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A Numerical Investigation of Low-Salinity Waterflooding Capability to Enhanced Oil Recovery

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Abstract: Low-salinity water flooding (LSWF) is one of techniques that can be used to improve oil production and has gained a significant attention in these days because of its advantages over conventional water flooding and chemical flooding. Even though many mechanisms have been recommended on an extra oil recovery achieved using LSWF process, the principle fundamental of the mechanism is still not fully understood. This research paper investigates the potential of oil recovery in an onshore sandstone reservoir using LSWF. A field-scale three–dimensional reservoir model has been developed via CMG's GEM compositional simulator where the model validated against a real production field data that were in good agreement with a deviation value of 8%. The primary mechanism of LSWF has been identified by providing incremental oil recovery due to a multi-component ion exchange mechanism that causes wettability alteration of reservoir rock from oil-wet to water-wet. The sensitivity study showed that LSWF provides a higher accumulative oil production compared to conventional high salinity water injection with 13.5 and 12 MMSTB. Moreover, the early time of low saline brine injection can provide a maximum oil recovery up to 71%. Therefore, implementing this scenario immediately after the primary recovery, it provides production benefits in both secondary and tertiary method. The oil recover factor increased to 75.5% with the increasing of brine injection rate up to an optimum value of 5320 bbl/d. A reservoir temperature also influenced the ion exchange wettability alteration during LSWF in which as the temperature increasing enhances the oil recovery. Therefore, a high temperature sandstone reservoir will be a potential candidate for LSWF.

1. Introduction

Conventional waterflooding is a secondary oil recovery method that involves the injection of water to improve the production and it typically follows primary recovery. The process is generally done by considering economic terms and based on the compatibility of the water with the existing reservoir brine to prevent any formation damage. However, in the early 1990's, several researchers recognized from their experimental work that the composition of injection water plays an important role in oil recovery.

From then onward, extensive coreflood tests were published, addressing the benefits of low-salinity effect in the process of oil recovery via waterflooding. Most of these experiment results showed that when the injection water has lower salinity compared to the formation water salinity, a higher oil recovery is obtained for both secondary and tertiary recovery modes. Several publications have reported that the injection of low-salinity brine increases the oil recovery by a factor up to 40 % compared with standard high-salinity waterflooding (HSWF) in different sandstone reservoirs [1]. LSWF has gained vast interest in the petroleum industry due to its practical advantages compared to other chemical EOR methods. LSWF is an emerging EOR technology and it has a promising future since half of the world's petroleum originates from sandstone reservoirs.

Various LSWF mechanisms have been proposed by several researches over the years such as fine migration, increase in pH and reduction in interfacial tension (IFT), multicomponent ion exchange, limited release of mixed-wet particles, salt-in effect, osmotic pressure and wettability alteration. Some of these mechanisms are related to each other with the main process being wettability alteration. Nevertheless, disagreements and contradicting experimental findings between the researchers have resulted in difficulties in precisely understanding the true mechanism of LSWF. It is still a challenge in capturing this effect brought by LSWF due to the complex crude oil/brine/rock interaction.

The injection of low-salinity brine does not necessarily assure higher oil recovery factors. The increasing application of LSWF in oil reservoirs makes it vital to determine the most effective process optimization via the manipulation of specific operating parameters to deduce possible approaches in maximizing oil recovery. Despite playing an important role in the practical implementation this subject has been poorly discussed in past studies. The attributes of simulation studies conducted on LSWF for the past 10 years suggests the need for developing a reservoir model to simulate a more systematic performance and optimization of LSWF process at field scale as previous models developed were focused more on simulating the mechanism rather than sensitivity analysis. Therefore, there is a need of evaluating LSWF using an appropriate reservoir model for a more successful field application. The focus of this study is to analyse the potential of LSWF in improving oil recovery in sandstone reservoirs for secondary and tertiary recovery modes. A three-dimensional reservoir model is built using the compositional equation of state CMG'S GEM simulator based on a given sandstone reservoir.

2. Methodology

2.1 Compositional Simulation using CMG'S GEM

The reservoir simulation model in this research is based on a given sandstone reservoir. Upon screening the reservoir to analyse its compatibility for LSWF, the development of the model is performed. The geometry of the reservoir is defined using corner point grid. The reservoir model consists of 9,600 number of blocks in total with 40×40×6 grid blocks in the direction of i, j and k respectively. Figure 1 shows the developed three-dimensional reservoir model that simulates inverted-5 spot injection pattern. The reservoir is a medium sand with medium porosity and high permeability. The horizontal permeability in I and j directions are equal while the vertical to horizontal permeability ratio of the reservoir is defined to be 0.1.

