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Mechanisms behind low salinity water injection in carbonate reservoirs

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HIGHLIGHTS

- History matching of recently published corefloods for low salinity water injection.
- Investigating the best way of history matching low salinity water injection effect on oil recovery.
- Highlighting important parameters that should be considered in modeling low salinity water injection effect in carbonates.
- Wettability alteration is still believed to be the main mechanism underlying the incremental oil recovery by LSWI.
- Oil endpoint relative permeability is more sensitive to the LSWI effect than is water endpoint relative permeability.

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ABSTRACT

The low salinity water injection method (LSWI) has become one of the important research topics in the oil industry because of its enormous possible advantages. The objective of this paper is to investigate the mechanism behind the LSWI effect on oil recovery through data matching. The UTCHEM simulator was used to match the cycles of the injected seawater and different dilutions of the latter for two recently published coreflooding experiments. The result from the history matching revealed that the wettability alteration mechanism is believed to be the main contributor to LSWI. Based on this finding, an analytical model for oil recovery predictions can be developed.

1. Introduction

Carbonate rocks account for more than half the world's hydrocarbon proven reserves. Oil recovery from these reservoirs is a challenge due to their complex nature. The problem becomes even more complicated when wettability ranges from mixed-wet to oil-wet rocks with a low permeability matrix and high fracture density as in most carbonate reservoirs. Consequently, several enhanced oil recovery techniques have been proposed to improve oil recovery of these reservoirs and overcome the high negative capillary pressure that holds oil in place. One of the suggested techniques is altering the wettability of these reservoirs from oil-wet towards more water-wet, which turns the capillary pressure positive and begins spontaneous water imbibition into the low permeability rock matrix resulting in higher oil recovery.

One of the emerging improved oil recovery (IOR) techniques for wettability alteration in carbonate reservoirs is low salinity water injection. The popularity of this technique is due to its efficiency in displacing light to medium gravity crude oils, ease of injection into oil-bearing formations, water availability and affordability, and lower capital and operating costs, all of which lead to favorable economics compared to other chemical and thermal EOR methods. The only concerns with this technique are water sourcing and water disposal. This low salinity water injection EOR technique is also known in the literature as LoSal, Smart Waterflood, and Advanced Ion Management. Several studies have been done on LSWI water injection at laboratory scale and to a limited extent at field-scale. A review of the effect of LSWI water injection on both sandstone and carbonate rocks is presented below.

Extensive laboratory studies were conducted on sandstone rocks after producing 15% additional oil from the Kansas field when brine was used as injection fluid compared to fresh water [1]. The relative effectiveness of fresh and salt water on oil recovery from synthetic and natural cores containing clays was investigated by Bernard [2]. An increase in oil recovery from Berea sandstone cores by increasing the salinity up to a certain level after which recovery did not increase significantly was reported by Al-Mumen [3]. Both connate and invading brines have major effects on wettability and oil recovery at reservoir temperature as was reported by both Tang and Morrow [4]. Several coreflood experiments investigated the effect of low salinity brine on improving

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Nomenclature

CPC	parameter related to the maximum capillary pressure	np	number of phases
EPC	capillary pressure exponent	S_l	phase saturation
k_{rl}^*	phase endpoint relative permeability	S_{lr}	phase residual saturation
n_l	phase Corey's exponent	σ	interfacial tension

oil recovery from Berea sandstone cores for both secondary and tertiary injection modes [5]. The incremental oil recovery from sandstone rocks was in the range of 5–20% of OOIP as reported by several studies [6–9].

The suggested mechanisms include fines migration, pH increase, multi-ion exchange (MIE), salting-in, and wettability alteration [10]. The wettability alteration process is the reason behind the low salinity effect as the decrease in salinity increases the size of the double layer between the clay and oil interface leading to organic material release [11]. Wettability alteration in sandstone rocks is related to the presence of clay minerals, oil composition, formation water with high concentrations of divalent cations (Ca^{2+}, Mg^{2+}), and the salinity level of the low salinity water (1000–5000 ppm) [12].

