gives the lowest viscosity of the oleic phase and lowest surface tension of the aqueous phase for the effluent fluids from the model.

Conclusions

- The value of the ultimate oil recovery factor increased by around 20%, over its value after the water flooding process, due to the use of bacteria *Pseudomonas aeruginosa*.
- A higher recovery can be obtained when:
    a. Increasing the injection pressure.
    b. Injecting the bacteria as early as possible during the water injection phase (i. e. higher Sor).
    c. Incubating the bacteria outside the reservoir.
- The presence of shale and dolomite has a minor effect on the bacterial growth, and its metabolisms and the ultimate oil recovery.
- The performance of bacteria, when increasing the temperature and salinity up to 70 ^{0}C and 150,000 ppm is nearly the same as its performance at 50 ^{0}C and 150,000 ppm. This is a new result that have not been reported in the literature.
- The reliability of the new technique for incubating the used bacteria, which make it able to stand with the high reservoir temperature and salinity, is proved in the

present study by a group of displacement runs at different conditions that simulate the hazard conditions of the reservoirs

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TABLE 1- THE COMPOSITION OF THE MODIFIED MEDIA (22)

Media No.	Composition	Weigh [gm/lit.]
Modified media	Proteose peptone	20
	Glycerol	10
	K_2HPO_4	10
	$MgCl_2.6H_2O$	1.4

TABLE 2– CHEMICAL COMPOSITION OF THE SEA WATER AND THE FORMATION WATER FOR THE FIELD UNDER STUDY.

Components	Sea water	Formation water
NaCl [ppm]	28,500	50,000
$CaCl_2$ [ppm]	1,500	42,000
$MgCl_2$ [ppm]	3,000	8,000
$CaSO_4$ [ppm]	7,000	0
Total salinity [ppm]	**40,000**	**100,000**

TABLE 3- PHYSICAL PROPERTIES OF THE CRUDE OIL USED.

Properties	**Value**
Initial reservoir pressure, psi	3000
Reservoir temperature, ^{o}F	180
Bubble point pressure, psi	1350
GOR, SCF/STB	260
Oil Gravity, API	20
Pour point, ^{O}C	-3
Density	0.92
Asphalt content	12 %

TABLE 4- SUMMARY OF THE CONDITIONS OF THE FIRST DISPLACEMENT RUN.

PARAMETER	**CONDITIONS**
Formation lithology	Sandstone with two different grain sizes.
Temperature	50 ^{O}C
Formation salinity	100,000 ppm
Sea water salinity	40,000 ppm
Bacteria type	*Pseudomonas aeruginosa*
Bacteria incubation place	Inside the model
Injection pressure	30 psi
Time of bacteria incubation	One week
Quantity of bacteria injection	1 PV of bacteria solution and nutrient number 8
Time of bacteria injection	The bacterial solution is injected by 1 PV only, just after the end of flooding the model with 1 PV of sea water.

TABLE 5- SUMMARY OF CONDITIONS OF THE DISPLACEMENT RUNS CARRIED OUT.

Run No.	**Conditions**
Run-2	The same conditions of run 1 except that injection pressure is 10 psi
Run-3	The same conditions of run 1 except that the lithology of the packing of model to be sandstone & silica with 5% Kaolinite and Dolomite
Run-4	Conditions of run 1 were used except that, incubation of bacteria was done outside model
Run-5	Conditions of run 1 were used except that, the temperature is increased to be 70 ^{O}C
Run-6	Conditions of run 5 were used except that, formation salinity is increased to 150,000 ppm

TABLE 6- THE BASIC PHYSICAL PROPERTIES OF THE POROUS MEDIA IN THE MODEL AS CALCULATED BEFORE EACH DISPLACEMENT RUN.

Item	Φ [%]	K [md]	Swi [%]	OOIP [CC]	Ko at Swi [md]
Run-1	38	834	9	360	705
Run-2	37	799	16	330	558
Run-3	31	236	23	280	162
Run-4	35	777	17	320	644
Run-5	38	846	16	340	632
Run-6	38	834	12	350	629

TABLE 7- THE VALUES OF THE AMOUNT OF RESIDUAL OIL, THE RECOVERY FACTOR AND REALTIVE PERMEABILITY TO WATER AT THE RERDIDUAL OIL AS CALCULATED AFTER EACH RUN.

