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Evaluation of Fines Assisted Low Salinity Water Flooding in Edge Water Drive Reservoirs

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Abstract

A common problem in edge-water drive reservoirs is inability to recover remaining oil bypassed by encroaching water from the aquifer. Early incidence of these water channels causes pre-mature water production that leads to well abandonment at high water cuts. This early water production leads to poor sweep efficiency and low recovery from the reservoirs. The goal of this study is to evaluate the effectiveness of fines migration in shutting off early water production during Low salinity water flooding in edge water drive reservoirs and consequently, determine its effects on oil recovery. Eclipse 100 (Black oil simulator) was used to model and simulate this recovery scenario and the performance is compared with two other water drive production scenarios namely: water influx and conventional water flooding. Model results showed that injecting low salinity water can yield an incremental oil recovery of 5% for the reservoir under study when compared to conventional water flooding and have prolonged life of 3.8 years and 15% recovery and prolonged life of 7.7 years when compared to the Natural depletion scenario.

Keywords: Low salinity; Edge-water drive; Enhanced oil recovery; By-passed-oil; Fines migration

Introduction

Oil recovery from heterogeneous sandstone reservoirs adjoining an aquifer is a challenge due to early water breakthrough as a result of high variation of permeability, especially with the presence of high thief zones and very low permeable zones within the same reservoir. One of the recently recommended enhanced oil recovery (EOR) techniques is fines assisted low salinity water flooding (FALSWF), which is believed to alter the permeability of the high permeable zone with entrapped mobile clay particles. The FALSWF technique has several advantages including high efficiency in displacing light to medium gravity crude oils [1], ease of injection into oil-bearing formations, availability and affordability of water, and lower capital and operating costs compared to other EOR methods, which leads to favorable economics [2].

A common problem in edge-water drive reservoirs is inability to recover remaining oil bypassed by encroaching water from the aquifer. The encroaching water from the adjacent aquifer overtakes oil phase and leaves appreciable volume of trapped residual oil behind. Early incidence of these water channels causes pre-mature water production that leads to well abandonment at high water cuts. This early water production leads to poor sweep efficiency and low recovery from the reservoirs in question. One solution to this problem is creating a barrier against the encroaching water in the zones where water had bypassed oil. Thus, in this study the possibility of using induced formation damage as a barrier to water encroachment will be investigated on Niger delta reservoirs. The main objective of this study is to evaluate the effectiveness of fines migration in shutting off early water production during Low salinity water flooding in edge water drive reservoirs and consequently, determine its effects on cumulative oil recovery, sweep efficiency and water cut will be analyzed.

Fines migration with subsequent reduction in permeability has been observed to occur as a result of decreased water salinity [3,4] increased flow velocity, and altered water PH and temperature [5]. Injection of low salinity water results in the mobilization of fine particles present in the pore walls that are not held in place by natural concentration during deposition [4]. It is from this that the traditional view that fines migration should be avoided at all cost because of its seeming detrimental effects on reservoir permeability. However, Low salinity water injection can be used in heterogeneous reservoirs to provide barrier against encroaching water in high permeable zones like any other barrier fluids and by this means improve the general producing characteristics of the reservoir. As a result provides a strategy for an effective means of preventing an early water breakthrough. The potential of this proposed recovery technique to slow down the mobility of water in edge water drive reservoirs while increasing the reservoir production characteristics makes this study worth pursuing.

Recovery from water drive reservoir is determined by the efficiency of the flushing action of the water in displacing the oil. As reservoir heterogeneity increases due to trapped oil, the recovery is expected to decrease due to uneven movement of the displacing water. The rate of water influx is normally faster in high permeability zones. This results in earlier high water-oil ratios and consequent earlier economic limits.

