EXPERIMENTAL STUDIES OF LOW SALINITY WATER FLOODING AND INTERPRETATION BY SIMULATION FOR LOW PERMEABILITY SANDSTONE

Quan Xie; Jiazhong Wu; Qingjie Liu

State Key Laboratory of Enhanced Oil Recovery·Research Institute of Petroleum Exploration and Development of CNPC,
Beijing, China

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Avignon, France, 8-11 September, 2014

ABSTRACT

The screening criteria of low salinity water flooding (LSWF) are proposed and implemented in sandstone. However, the recovery of low salinity water flooding is not always obtained from both coreflood experiments and oil fields. The mechanisms behind enhanced oil recovery of LSWF are still uncertain. The objective of this study is to present an investigation on the relationship between rock wettability and oil recovery with LSWF in secondary and tertiary mode in low permeability sandstones. Coreflood experiments were implemented at 65℃ with two different wettabilities ranging from water- to oil-wet. Relative permeability curves were obtained by history matching experimental production and differential pressure across cores at core scale through ECLIPSE 100. Piston-like displacement was found for high salinity water flooding as the core was water-wet, while the oil was produced over much longer periods for high salinity water flooding as the core was oil-wet. The estimated relative permeability curves showed that the reservoir core which was oil-wet in the high salinity became water-wet during the low salinity flooding. Nevertheless, there is no fundamental wettability change for the water-wet rock after low salinity flooding under tertiary mode. Additionally, 10.0% incremental recovery was achieved by LSWF for the oil-wet rock under tertiary mode. But only 3.4% recovery growth was observed by LSWF for the water-wet rock. It is concluded that the low salinity water altered the wetting state of the reservoir core. The application of LSWF in oil-wet reservior has more potential to enhance oil recovery. The incremental recovery can be explained by the interactions between the rock type, oil components, formation brine and injected brines.

INTRODUCTION

Waterflooding technology has been the most successful approach to improve oil recovery. The key point to reach this success of waterflooding is that the differential pressure can be formed by the water injection which is necessary to displace oil out of formation. And also, Waterflooding involves much lower cost investment and convenient operation. However, it was found that water chemistry and salinity level have a significant influence on oil recovery during the past decade from the experiments in laboratories and field trials [1, 2]. In recent years, several mechanisms were proposed to account for how low-salinity waterflooding can recover additional oil. (1) Fines migration and clays swelling caused by low salinity waterflooding [3, 4]. (2)Multi-component ionic exchange between the rock minerals and the injected brine [5, 6] . (3) Expansion of the double layer [7]. The general agreement among researchers is that low salinity waterflooding cause reservoirs become more water-wet. Even though different mechanisms have been proposed to explain the wettability alternation, the primary mechanisms are still uncertain. In this paper, the low salinity EOR-effect was investigated in low permeability sandstone under secondary and tertiary mode and relative permeability curves were acquired by history matching through ECLIPSE 100.

EXPERIMENTAL

Materials

The core plugs for coreflood experiments were extracted from the Chang Qing oilfield and outcrop in Chang Qing. The content of clays was analyzed by X-ray test to unveil the importance of the clays on the low salinity EOR-effect in low permeability reservoirs (Table 1). The reservoir cores were rich in clays, which was more than 23% in total. 90% quartz and 4.2% clay content were observed from the outcrop core plugs. The composition of the outcrop indicated that it would be water-wet. Synthetic formation water was used in the coreflooding experiments. The composition of the formation brine (high salinity) and low salinity water were given in Table 2. The total salinity of the brine water was 57114mg/L with the concentration of Ca^{2+} and Mg^{2+} at 2460mg/L and 317mg/L, respectively. The density of oil sample was 0.81g/cm^3 at temperature of 65℃. The oil sample viscosity was 9.0 cp, and the composition of the oil used in the experiments can be seen from Table 3.