Item	Sor [%]	Kw at Sor [md]	RF [%]
Run-1	16	348	84
Run-2	18	350	82
Run-3	17	139	83
Run-4	11	373	89
Run-5	14	360	86
Run-6	18	346	82

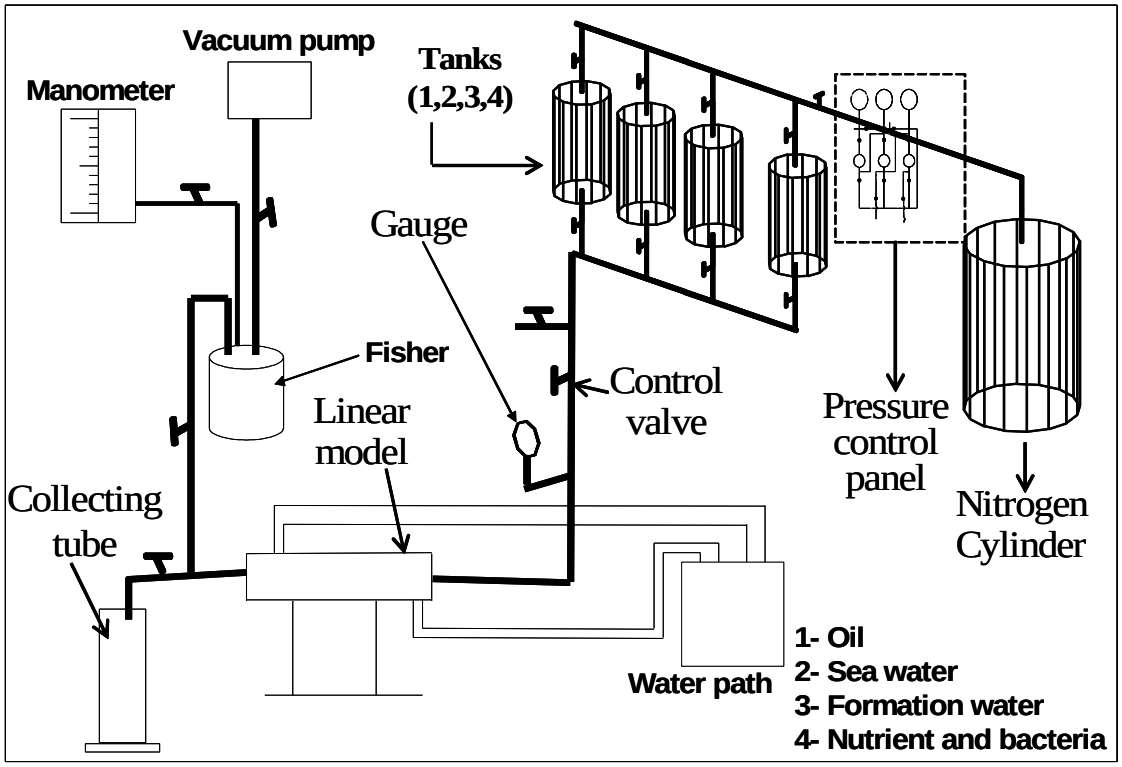

Fig. 1- The systematic diagram for the local manufacture model

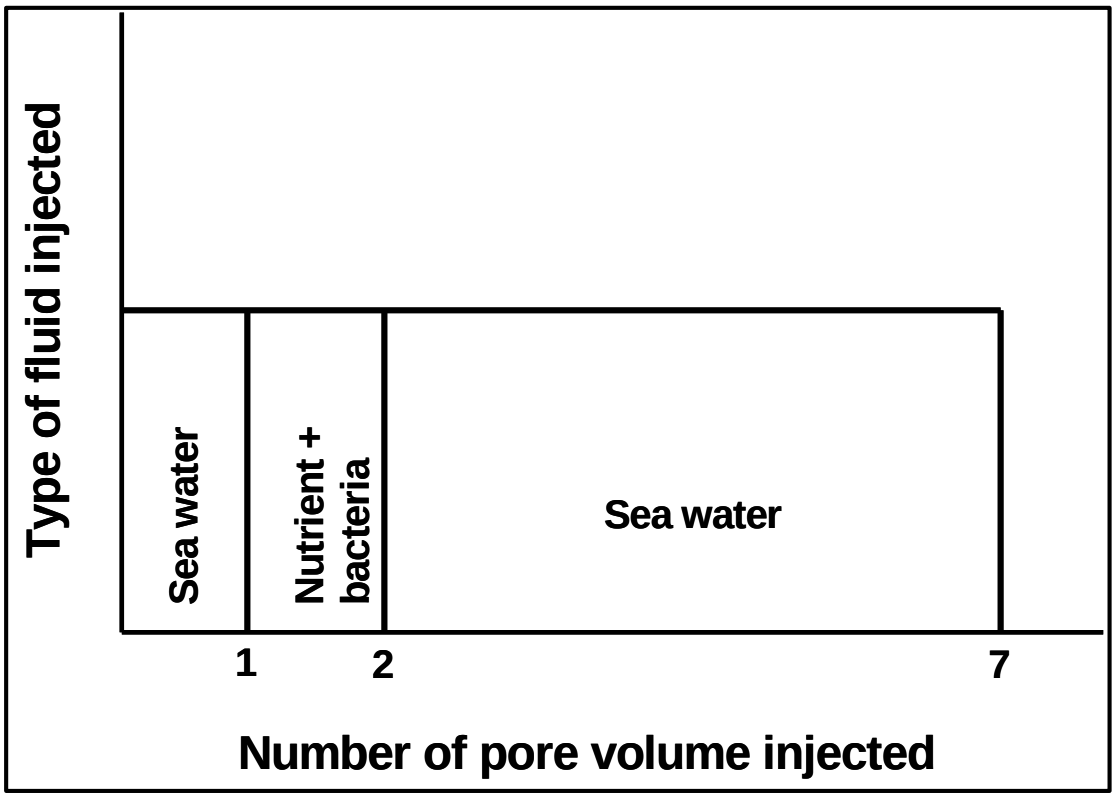

Fig. 2- The type of fluid injected Vs the number of pore volume injected.