The reservoir consists of 11 oil-phase components with no gas phase as gas cap is not present in the reservoir. The presence of CO_2 in the oleic phase gives the connate water an initial pH of 5.2 which is in acidic condition. The formation water is composed of five components with a total salinity of 240,000 ppm. As a base case prediction, the salinity of the injection low-saline brine is defined at a default value of 1,873 ppm as provided by GEM Simulator. It has been assumed that the conventional HSWF is done by seawater injection, the salinity of the injection brine was defined at 40,000 ppm.

The reservoir is initially at oil-wet condition and a total of four vertical producer wells are positioned at each corner edge with an average spacing of 4920 ft between the wells while a vertical injector well is located at the centre of the model to simulate an inverted five-spot injection pattern. The production is carried out from all the four production wells with only layer 1, 2, 3, 4 and 5 perforated. It was assumed in this study that reservoir is in isothermal condition, the reservoir consists of clay minerals which are distributed by the upscaling of reservoir core data, basic cation exchange between sodium ion as dominating wettability alteration during brine injection and fault structure is not considered in the model due to the unavailability of reservoir seismic data.

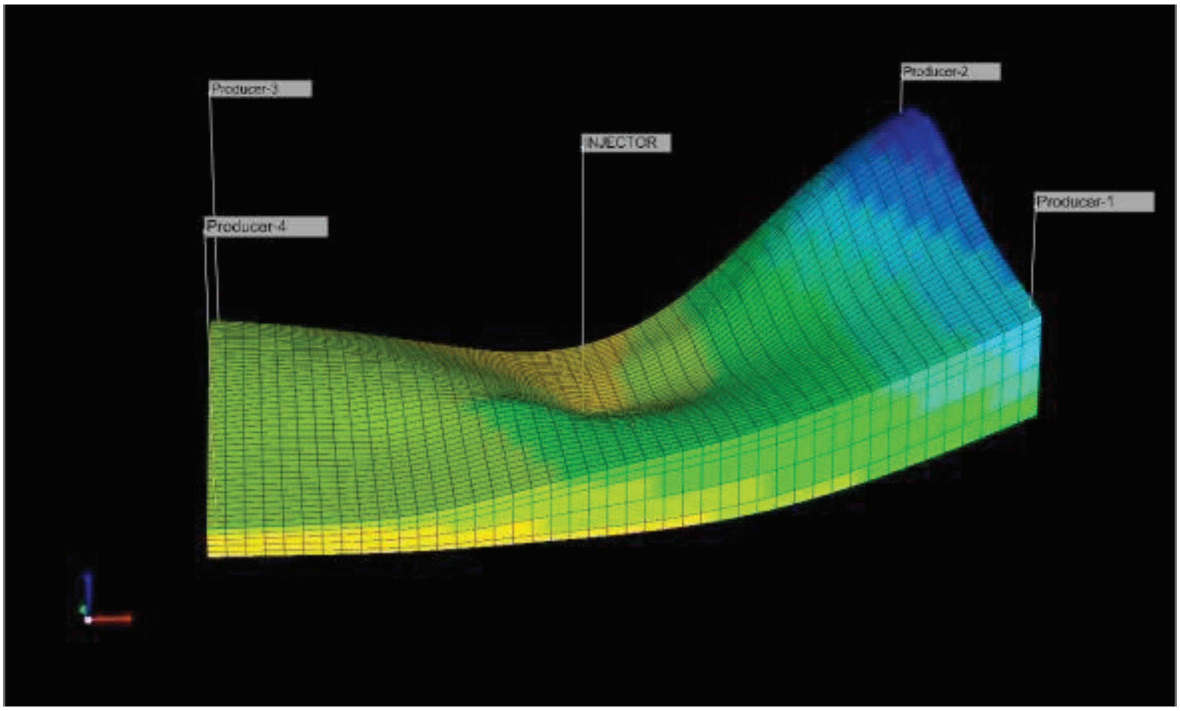

Figure 1: Field scale three-dimensional reservoir model developed using CGM'S GEM simulator.

2.2 Primary production and history matching
Upon the primary oil recovery implementation, the results of the model are matched with the historical production as closely as possible by inspecting total fluid withdrawal rates by well, and individual fluid withdrawal rates by well. The accuracy of the model is evaluated by calculating root-mean-square deviation (RMSD).

2.3 Secondary and Tertiary Oil Production Forecast
To investigate the field-scale implementation of LSWF, secondary oil recovery method is implemented to the reservoir immediately after primary oil recovery. HSWF, which is the injection of seawater and LSWF are applied distinctly and prominent reservoir production parameters are forecasted for a period of 30 years. In both the injection cases, the rate of injection of water into the reservoir is kept constant. To determine the potential benefits of LSWF for tertiary oil recovery process, seawater is injected in the reservoir model as a conventional waterflooding method then LSWF method was applied for the remaining operation time.