Research Methodology

Mechanism underlying incremental oil recovery by low salinity water flooding

Several researchers have proposed different mechanism for low salinity water flooding. Sheng [6] highlighted the seventeen suggested mechanisms of low water flooding as: (1) Fine migration [7]; (2) Mineral dissolution [8]; (3) Limited release of mixed-wet particles [8]; (4) Increased pH effect and reduced interfacial tension (IFT) [9]; (5) Emulsification/snap-off [9]; (6) Saponification [9]; (7) Surfactant-like behavior [9]; (8) Multicomponent ion exchange (MIE) [10]; (9) Double

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layer effect [11]; (10) Particle-stabilized interfaces/ lamella [8,12]; (11) Salt-in effects [13]; (12) Osmotic pressure [8]; (13) Salinity shock [8]; (14) Wettability alteration (more water-wet) [8]; (15) Wettability alteration (less water-wet [8]; (16) Viscosity ratio [8]; and (17) End effects [8]. Among them, wettability alteration, fines migration and multi ion exchange have received large supports and deemed most probable". Although, most investigations of water salinity have been channeled towards its effects on wettability, relative permeability, residual oil saturation and capillary pressure [7,14] these effects appear to be a different mechanism from the mobilization of fines but may occur simultaneously with fines migration.

Mechanism of fines mobilization

Hydration of clay particles occurs whenever clay is in contact with fresh water resulting to clay swelling issues. Also at low salt concentrations low salinity water does not eliminate clay hydration and swelling unlike at high salt concentrations. Fine migration occurs if the ionic strength of injected brine is less than a critical flocculation concentration. The critical flocculation concentration is strongly dependent on the relative concentration of divalent cations. Divalent cations lower the repulsive force by lowering the Zeta potential [6]. The injected low salinity water has lower ionic strength compared with the formation water and hence will cause dispersion of clay and silt in the formation. The clay and silt upon dispersion, flow with water. Channels or zones with least flow resistance will preferentially have high water permeability. The mobilized clay and silt particles are deposited at the narrow pore throats or small pore sizes. Deposition of clay and silt particles in these channels will lead to reduced formation permeability in the zone. Therefore water will be forced to take other flow paths. As a result, the sweep efficiency is increased.

Materials

In order to justify the technical advantage of this recovery process, the performance of the investigated recovery scenario; Fines assisted low salinity water flooding was compared to two other water drive production cases namely Natural pressure depletion which involves producing the reservoir under the natural energy supplied by the encroaching water. Natural pressure depletion is regarded as case A in this study. The second case (case B) is that of conventional water flooding, which involves injection of formation (high salinity) water.

Mapping of fines assisted low salinity water flooding on polymer flooding model

As conceived earlier, this technique of controlling water encroachment in edge water drive reservoirs by mobilizing *in- situ* fines present in the reservoir is similar to other conventional techniques which involves the use of barrier fluid such as cement, gels, resins, foams and polymers. However, from a practical point of view, the advantage of this method is that it requires relatively less capital cost and can be readily incorporated into existing polymer simulator without the need of developing new software or modifying the current simulators.

Following Nguyen et al. and Zeinijahromi et al. [4,5] we transformed the model for water- oil flow into the system of equations for polymer flooding in the simulator used. From the polymer flooding model, it is assumed those oil and water phases are incompressible which leads to the volume conservation for the total 2- phase flux. The volume concentration for incompressible aqueous phase which is immiscible with oil is modeled with the system of equations used to modify the simulator.

Model description

A synthetic 3D Cartesian reservoir was modeled. The model consists of 4 layers with varying permeability. The model dimension is 3850 ft × 3850 ft × 200 ft. The number of cells in the x, y and z direction are 11, 11 and 4 respectively. Each grid size measures 350 ft × 350 ft × 50 ft. total number of cells in this block centered geometry is 484. Oil and water are the only flowing fluid in the reservoir. The flow rate of the producer and injectors in the two injection cases are set at 4,000 STB/day and 4,000 STB/day respectively while the production rate for the natural water driven case is 4,000 STB/day. The production time in the simulation was set to 32 years

Model development

Eclipse 100 black oil simulator was used to execute this work. The PVT properties of the selected fluid phases (oil and water) were input into the simulator. The PVT data for oil was sourced from a differential liberation test data conducted on oil samples obtained from Field X in Niger delta region. The reservoir model data is as presented in Tables 1 and 2 gives the PVT data. To account for the effect of surface separation on the basic PVT parameters, the lab PVT data were input into the eclipse correlation interface to generate the corrected PVT parameters for the case under study. The results obtained are presented in Table 3.

Special core analysis (SCAL) section accepts the input of saturation dependent parameters such as relative permeability and capillary pressure. In this study, both oil and water are active phases, thus, their relative permeability data was generated from Eclipse inbuilt empirical correlation. Presented in the Figure 1 is the oil-water relative permeability curve for the reservoir system based on the initialized data set.