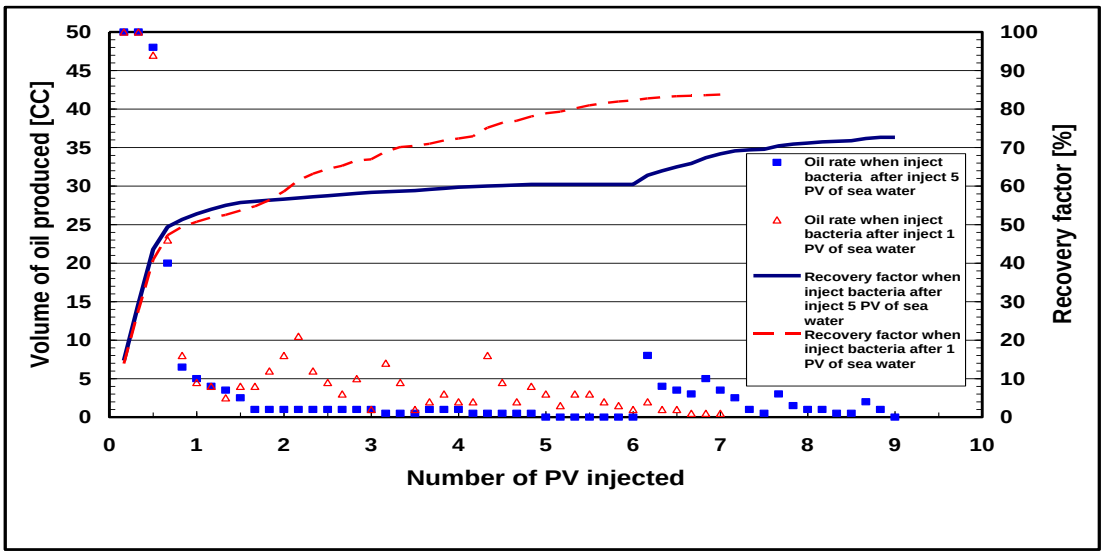

Fig. 3- Effect of time of bacteria injection on the volume of oil produced and recovery factor.

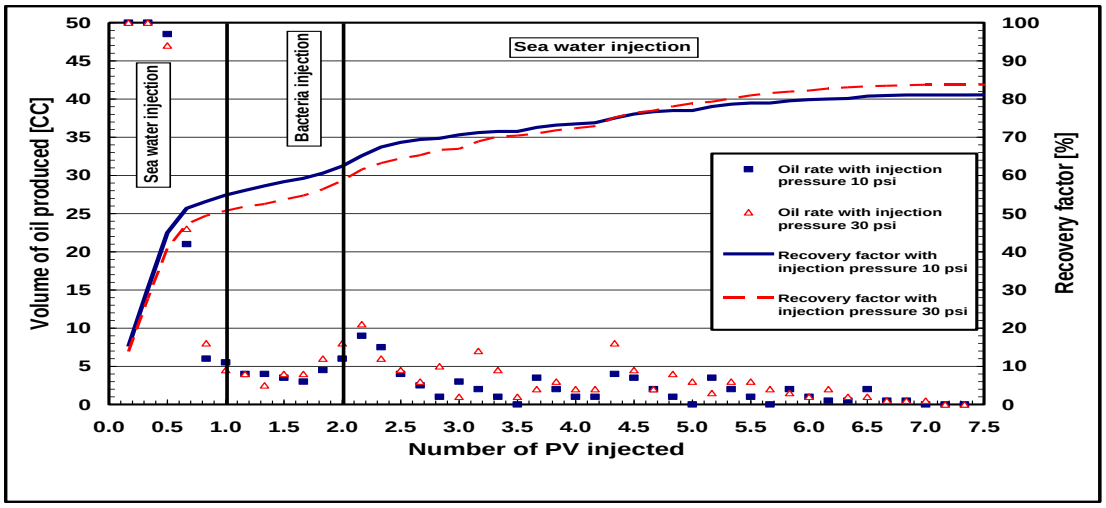

Fig. 4- Effect of injection pressure on the volume of oil produced and recovery factor.