2.4 Sensitivity analysis
Effects of changes in various operational parameters of LSWF are investigated to determine the optimum conditions of the method to maximize oil production and recovery rate. In all the cases, when one parameter is studied, all the other parameters are kept constant.

2.4.1 Starting time of brine injection. This study is aimed to determine the best period of low saline brine injection into the reservoir for the most effective process of oil displacement. Following the base case of low saline brine injection immediately after primary production, LSWF method was introduced 5, 10 and 15 years after conventional high salinity secondary waterflooding to simulate its effect on oil recovery factor.

2.4.2 Brine injection rate on oil recovery. This simulation varies the rate of low saline brine injection into the reservoir. Upon the determination of best and optimum time of low saline brine injection, while maintaining constant composition of injection water, the rate of brine injection is appropriately increased and decreased from the base model to simulate the effects of injection rate on oil recovery obtained.

2.4.3 Injection brine composition on oil recovery. This simulation is done by studying the effect of injection brine composition on oil recovery factor. The low saline injection brine consists of three cations namely, sodium, magnesium and calcium and an anion which is chloride. Using the best time of injection, the effects of cations and anion compositions in injection brine is studied. By keeping the formation water composition and other parameters constant, the concentration of ions is slowly increased and the effect is observed by analysing the cumulative oil production obtained.

2.4.4 Effects of reservoir temperature. During the injection of low-saline brine in the reservoir, the wettability alteration of the reservoir rock from initial oil-wet to water-wet occurs due to interactions between multiple ions that are present in the water. As this is a chemical reaction, the rate of the process may be affected by changes in temperature. This study investigates the effects of reservoir temperature on wettability alteration that occurs in which the oil recovery obtained via LSWF may increase with increase in temperature.

3. Result and Discussion

3.1 Primary Production and History Matching
Based on the proposed method, the developed three-dimensional field-scale reservoir model consisting of four vertical production wells are allowed to produce naturally for the purpose of history matching. The first oil production in the field begins on January 1967. The field was naturally produced without any external aid or supply in the energy for a period of 37 years until the end of December 2003.

Initial observation of excessive water production from the model that deviates from field data was alleviated by reducing the water relative permeability. Besides, appropriate reductions on the thickness and permeability of the aquifer were done to closely match the reservoir water production. The results of history matching conducted on oil and water production for the reservoir model are presented on Figure A.2 and A.3 respectively. Based on the results, the simulated oil production matches exactly with the actual field data while small deviations are observed for water production at the end of primary oil recovery. The deviations arise due to the uncertainty of the aquifer properties that is connected to the reservoir. The calculated root-mean-square deviation (RMSD) to validate the model yielded a value of 8.2 % denoting an accuracy of 91.8 % of the simulated reservoir model against the actual field.

3.2 Secondary Oil Recovery
The injection of water is done distinctively using the methods of conventional HSWF and LSWF with injection water salinity of 40,000 ppm and 1,873 ppm respectively. These water compositions were determined based on the default values for sea water and low salinity brine composition provided in CMG's GEM Simulator. Secondary waterflooding is effectuated immediately after primary recovery beginning from January 2004 and the oil production is forecasted for a period of 26 years until December 2030. Figure 2 compares the oil production rate after the implementation of HSWF and LSWF for 26 years of the forecast.

The separate applications of secondary HSWF and LSWF following primary oil recovery improved the oil production of the reservoir as the production plateau was maintained for an additional four years compared to the case of without water injection. As suggested by the literature, the injection of water into the reservoir has provided pressure support and improved the sweep efficiency that pushes the remaining oil to the production wells [2]. It was also observed from Figure 4.5 and 4.6 that implementation of LSWF resulted in a lower drop of oil production rate and more oil was recovered that grows significant over the years compared to HSWF. The analysis was conducted by examining the cross-section of the reservoir model to have some insights of the process that occurs during water injection. Taking layer 3 of the reservoir as an example, Figure A.3 and A.4 indicates the remaining oil