The effect of low salinity water injection on carbonate has not been thoroughly investigated in contrast to sandstone rocks because wettability alteration by low salinity water is related to the presence of clay, which is not the case in carbonate rocks. To our knowledge, no field scale pilots have been conducted so far to investigate the effect of low salinity water injection on carbonate rocks. However, some work was done at laboratory scale on the effect of low salinity water injection on oil recovery from carbonate rocks. Based on their spontaneous imbibition experiments, Hognesen et al. [13] concluded that increasing sulfate ion concentration at high temperature leads to increased oil recovery. Also, through spontaneous imbibition experiments, Webb et al. [14] investigated the effect of sulfate on oil recovery from North Sea carbonate core samples. They found that seawater has the ability to alter the wettability of the carbonate system to a more water-wet state compared to sulfate free water. Wettability alteration in North Sea chalk reservoirs in the Ekofisk field, showing the effect of adding calcium and/or magnesium ions at various temperatures, was studied by Zhang et al. [5]. In the latter study, they concluded that wettability alteration occurs if the imbibing water contains either Ca^{2+} and SO_4^{2-} or Mg^{2+} and SO_4^{2-}.

The feasibility of low salinity water injection (Smart Waterflood) on carbonate rocks to improve oil recovery by using different dilutions of sea water was investigated by Yousef et al. [12]. Their coreflooding tests showed incremental oil recovery up to 18% with stepwise dilution of the sea water in the tertiary water injection mode. Incremental 15% and 20% OOIP recovery were feasible using borate (BO_3^{3-}) and phosphate (PO_4^{3-}) as modified ions, respectively [15]. They concluded that the wettability alteration mechanism in carbonate rocks takes two forms: either dissolution by softening of the injected brine or surface charge change by modifying the injected ions.

Several mechanisms describing the low salinity process have been suggested in light of this enormous body of research. However, there is no consensus on a single main mechanism for the low salinity effect. This is due to the complex nature of interaction between crude oil, brine, and rock, as well as a number of conflicting observations from experimental studies. This paper investigates the mechanism behind the LSWI effect on oil recovery through history matching of oil recovery and pressure drop data on Yousef et al.'s [12] first and second coreflooding experiments. We use the UTCHEM simulator, which is a 3D multiphase flow, transport, and chemical flooding simulator, developed at The University of Texas at Austin. UTCHEM is a three dimensional non isothermal finite different compositional flow simulator. It has the capability of modeling different chemical enhanced oil recovery processes such as polymer, surfactant/polymer flooding. It uses high-order numerical technique to control numerical dispersion. The method used to solve flow equations is implicit in pressure and explicit in concentration. Understanding the mechanism and matching the data enable the development of a LSWI model for oil recovery prediction.

2. Experimental data

By measuring both IFT and contact angle at reservoir conditions, Yousef et al. [12] suggested that the obtained incremental oil recovery using LSWI is due to wettability alteration. They conducted two corefloods at reservoir conditions using two sets of composite carbonate cores. Carbonate reservoir cores with average porosity of 25.1% and 24.65%, and average liquid permeability of 39.6 mD and 68.3 mD were used for both first and second coreflooding experiments, respectively. In these corefloods, the cores were saturated with live reservoir oil at the irreducible water saturation, and then field seawater was injected at the reservoir temperature and pressure, followed by the injection of various seawater dilutions for the tertiary recovery. The seawater was diluted in four cycles with the dilution factors of twice, ten-times, twenty-times, and hundred-times. The experimental procedures and fluid properties, including oil and dilutions of seawater, are described elsewhere [12].

2.1. Experimental data analysis

Data digitizing, JBN Method, pressure drop data analysis, and capillary number analysis were conducted on Yousef et al.'s work as discussed in this section.

2.1.1. Data digitizing

Oil recovery and pressure drop data were digitized using Engauge Digitizer software to history match the data using UTCHEM. Error bars with upper and lower bounds were used to account for the uncertainty in the data by assuming a 2% error in oil recovery data and 1 psi error in pressure drop data. These error ranges were assigned based on the accuracy of equipment used for conducting the experiments and assuming the least encountered experimental error. Thus, history matching is acceptable within the defined upper and lower error bars.

2.1.2. JBN method

A set of parameters is needed to history match the experimental data using UTCHEM which includes relative permeability parameters (endpoint relative permeability and Corey's exponents), and capillary pressure parameters (CPC and EPC). These parameters are used as input data to calculate relative permeability curves using Corey's Model [16] and capillary pressure curves using Brooks–Corey Model [17].