Production schedule

With the built reservoir model, a five spot well pattern was used to evaluate the reservoir performance under different production schemes. Three production scenarios were considered; case A, case B and case C. In the Natural depletion scenario (Case A), only one well was specified, this well was completed over a length of 100 ft and is allowed to produce under the influence of its natural energy only. The Conventional water flooding is the second case (Case B) In the Fines assisted Low salinity water flooding scenario (Case C), the reservoir is made to produce through one (1) producer and four (4) injectors forming the regular five spot pattern/ arrangement, the injected low salinity water provides pressure maintenance and also mobilizes fines which reduce water relative permeability in order to extend breakthrough time. 3D view of the model is shown in Figure 2.

The number of wells and well pattern is the same as in Cases B and C, the only distinction between Case B and Case C is the salinity of the injected water. The water injection in cases B and C is assumed to begin at day 1 of production.

Production constraints/variables

The following variables/ constraints show in Table 4 were applied to the various specified wells (production and Injection).

Results and Discussion

The reservoir studied has a rectangular geometry and is connected to an active aquifer from the edges (Figure 3). The reservoir contains 65 490 686 STB of Oil with water saturation of 54%. Reservoir and fluid properties in the three (3) cases modeled are identical. Results of the simulation runs for the three production scenario are as presented in the Figures 4 - 6 below and Table 4.

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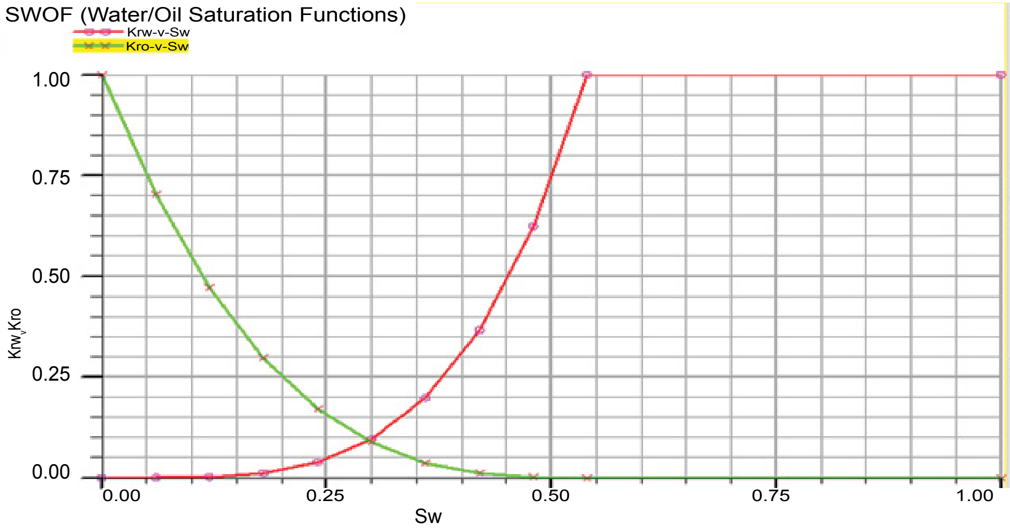

Figure 1: Chart showing oil-water relative permeability curve.

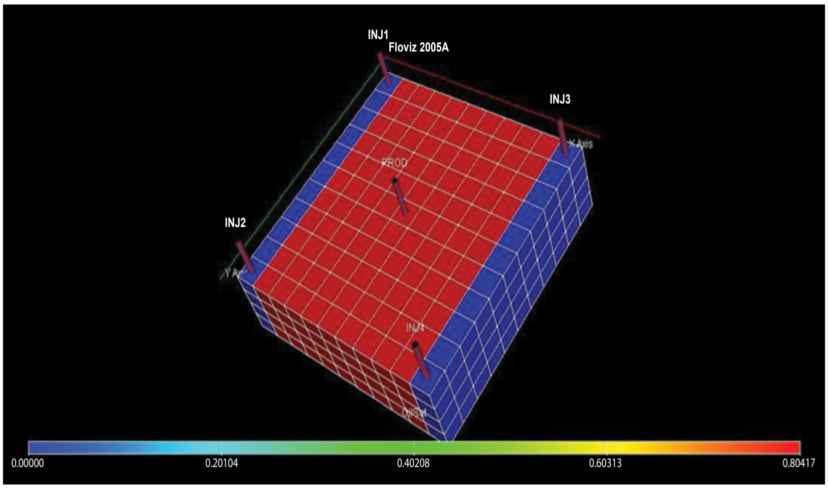

Figure 2: 3D model showing a saturation reservoir bounded with edge water for Cases B and Case C.