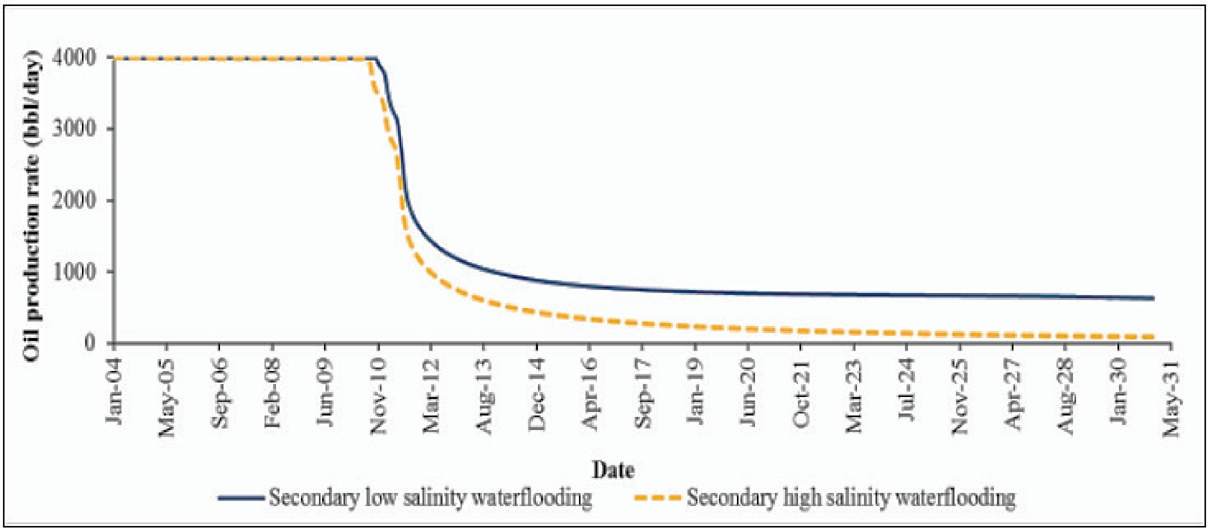

Figure 2: Oil production forecast after secondary LSWF and HSWF.

saturation after the implementation of LSWF and HSWF respectively. In all the reservoir layers, it was also observed that for the same reservoir condition and same period of implementation, LSWF has reduced the oil saturation in the reservoir more compared to conventional HSWF.

As the modelling was conducted using the technique of Na+ ion exchange as the relative permeability interpolant to catch the effects wettability alteration, the amount of Na+ ions that remains bonded with clay is analysed in the reservoir model. Figure A.5 and A.6 depicts the ion exchange equivalent fraction of Na-X in the cross-section of reservoir layer 3 for LSWF and HSWF respectively. Significant reductions on the fraction of Na-X that is, the amount of Na+ ions bonded on the clay surface is seen for the case of LSWF due to ion exchange mechanism. It is obvious that the injection of low salinity brine has created a favourable condition in the reservoir that promoted the process of ion exchange on the clay surface compared to high salinity brine injection, thus, resulting in higher oil recovery. The observation is analogous to the LSWF field scale simulation study conducted by [3] on Brugge field that suggest multicomponent ion exchange is the key mechanism of LSWF. Throughout the years, low saline brine has changed the wettability of the reservoir towards more water-wet making the immovable oil mobile again and significantly reducing the residual oil saturation.

3.3 Tertiary Low-salinity Waterflooding Response

Since conventional high salinity waterflooding seawater injection have already been implemented in the majority of sandstone reservoir currently present in the world, it is important to analyse the performance of LSWF as a tertiary recovery method if it was to be applied. LSWF was conducted after 5 years of secondary HSWF using the same brine composition. The result of oil production rate forecast for tertiary LSWF is shown in Figure A.7. During the forecast period, tertiary LSWF had a higher production rate compared to secondary HSWF baseline. This demonstrates that the application of LSWF during tertiary oil recovery could improve the production capability of an oil reservoir. However, from Figure A.7, it could be observed that secondary application of LSWF is more effective than implementing it at tertiary mode.

To further extend the study on the effectivity of LSWF as a tertiary oil recovery method, sensitivity study on the starting time of injection has been conducted in which LSWF was introduced to the reservoir at a time of 5, 10 and 15 years after secondary seawater flooding. Figure 3 compares the various injection time of low salinity brine against the oil recovery obtained. Based on the results, it can be noticed that as the injection time of low salinity brine is delayed, less oil recovery is obtained. While the application of secondary LSWF resulted in highest oil recovery, later injections of LSWF have resulted in reduced benefits of additional oil recovery obtained. This observation can be related to previous studies conducted on the effectivity of waterflooding. Firstly, for a brown reservoir which has been waterflooded for a certain period, there is a high potential for the reservoir to have low-resistance water channels that bypass the late injected water during oil production [4]. Secondly, the injection of high-salinity brine into the reservoir compresses the ionic double layer and increases clay-clay attraction making the oil to be strongly attracted onto the rock surface [5]. Time of injection is a very important criterion as it demonstrates that LSWF is most effective when it is effectuated at the first stage of secondary oil recovery compared to secondary HSWF or tertiary LSWF.