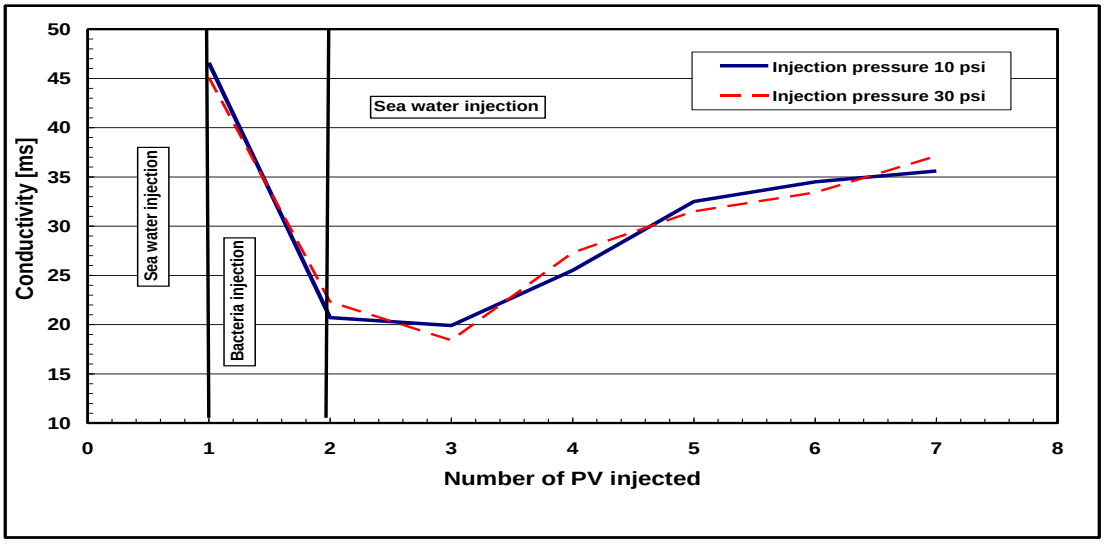

Fig. 5- Effect of injection pressure on the conductivity of the aqueous phase produced.

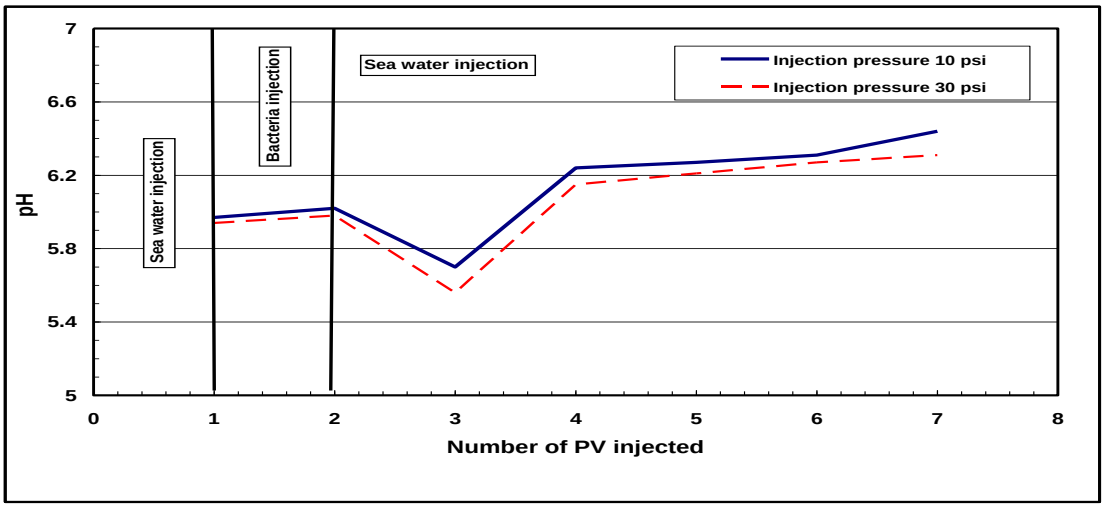

Fig. 6- Effect of injection pressure on the pH of the aqueous phase produced.

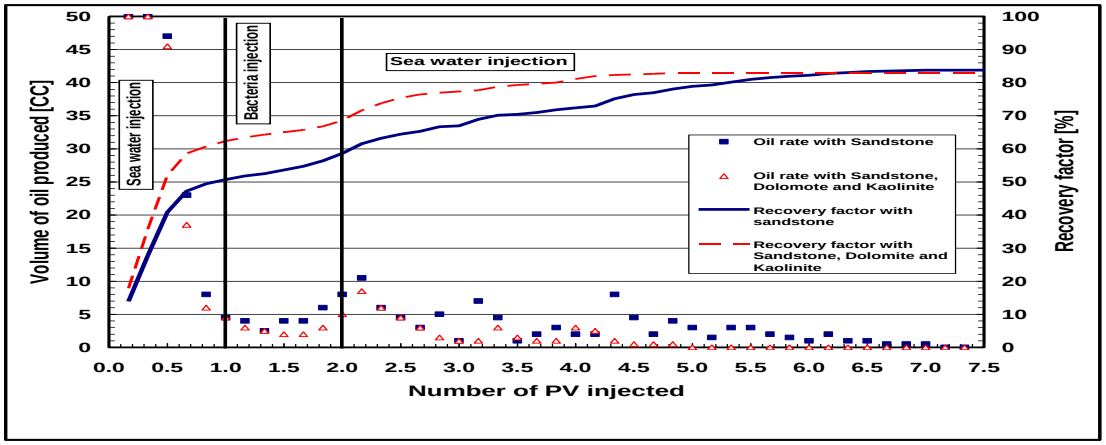

Fig. 7- Effect of different lithology on the volume of oil produced and recovery factor.