Coreflood

A Quizix-SP-5400 pump with the accurate control at the constant low flow rate was set up in the flooding system. All of the coreflood experiments were conducted under 65℃. The parameters of the core plugs were given in Table 4. The experimental procedures adopted in this paper are given as below. 1) Core plugs of approximately 2.5 cm in diameter were cut from the whole core, which was drilled from the reservoir with formation brine. 2) The core plugs were evacuated for 10 hours, and then were saturated with formation brine for another 10 hours at room temperature. The porosity of the core was calculated from the bulk volume of the rock and the weight difference between dry weight and the weight of core saturated with formation brine. 3) Afterwards, the initial water saturation (i.e. irreducible water saturation), Swi was established by injecting 2.0-2.5 PV of mineral oil with the viscosity at 15.5 mPa.s in room temperature in each of the direction. It was injected at a rate of 0.01 mL/min with a net confining pressure not exceeding 3 MPa under room temperature. The weight of the cores before mineral oil displacement was measured to calculate the Swi. 4) Then, the core plugs were flooded by the crude oil under 65℃ to displace mineral oil out of the porous media. The cores were put inside of the oven at temperature 65℃ for four weeks to restore the wettability. 5) Ultimately, the core plugs were flooded with formation brine and low salinity water with flow rate at 0.025 ml/min at the 65℃ to obtain S_{orw}. The volume of oil displaced by the formation brine and the weight of the core before brine displacement were measured to calculate the oil recovery factor.

History Matching for Relative Permeability Curves

A two-dimensional homogeneous permeability core model was established to simulate the characteristics of oil recovery by forced imbibition with the finite difference simulator ECLIPSE 100. Cross-sectional area and length of the experimental core model were reproduced to the core model. There are 22 equal-sized grid blocks in the core model. The first grid which was located at the upstream of the core was saturated with 100% formation brine with 100% porosity, but 1000 D permeability was assigned to simulate the experimental injection. The last grid at the outlet of the core was saturated 100% oil with 0.001% porosity and 1000 D permeability since at beginning of the forced imbibition the outlet of the core was filled with 100% experimental oil. Porosity and permeability of each of the grid except of grids at the both sides was assumed to be equal and was obtained by core-scale experiment. The summary of composite core model for four experiments was given in Table 4 and Table 5.

RESULTS AND DISCUSSION

According to the outcrop coreflood experiments, Fig. 1 and Fig. 2 indicated that slight low salinity EOR-Effect was observed from low salinity waterflooding under secondary and tertiary mode. Fig. 1 shows that 50% oil recovery of OOIP was obtained by the high salinity waterflooding under secondary mode. Additional 3.4% oil recovery of OOIP was observed by low salinity waterflooding under tertiary mode. Relative permeability curves illustrated that the wettability of the outcrop is preferential to water-wet and no wettability change during the low salinity waterflood was observed (Fig. 5). Coreflood in the outcrop verified that low salinity effect may not work in the water-wet reservoirs. However, on the basis of reservoir coreflood, Fig. 3 and Fig.4 showed that the low salinity EOR-Effect was observed at both secondary and tertiary mode. Low salinity waterflood can recover about 10% oil recovery of OOIP during tertiary and secondary mode. Fig. 6 also indicated that relative permeability for low salinity waterfood moves toward to the right, which demonstrated the variation of the wettability of the rock. From the relative permeability curves (Fig. 6), the reservoir rock was oil-wet at the initial state during the high salinity waterflooding, but it was transformed to be water-wet state as followed by the low salinity waterflooding. This coreflood phenomenon proved that the great potential of low salinity waterflood effect may be observed as the reservoir is oil-wet initially. With comparison of Fig. 1 and Fig. 3, piston-like displacement was found for high salinity water flooding as the core was water-wet, while the oil was produced over much longer periods for high salinity water flooding as the core was oil-wet. Moreover, piston-like displacement was observed in the low salinity water flooding in the oil-wet rock under secondary mode (Fig. 4), which can be explained by the variation of wettability during the low salinity waterflood. The influence of capillary pressure on the history matching was considered, but it was found that the capillary pressure plays minor role in the history matching compared to the relative permeability in the low permeability coreflood.

CONCLUSION

In this study, the influence of rock wettability on the low salinity EOR-Effect was investigated by coreflood and history matching through ECLIPSE 100. Several observations were made in this study.

- Piston-like displacement was found by high salinity water flooding as the core was water-wet, while the oil was produced over much longer periods for high salinity water flooding as the core was oil-wet.
- Slightly wettability change and additional oil recovery were observed during the low salinity waterflood in the water-wet outcrop rock
- Low salinity EOR-effect was observed during the low salinity waterflooding at both secondary and tertiary mode in the oil-wet reservoir rock.

ACKNOWLEDGEMENTS

We greatly appreciate the constructive and helpful comments from Andrew Fogden. This paper was funded by the China National “973” Project with the title-“Mechanisms Investigation of Ions Tuning Water Flooding to Enhance Oil Recovery” and the Project Number is 2012CB723601.