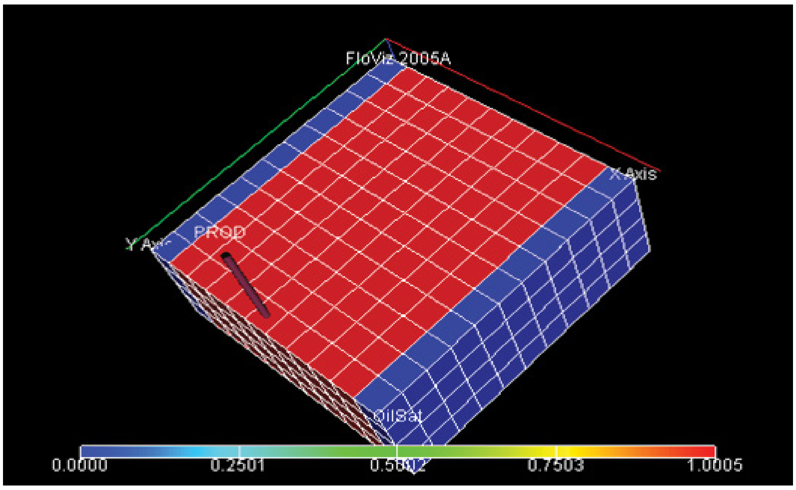

Figure 3: 3D model showing saturation reservoir bounded with edge water for Case A.

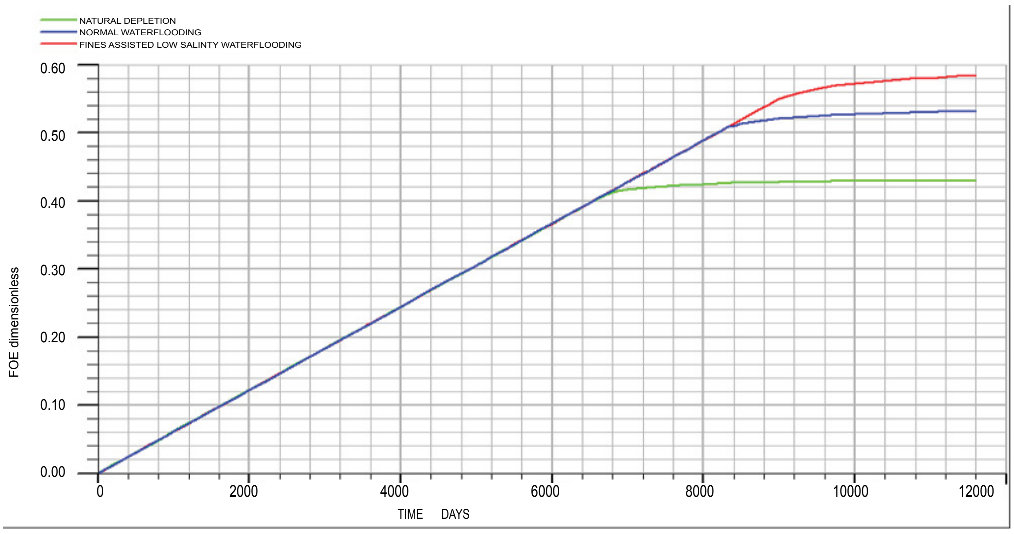

Figure 4: Comparison chart of the field oil recovery efficiency for the three (3) cases.