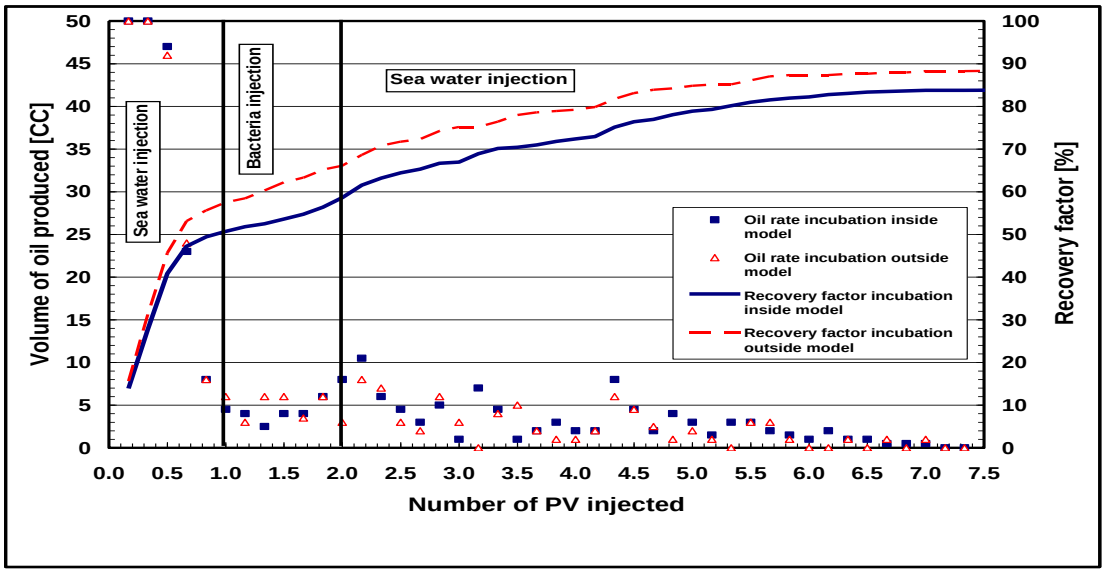

Fig. 8- Effect of bacteria incubation place on the volume of oil produced and recovery factor at 50 ^{O}C.

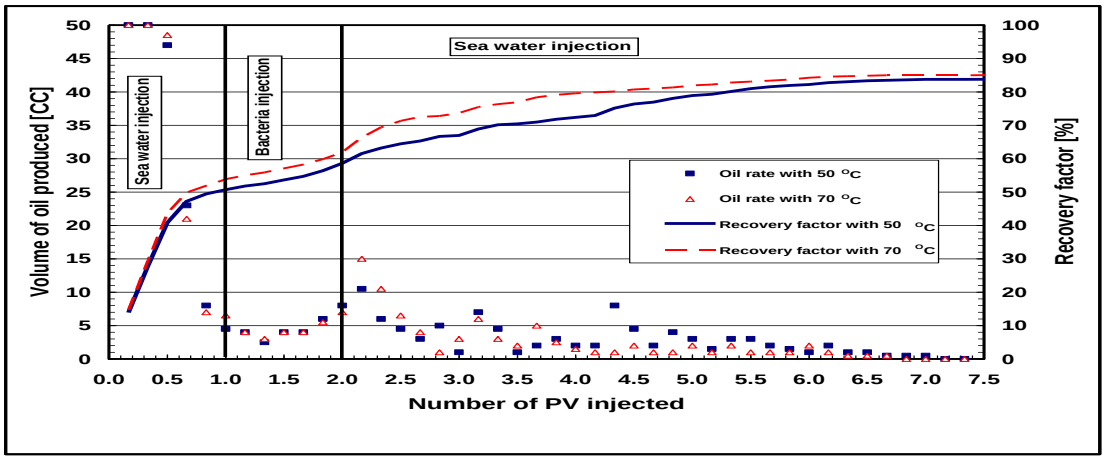

Fig. 9- Effect of temperature change on the volume of oil produced and recovery factor while the bacteria incubate inside model.