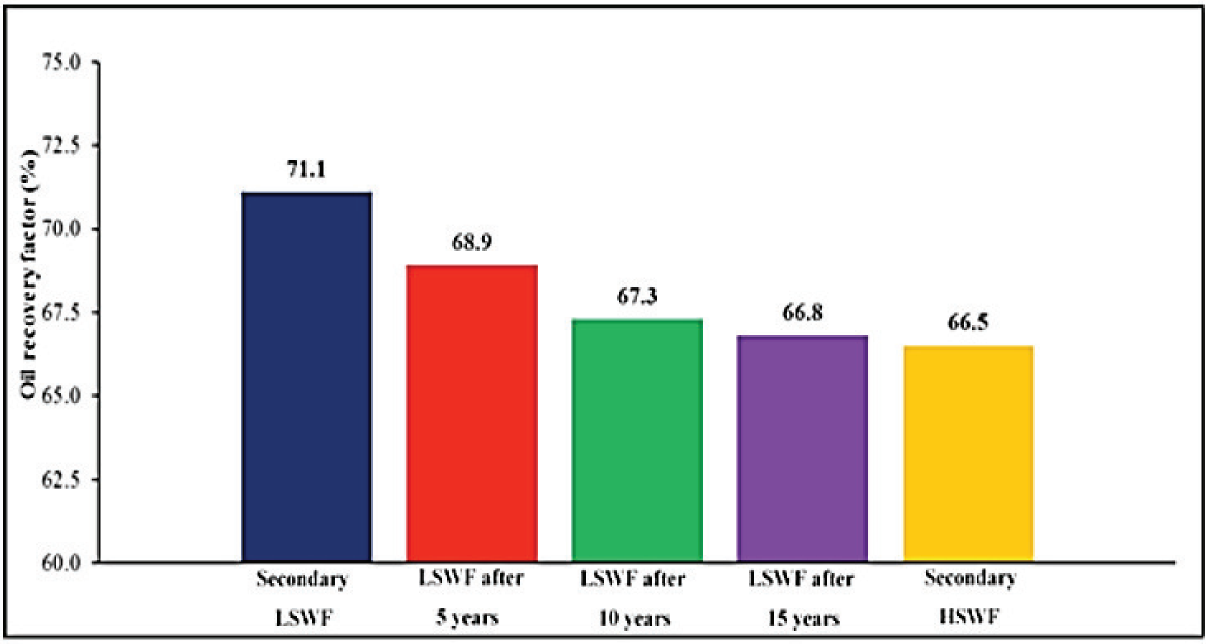

Figure 3: Comparison of oil recovery factor for different injection time of LSWF.

3.4 Injected Low-saline Brine Composition

In this study, using the base composition of low-salinity brine that was implemented into Sarir reservoir model on previous investigations of secondary and tertiary waterflooding, the concentration of an ion is varied over its range while maintaining the concentration of other ions to determine its effects on cumulative oil production. During LSWF, for a sandstone reservoir, only monovalent and divalent cations are involved in the ion exchange mechanism that alters the wettability of a sandstone reservoir. Various published reports agree and confirmed this observation during LSWF suggesting that increasing the concentration of divalent cations will result in a higher oil production. Figure A.8 and A.9 shows the effect of increasing the concentration of injection Ca2+ and Mg2+ ion respectively on the cumulative oil production.

As observed by previous researchers, increasing the concentration of Ca2+ and Mg2+ ion in the injection brine have resulted in a higher cumulative oil production. These results can be related to the observation made by British Petroleum (BP) after implementing LSWF on Alaskan sandstone reservoir. When the concentration of Ca2+ was modified from about 70 ppm to 100 ppm, 10 % additional oil recovery was obtained from the field [6]. As explained previously, when the salinity in the reservoir is reduced during LSWF, displacement and release of organic molecules or polar components from the clay surface occurs due to ion exchange mechanism. Divalent cations are able to displace oil molecules from clay surface which increases the water-wetness of the rock surface. The increase in concentrations of divalent cations in injection water promotes this process describing the incremental oil production. However, increasing the concentration of divalent cations highly may also displace H+ ions from the clay surface. When this occurs, adsorption of organic molecules onto the rock will be promoted due to the decrease in pH and water-wetness of reservoir rock will decrease resulting in only a slight increase in oil recovery [7]. This theory explains the maintenance of cumulative oil production when the concentration of Ca2+ and Mg2+ is increased beyond the optimum concentration.