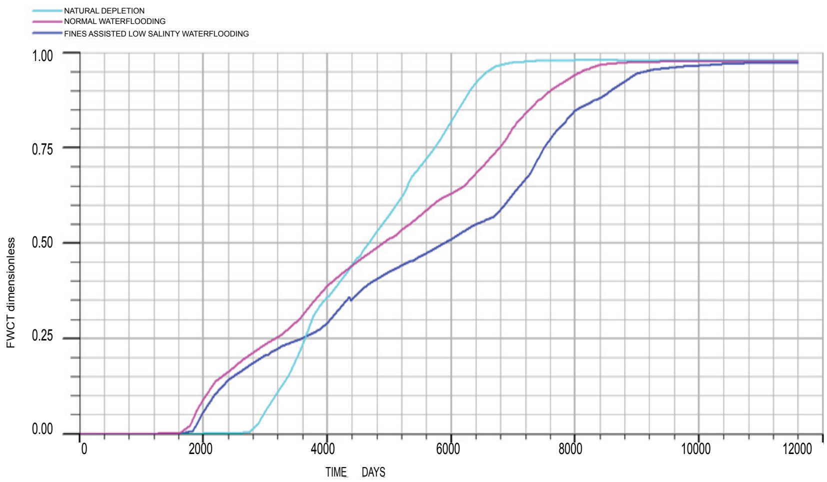

Figure 5: Comparison chart of the field water cut for the three (3) cases.

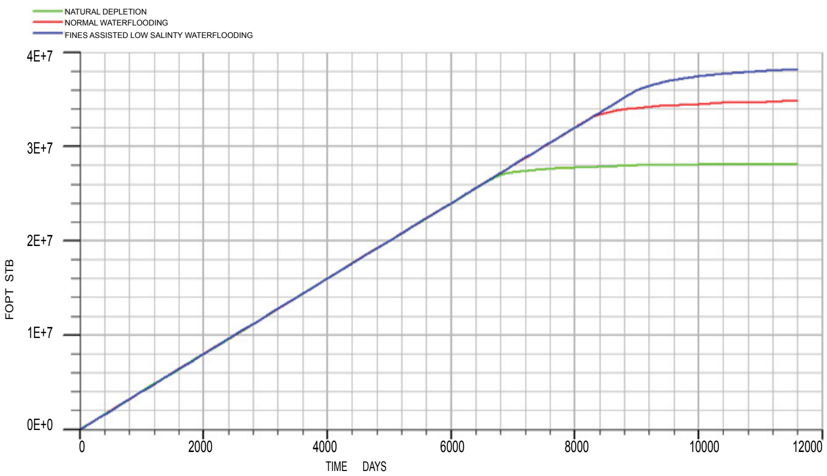

Figure 6: Comparison chart of field oil production total for the three (3) cases.

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Parameters	Layer 1	Layer 2	Layer 3	Layer 4
No of Blocks	121	121	121	121
Reservoir Top Depth	8500 ft	8550 ft	8600 ft	8650 ft
Layer thickness	50 ft	50 ft	50 ft	50 ft
Porosity	25%	25%	25%	25%
Permeability X	700 md	1000 md	800 md	1000 md
Permeability Y	700 md	1000 md	800 md	1000 md
Permeability Z	70 md	100 md	80 md	100 md

Table 1: Eclipse model parameters.

Properties	Values
Initial water Saturation	0.25
Water saturation (base case)	0.54
Residual Oil Saturation (base case)	0.46
Water Viscosity	0.3501681cp
Oil Density	51.45684 lb/ft^3
Water Density	62.43071 lb/ft^3
Water Compressibility	2.4993894 E^{-6}
Reference Pressure	5500 psia
Bubble point pressure	4548 psia
Reservoir temperature	204^{o}F

Table 2: PVT properties.

Row Press (psia)	FVF 6b /stb)	Visc (cp)
4548	1.6695698	0.256751
4736.8421	1.667724	0.260974
4947.3684	1.6621762	0.26586
5157.8947	1.6570975	0.270922
5368.4211	1.6524308	0.276148
5500	1.6497017	0.279494
5789.4737	1.6441482	0.287056
6000	1.6404563	0.292716

Table 3: Dead oil PVT properties (Generated from correlation).

Well / Constraints	Prod	Inj 1	Inj 2	Inj 3	Inj 4
Wellbore ID, ft	0.5	0.5	0.5	0.5	0.5
Perforation thickness, ft	150	50	50	50	50
Perforated layers	1 - 3	4	4	4	4
Surface Rate, STB/ day	4000	1000	1000	1000	1000
BHP Target, psi	1000	6000	6000	6000	6000

Table 4: Summary of production constraints.