REFERENCES

1. Suijkerbuijk, B., et al. The Development of a Workflow to Improve Predictive Capability of Low Salinity Response. in 6th International Petroleum Technology Conference. 2013.
2. Shaikh, M. and M. Sharifi, Investigation of Optimum Salinity of Injected Water in Carbonate Reservoirs using Wettability Measurement and Core Flooding, in SPE Reservoir Characterisation and Simulation Conference and Exhibition2013, Society of Petroleum Engineers: Beach Rotana Hotel, Abu Dhabi, UAE.
3. Sohrabi, M. and A. Emadi, Visual Investigation of Oil Recovery by Low Salinity Water Injection: Formation of Water Micro-Dispersions and Wettability Alteration, in SPE Annual Technical Conference and Exhibtion2013, 2013, Society of etroleum Engineers: New Orleans, Louisiana, USA.
4. Morrow, N. and J. Buckley, Improved Oil Recovery by Low-Salinity Waterflooding. Journal of Petroleum Technology, 2011. **63**(5): p. 106-112.
5. Lager, A., et al., Low Salinity Oil Recovery-An Experimental Investigation1. Petrophysics, 2008. **49**(1).
6.A.Lager, K.J.W., C.J.J.Black, M.Singleton, K.S.Sorbie, Low salinity oil recovery-an

experimental investigation. SCA2006-36, 2006.
7. Nasralla, R.A. and H.A. Nasr-El-Din, Double-Layer Expansion: Is It A Primary Mechanism of Improved Oil Recovery by Low-Salinity Waterflooding?, in SPE Improved Oil Recovery Symposium2012, Society of Petroleum Engineers: Tulsa, Oklahoma, USA.

Table 1 Mineralogy of the experimental core plugs

Sample	Relative content of clay minerals（%）				Mineral types and content（%）				Total clay minerals（%）
	I/S	I	K	C	quartz	potassium feldspar	plagioclase	calcite	
Outcrop	25	25	5	45	92.8	/	1.4	1.6	4.2
Reservoir core	32	12	28	28	43.2	11.9	20.9	0.4	23.6

Note: I/S, I, K and C denote illite/smectite, illite, kaolinite and chlorite, respectively.

Table 2 Composition of the formation brine and ions tuning water (ITW)

Sources	Ingredients（mg/l）					Total salinity (mg/l)
	K^++Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	
Formation brine	19249	2460	317	308	34780	57114
Low salinity brine	1924.9	246	31.7	30.8	3478	5711.4

Table 3 Ingredients of the oil sample from Changqing Oilfield

Ingredients	Saturated hydrocarbon	Aromatic hydrocarbon	Non-hydrocarbon	Asphaltic bitumen
wt%	65.05	23.30	6.68	4.97

Table 4 Summary of composite core model for four experiments

Properties	Outcrop		Reservoir cores	
Samples	OC-2#	OC-3#	RC-1	RC-2
Flooding sequences	HS + LS	LS	HS + LS	LS
Porosity	0.136	0.140	0.129	0.123
Kw (mD)	0.331	0.340	0.92	0.82
Pore volume (cm^3)	4.770	4.810	4.3665	4.2029
Length (cm)	7.115	6.990	6.867	6.927
Diameter (cm)	2.504	2.504	2.5059	2.5068
Bulk volume (cm^3)	35.03	34.37	33.849	34.170
Cross sectional area (cm^2)	4.924	4.917	4.9292	4.9328
Grid block dimensions	20 × 1 × 1	20 × 1 × 1	20 × 1 × 1	20 × 1 × 1
Width (cm)	0.35575	0.34955	0.34335	0.34635
Height (cm)	2.219009	2.217431	2.2202	2.2210

Table 5 Summary of composite core model for four experiments

Properties	Outcrop		Reservoir cores	
Samples	OC-2#	OC-3#	RC-1	RC-2
Flooding sequences	HS + LS	LS	HS + LS	LS
no	2.2	2.1	5.2	3.2
nw	6.2	6.3	3.1	4.8
Krwro	0.09	0.09	0.35	0.2
Krocw	1.0	1.0	1.0	1.0
Residual oil saturation (Sorw)	0.363(HS) /0.331 (LS)	0.339	0.412	0.382
Connate water saturation (Swc)	0.268	0.291	0.322	0.315