3.5 Rate of Low-saline Brine Injection

This analysis is purposed to determine the behaviour of LSWF towards oil recovery when the rate of brine injection is varied. Using the previously determined optimum composition, the rate of brine injection is varied over a range while other operational parameters remain unchanged. The simulation results are shown in Figure A.10 and A.11 that indicates the change in reservoir pressure and oil recovery obtained respectively at different injection rates. Figure A.11 shows that the optimum rate of low-salinity brine injection for Sarir field is 5320 bbl/day which in fact is lower than the base rate of 6000 bbl/day for previous sensitivity study simulation runs. This result can be related to the changes in reservoir pressure and sweep efficiency during waterflooding. As the rate of brine injection increases, the reservoir pressure increases at a higher rate. However, a very high rate of injection is not necessary as it can be observed that an injection rate of 5320 bbl/day is sufficient to provide pressure support and energy for the reservoir to maintain its oil production potential.

When the injection rate is above the optimum value, although enough pressure is present in the reservoir, a lower oil recovery is obtained during the forecast period. The impact of mobility ratio starts to arise in which at high injection rates, the possibility of mobile oil being bypassed by water grows together with the initial increase in oil drainage. At this point, the end-point mobility ratio increases at a value above one implying unstable flood front. A phenomenon known as 'viscous fingering' is induced that results in inefficient displacement of oil due to an early water breakthrough [8]. Consequently, the injected water moves ahead of the displacement fronts resulting in lower oil production or oil recovery. During slower or optimum injection rate, adverse effects of mobility ratio is prevented as stable displacement front is maintained providing better sweep efficiency.

3.6 Temperature Effect on Low-salinity Process

The alteration of reservoir rock wettability towards more water-wet occurs due to multi-component ion exchange mechanism induced by chemical in-equilibrium during low salinity brine injection. Theoretically, at elevated temperatures, the rate of chemical reactions will be higher. Hence, favourable wettability alteration will also occur at a faster rate and additional oil recovery will be realised at a short period. Multiple simulation runs were conducted by increasing the initial reservoir temperature of 200 oF to a certain degree to study its effects on oil recovery achieved. The simulation result as denoted by Figure A.12 supports the theory as slight increment in oil recovery is observed at higher reservoir temperature.

The temperature on LSWF can be related to the hydration energies of different cations that involve in ion exchange that alters the wettability of reservoir rock. Hydration energy varies according to varying temperature condition and at low temperatures, divalent cations such as Ca2+ and Mg2+ are highly hydrated in water compared to monovalent cations such as Na+. At this condition, although chemical in equilibrium is induced by low-salinity brine injection, lesser divalent cations are available to displace monovalent cations and polar oil components from rock clay surface. At a high temperature condition, the reactivity of divalent cations increases due to partial dehydration prompted by disruptions in water molecule structure [9].

4. Conclusion

The application of LSWF in tertiary mode after secondary conventional HSWF yielded an additional oil recovery of 5.8%. This implies that LSWF even has an enhanced oil recovery (EOR) potential. LSWF could be a prospective substitute for chemical EOR method that is currently practised in the oil industry that develops an issue of high cost and adverse environmental impacts. From the observed results, it was concluded that the wettability alteration due to multi-component ion exchange is the primary mechanism that dictates the whole process of LSWF. It was deduced that the earlier the injection of low-salinity brine as soon as a decline in oil rate is observed, the higher the oil recovery would be. Optimization on

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the composition of injection brine is vital to maximize oil recovery via LSWF. Generally, a high concentration of divalent cations and low concentration of monovalent cation are necessary for favourable wettability alteration. Although the injection rate of 5320 bbl/day is optimum for Sarir reservoir, this may vary from one reservoir to another. The injection rate is a factor of reservoir pressure and stable flood front maintenance. As the reservoir temperature influences the wettability alteration via ion exchange mechanism during LSWF in which at an elevated temperature this process is enhanced, deep high temperature sandstone reservoir will be a prospective candidate for LSWF.

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APPENDIX A

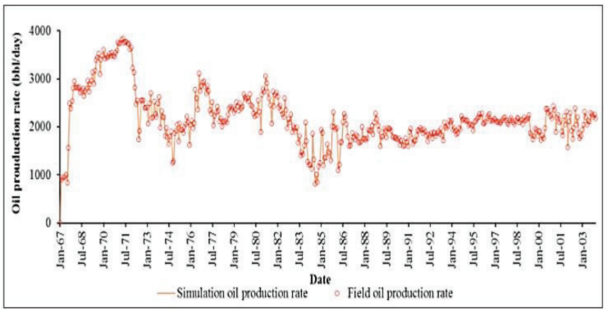

Figure A.1: Primary oil production history matching for the period of 37 years.