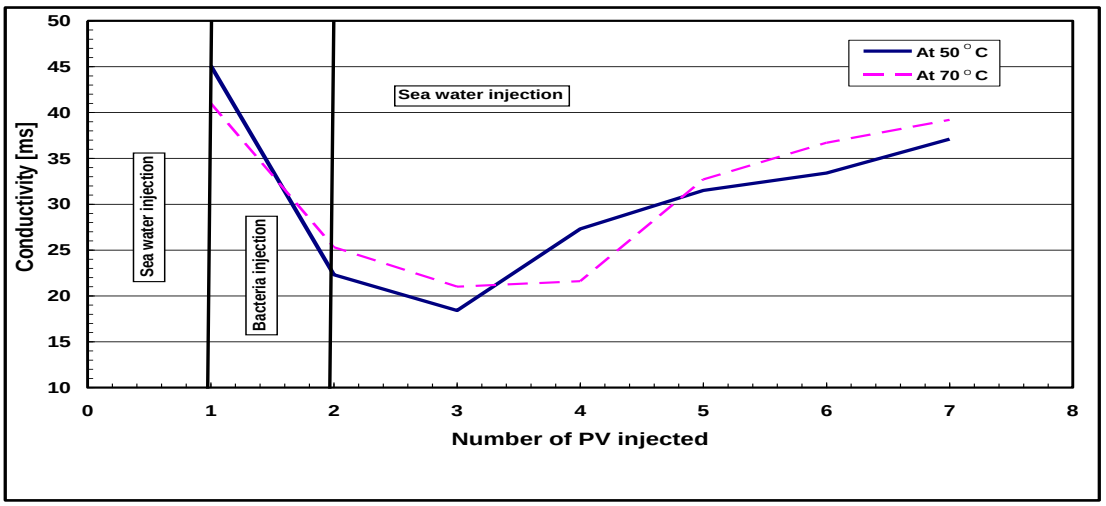

Fig. 10- Effect of temperature change on the conductivity of the aqueous phase produced while the incubation of bacteria inside model.

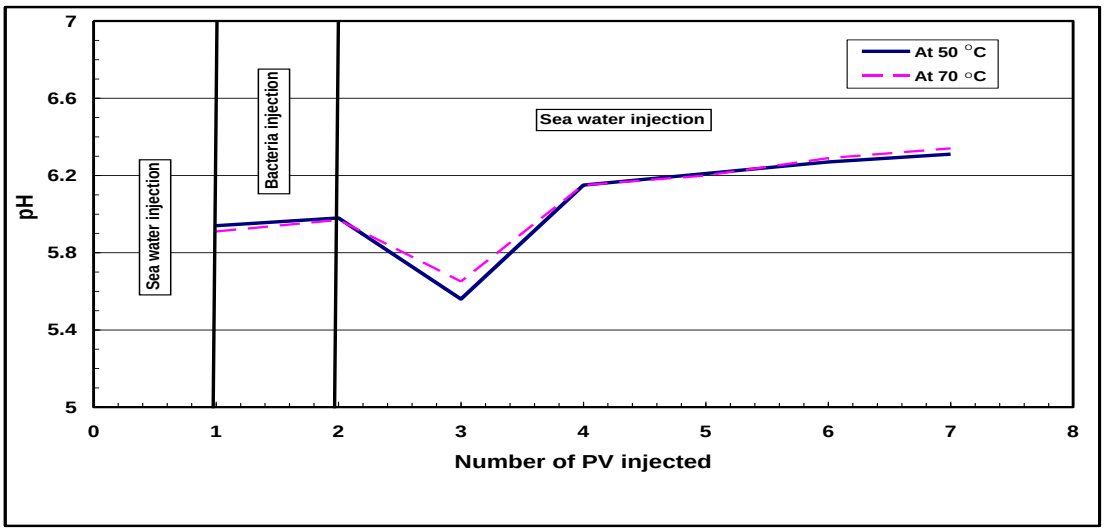

Fig. 11- Effect of temperature change on the pH of the aqueous phase produced while the incubation of the bacteria inside model.

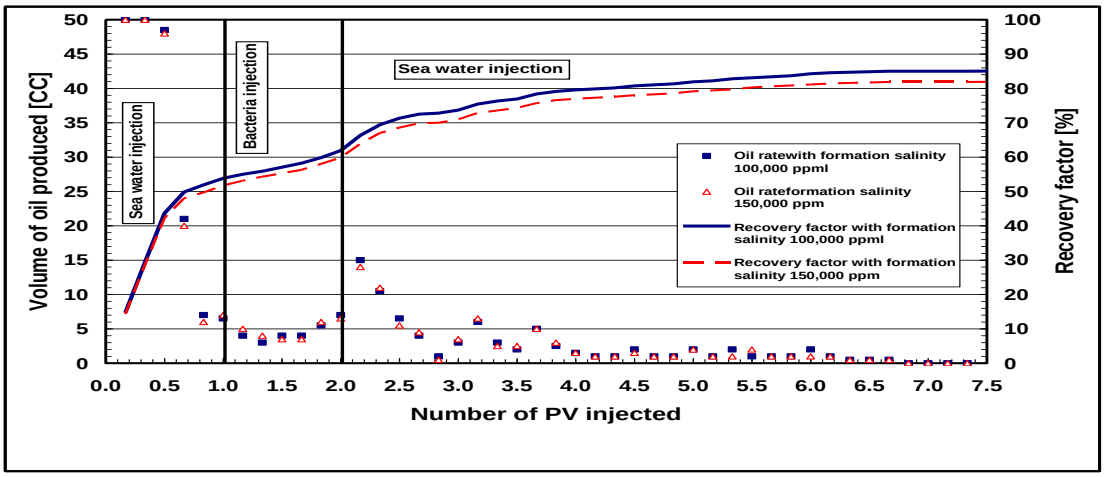

Fig. 12- Effect of formation salinity change on the volume of oil produced and recovery factor.