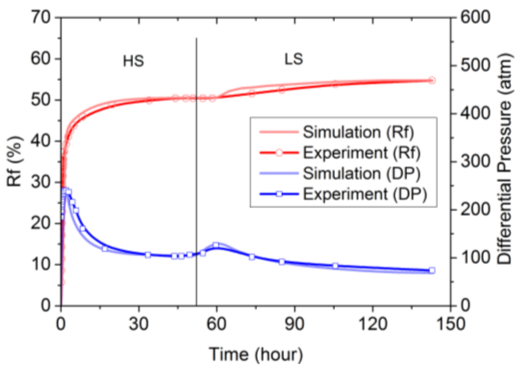

Fig. 1 Low salinity waterflooding under tertiary mode with the core from outcrop (water-wet)

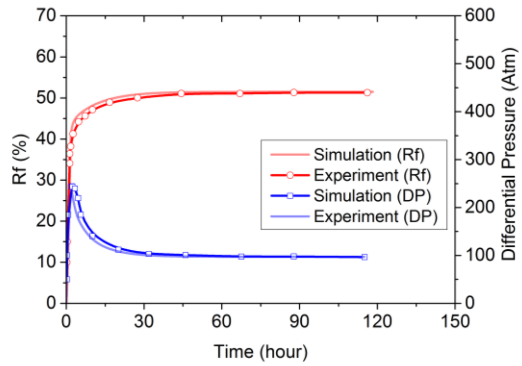

Fig. 2 Low salinity waterflooding under secondary mode with the core from outcrop (water-wet)

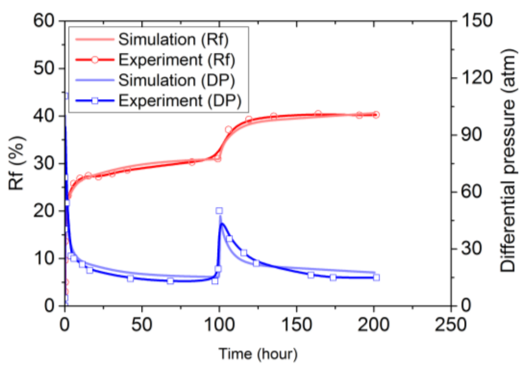

Fig. 3 Low salinity waterflooding under tertiary mode with the core from the reservoir (oil-wet)

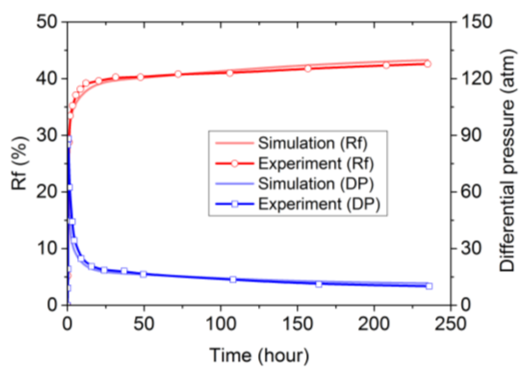

Fig. 4 Low salinity waterflooding under secondary mode with the core from the reservoir (oil-wet)

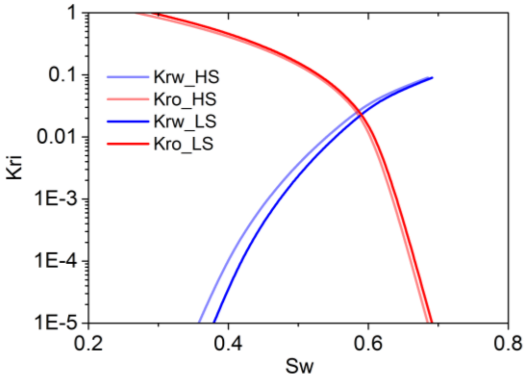

Fig. 5 Relative permeability curves of low salinity and high salinity waterflooding (outcrop, water-wet)

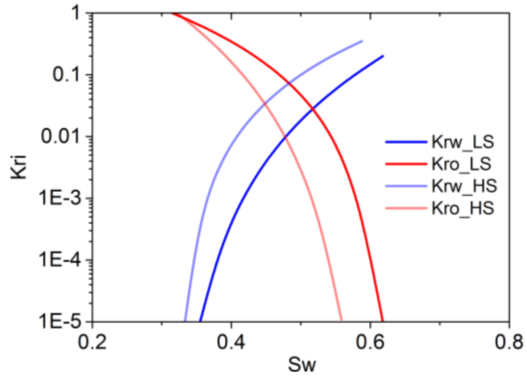

Fig. 6 Relative permeability curves of low salinity and high salinity waterflooding (reservoir, oil-wet)