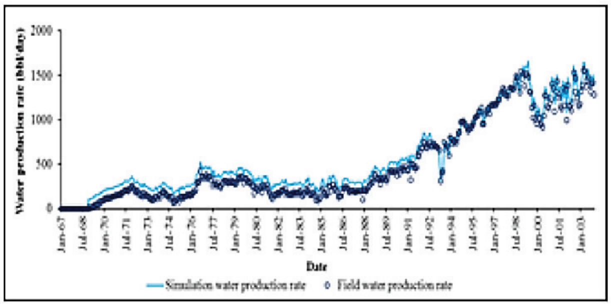

Figure A.2: Primary oil recovery water production history matching for the period of 37 years.

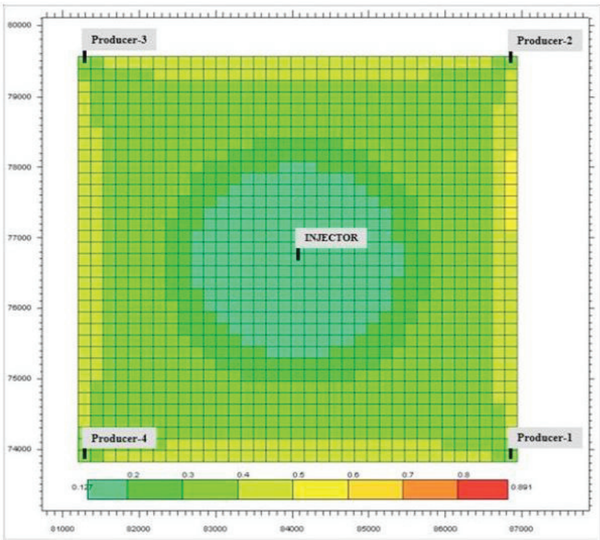

Figure A.3: Remaining oil saturation in layer 3 after implementing LSWF.

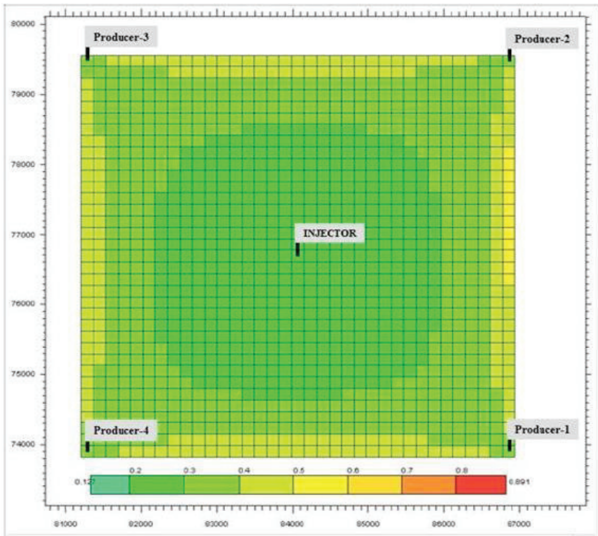

Figure A.4: Remaining oil saturation in layer 3 after implementing HSWF.

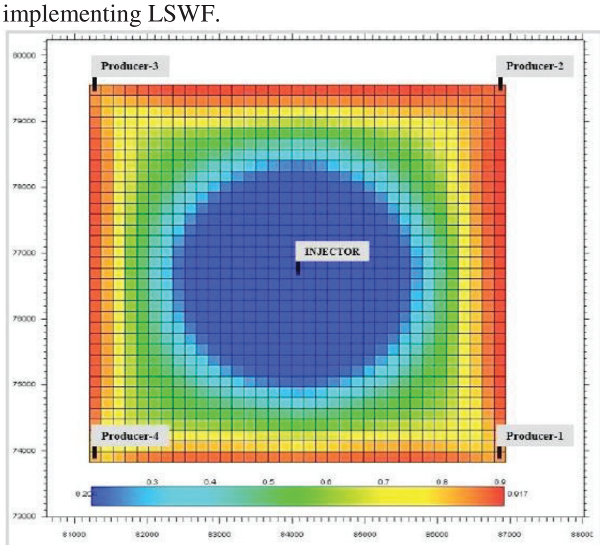

Figure A.5: Ion exchange equivalent fraction of Na-X during LSWF in layer 3.

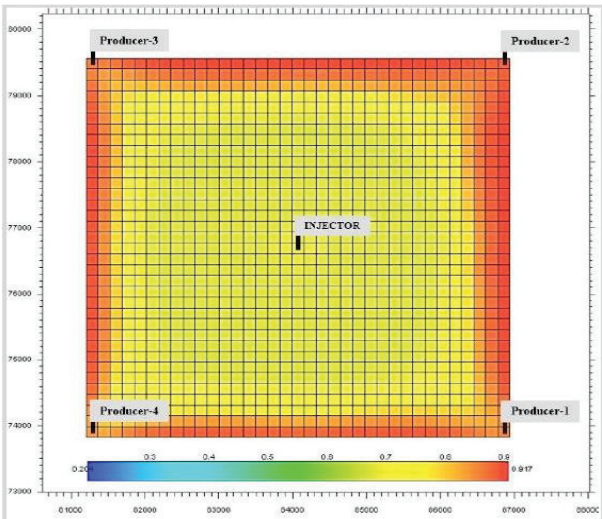

Figure A.6: Ion exchange equivalent fraction of Na-X during HSWF in layer 3.