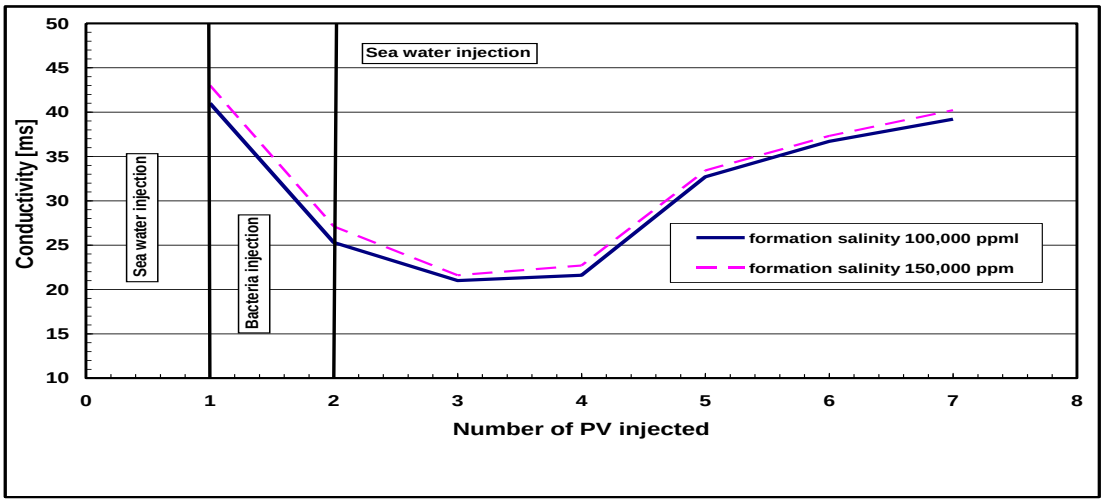

Fig. 13- Effect of formation salinity change on the conductivity of the aqueous phase produced.

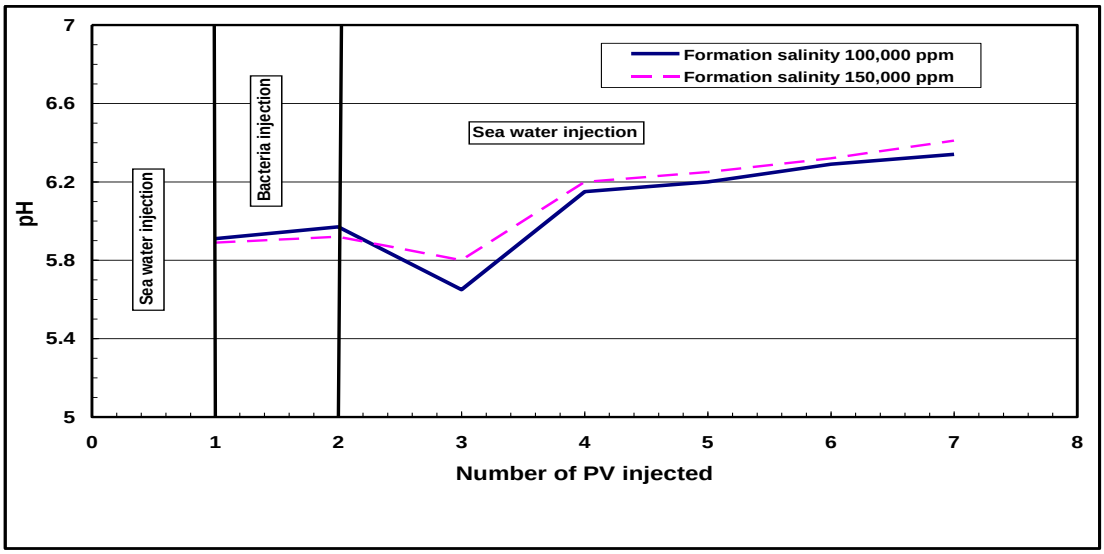

Fig. 14- Effect of formation salinity change on pH of the aqueous phase produced.