Comparison of the three cases for Field Oil Efficiency (FOE)

Figure 4 presents the field oil recovery efficiency for the three production scenarios. As can be seen, the field oil Efficiency for the three cases is approximately the same for the first 4000 days (approx. 11 years) of production (Table 5). The drastic drop in the Recovery Factor for the Natural drive case is due to high water production. The well watered out at 6700 days. Oil recovery efficiency for depletion case is 43%, conventional water flood technique is 53% and that of fines assisted water flooding is 58%. These were achieved after 11,600 days of production. Following the result shown in Table 6, the incremental oil recovery (IOR) of Fines Assisted Low salinity water flooding as compared to Normal water flooding and depletion case are given as 5% and 15% respectively.

Water breakthrough time and productive life

As can be seen from Figure 5, case B (conventional water flooding) started water production at about 1600 days from start of production; Case C (FALSWF) started making water from 1800 days from start time. This early water production is caused by additional water injection compared to natural water influx in case A where water production commenced at about 2700 days (Green line in Figure 5) water production started at 1600 days in the case of conventional water flooding and at 1800 days in case of fines assisted water flooding. The fines assisted technique has difference of 200 day to produce without water over the conventional water flooding case. The productive life observed from the cases are 18.6 years, 22.5 years and 26.3 years respectively for depletion case, conventional and low salinity water flooding. This means more oil production since the oil production rate is the same. A prolonged life of 77 years and 3.8 year over depletion case and conventional water flooding was recorded respectively.

Comparison of the three cases for Field Water Cut (FWCT)

In Table 5, the summary of the FWCT for the three cases read off from the plot in Figure 5 after 11 years of production is presented. As seen in Table 5, the producing field water cut for case C (Fines Assisted Low salinity water flooding) is as low as 29%, this is obviously small compared to the two other cases ; 35% and 39% respectively for case B and A. This positive result could be attributed to the mobility control caused by permeability reduction with respect to water due to detachment and straining of fines in the pore throat.

A close observation of the FWCT curves Figure 5 for the depletion case reveals that a better control of water was achieved in the first 2750 days (approx. 7.4 years) as compared to cases B and C. However, this benefit is largely outweighed by the steady and drastic increase in the FWCT beyond 2800 days and the relatively low recovery factor after 11,600 days of production. Beyond 2800 days of production, Fines Assisted Low salinity water flooding offers a better control on water production over the two other cases until the end of 11, 600 days where they overlap (Figure 5).

Comparison of the three cases for Field Oil Production Total (FOPT)

In order to correlate the effects of delayed water breakthrough by Fines migration in the reservoir on the cumulative Oil recovery, the plot in Figure 6 was generated.

Figure 6 compares the field oil production total for three cases. This plot shows that creating permeable barriers by injection of Low Salinity Water results in a higher cumulative oil recovery (FOPT) compared to other recovery cases considered. In essence, 38.26 MMSTB of cumulative oil was recovered from the initial 65.49 MMSTB of oil originally in place using Fines Assisted LSWF. This figure represents

Cases	Scenario	RF (%)	FWCT (%)	Cum REC (MMSTB)
A	Natural Edge Water drive	24	39	16.06
B	Conventional Water Flooding	24	35	16.06
C	Fines Assisted LSWF	24	29	16.06

Table 5: Simulation results for the three (3) cases after 4000 days (approx. 11 years) of production.

Cases	Scenario	RF (%)	FWCT (%)	Cum REC (MMSTB)
A	Natural Edge Water drive	43	97	28.07
B	Conventional Water Flooding	53	97	34.86
C	Fines Assisted LSWF	58	97	38.26

Table 6: Simulation results printed after 11, 600 days (approx. 32 years) of production.

approximately 58% recovery Efficiency. While the conventional water flooding recovered 34.86 MMSTB of the total oil in place representing about 53% recovery Efficiency, the depletion (Natural water drive) case yielded the least recovery of 28.07 MMSTB representing just 43% of the total oil in place.

Effect of fines assisted low salinity water injection on permeability

Based on the recovery contrast between low salinity water injection and conventional water flooding, it could be inferred that the ability to recover oil in the low permeable zones is due to restricted water mobility in the high permeable zones. This restricted mobility is caused by trapped fine particles in these zones. The report of Kia et al. [15] agreed with this result. The study reported that flooding sandstones previously exposed to high brine with fresh water resulted in the release of clay particles and subsequent reduction in permeability. Increment in oil recovery due to fines mobilization has also been confirmed by Tang and Morrow [7].