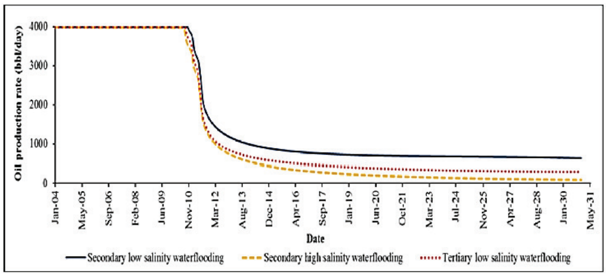

Figure A.7: Oil production forecast comparison between secondary and tertiary waterflooding.

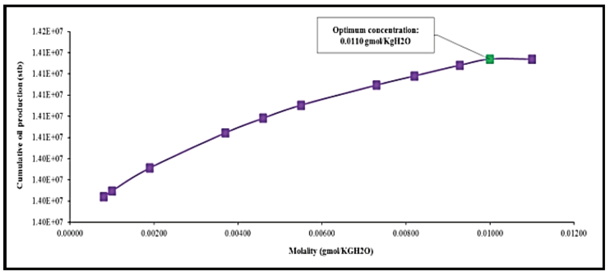

Figure A.8: Effect of injection calcium ion concentration on cumulative oil production.

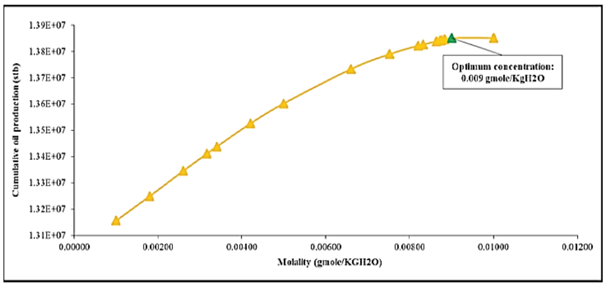

Figure A.9: Effect of injection magnesium ion concentration on cumulative oil production.

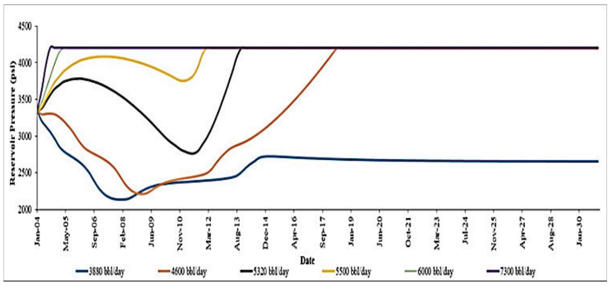

Figure A.10: Changes in reservoir pressure for different rates of brine injection.

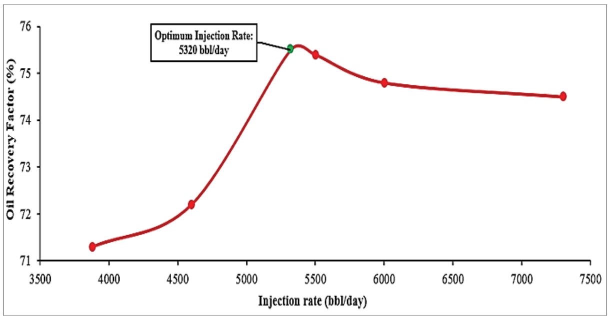

Figure A.11: Oil recovery factor for different rates of brine injection.

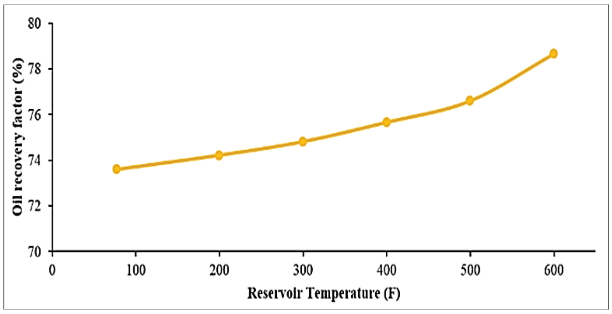

Figure A.12: The effect reservoir temperature on oil recovery during LSWF.