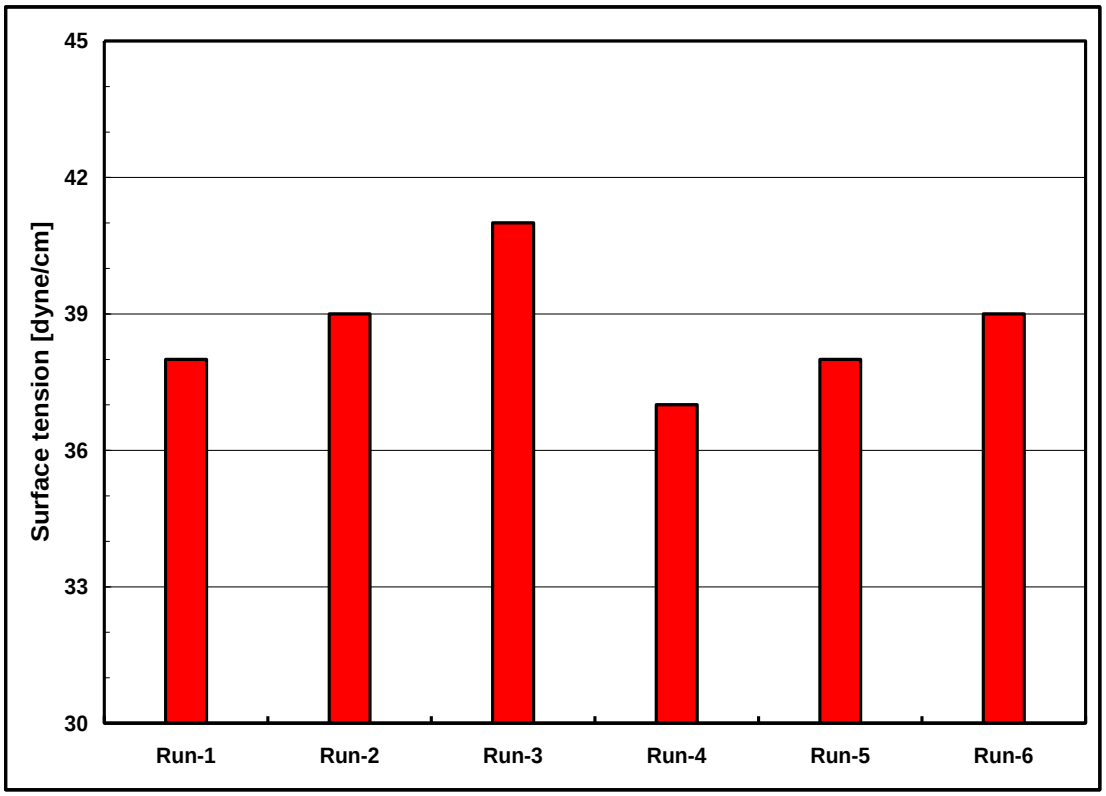

Fig 15- The surface tension of the aqueous phase as a recovery from the model for all runs.

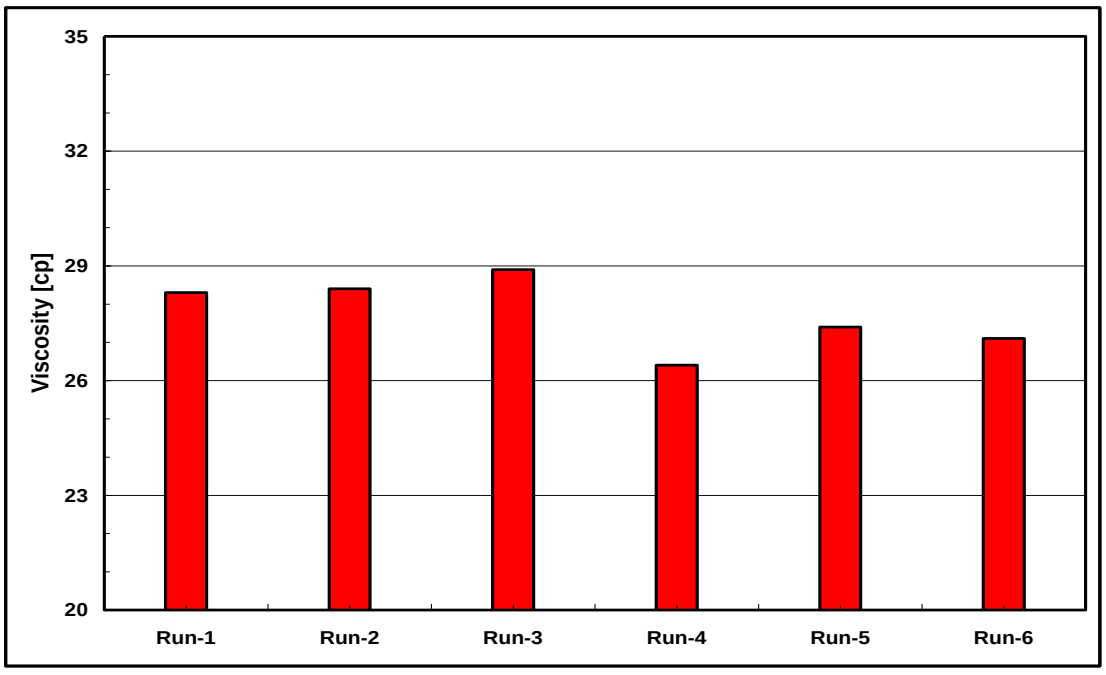

Fig. 16- The viscosity of oleic phase as a recovery from model for all runs.