Validation of model results

We used the reports of previous work to validate our results. In a similar study carried out by Zeinijahromi et al. [5], which involves injection of slug of low salinity water into structurally low wells to create a permeable barrier, an incremental oil recovery of 4.5% compared to depletion (natural drive) case was obtained following a prolonged well's life of approximately 4 years. This incremental oil recovery is low compared to the 15% additional oil and prolonged life of 7.7 years obtained in this study, this discrepancy may be attributed to the fact that the injection of low salinity water in this study is "continuous" as opposed to the "slug" approach used in Zeinjahromi et al. [5]. Thus, in this present study, the injected water provides both additional recovery energy and control on the water (displacing fluid) permeability. Accordingly Farzin et al. [16] in an experimental work with limestone cores showed an incremental oil recovery of 8%.

Also, in McGuire et al. [9], field trial of low salinity water injection on four wells consisting of single well chemical tracer test showed incremental oil recovery rates from 8% to 19%. Results of this field study is in close agreement with the 5% incremental oil recovery compared to Normal water flooding obtained in this present study.

Conclusion

There were three cases considered in this study, the natural depletion, conventional water flooding and fines assisted low salinity water flooding. The first two models were not modified to account for variation in salinity of the injection water.

Laboratory observations and analytical equations have been used to demonstrate that fines mobilization can lead to permeability reduction as a result of variation in water salinity. There is rapid water breakthrough during water flooding resulting to high water cut in the producing wells and lower volumetric sweep efficiency especially in heterogeneous reservoirs like the one considered in this work. This problem can be solved by either increasing the viscosity of the injected water or by lowering the permeability to water in the swept zones behind the flood front with mobilized fines. This will reduce the fraction flow of water in the reservoir and ultimately lower the water cut. Fines detachment, mobilization and straining caused by low salinity of the injected water may be responsible for the mobility control and increase in water flood recovery over the other cases considered in this study.

The simulator on its own does not have the ability to differentiate between low and high salinity, but it was modified based on the work of Nguyen et al. and Zeinijahromi et al. [4,5,17]. We transformed the model for water- oil flow into the system of equations for polymer flooding in Eclipse. These model equations were mapped into the polymer model of the simulator used in this work to study the effect of induced fines mobilization and trapping on water flooding. This approach is supported by the works of Lemon et al. [18] and Zeinijahromi et al. [5,17]. Fines assisted low salinity water flooding has been used to delay water production reduce water cut and increase efficient oil displacement. Other advantages of FALSWF include ease of injection into oil-bearing formations, availability and affordability of water, and lower capital and operating costs. The use of FALSWF has reduced the challenge of by-passed oil in the reservoir by creating permeability barriers along high permeability zones and reversing the direction of flow to mobilize any by passed oil.

The following results were drawn from this study:

i. Creation of permeable barriers by injection of low salinity water results in extending the water breakthrough time for the reservoir under study by 2 years. The performance report showed that the cases B and C from 4400 days to economic limit produced less water than case A. with best performance from case C, reduction in water permeability prolonged the field life than other production schemes used in this study. These are shown in Figure 5.

ii. The productive life observed from the cases are 18.6 years, 22.5 years and 26.3 years respectively for depletion case, conventional and low salinity water flooding. This means more oil production since the oil production rate is the same. A prolonged life of 7.7 years and 3.8 year over depletion case and conventional water flooding was recorded respectively.

iii. In this study oil recovery from natural depletion was 43% while recovery from fines assisted low water salinity injection was 58% giving an incremental oil recovery of 15%.

iv. An incremental recovery of 5% was recorded using Fines Assisted LSWF relative to conventional Water Flooding (high salinity water injection). This seeming good result is not unconnected with the success of these recovery techniques in slowing down the mobility of water and thereby imposing a relatively uniform propagating displacement front.

v. On the basis of the premises above, Case C (Fines assisted Low salinity water flooding) could be said to be technically viable if conditions permitting its application are present. However, economic analysis will offer a better justification of this recovery technique for the purpose of application.

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