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Review article

Data-driven analyses of low salinity water flooding in sandstones

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ABSTRACT

Low salinity water flooding (LSWF) has been intensively investigated but the conditions for LSWF to work are still unclear and the EOR mechanisms are still debatable. In this study, we extracted data from hundreds of LSWF flooding tests using sandstone cores and sand packs that have been published to date (by January 2018), and analyzed the tertiary recovery results (202 groups) collectively. First, all initial experimental conditions are correlated to the tertiary recovery factors in both single and combinatorial manners. Correlation charts show that no single experimental condition constitutes ***necessary*** or ***sufficient*** conditions for incremental oil recovery; combinatorial conditions show stronger correlations with the recovery factors, but still do not constitute sufficient conditions for incremental oil recovery. Secondly, incidental property changes are correlated to tertiary recovery factors in order to evaluate the related EOR mechanisms. Wettability alteration towards more water-wet shows a strong correlation with improved oil recovery. Finally, all previously proposed EOR mechanisms for LSWF in sandstones are linked in a chart to demonstrate an in-depth overview of all these mechanisms. We use experimental data analyses to provide a solid basis for reviewing LSWF and provide unique perspectives in understanding this process.

1. Introduction

Water flooding is the most frequently implemented secondary oil recovery method worldwide. Generally, seawater or produced water of high salinity is injected into the reservoir to displace the oil in place. Over the last two decades, many laboratory experiments and several single well tests have shown that low salinity water flooding (LSWF) can achieve higher oil recovery and lower residual oil saturation compared to high salinity water flooding (HSWF). On the other hand, in many LSWF cases no incremental oil recovery was observed. The conditions for LSWF to work are still unclear and the EOR mechanisms associated with LSWF are still debatable. No predicative approach exists given a certain reservoir rock and fluids system, and core flooding experiments are required to estimate the extent of low salinity effect (LSE).

LSWF studies started decades ago. As one of the earliest, Martin [22] suggested that fresh water is more desirable than brine for heavy oil displacement. Later, Bernard [7] observed increased oil recovery from sandstone cores by injecting fresh water. These early studies attributed the incremental oil recovery to clay hydration and migration, which had been identified as a cause for formation damage rather earlier [17,8,6]. Not until the mid-1990s did LSWF regain researchers' attention. For example, Morrow's group extensively investigated the effect of brine salinity/composition, oil composition and clay content on oil recovery in both secondary and tertiary modes using sandstone cores ([40,41,44]). A major EOR mechanisms they proposed is that residual oil becomes mobile as mixed-wet fines detach from pore walls during LSWF. Based on these comparative tests, presence of potentially mobile fines, polar components in crude oil, and presence of connate brine are considered as necessary conditions for observing LSE in Berea sandstone cores [41]. Nevertheless, these conditions are not sufficient to generate the LSE [24]. Recently, the role that clay minerals play during LSWF has been visualized in microfluidic chips by depositing kaolinite to coat the micrometer pores [38]. Tertiary injection of deionized water yielded an incremental oil recovery of 14%, primarily attributing to clay stripping and wettability alteration from mixed-wet to more water-wet. Austad et al. [5] proposed a chemical mechanism that consists of adsorption/desorption of organic acid and base components onto rock surfaces, water dissociation, and multi-ion exchange (MIE). Low initial pH (~5) of connate brine, presence of clay, polar components in crude oil, and divalent cations in connate brine are conditions needed to activate this mechanism. Substitution of Ca^{2+} on clay surface by H^{+} dissociated from water creates a local pH increase, which is an observation that is believed to trigger the LSE [30]. Nasralla and Nasr-El-Din [27] measured the zeta potentials at Berea sandstone/brine interfaces and oil/brine interfaces, and demonstrated that electric double

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layer expansion (DLE) is a dominant EOR mechanism for LSWF. Additional mechanisms include saponification and surfactant effect [23], flow diversion due to fine particle straining and consequent formation damage [14,43], improvement of interfacial viscoelasticity and suppression of snap-off [12], osmotic water transport across oil phase [11], and wettability alteration toward more water-wet [21], etc. These mechanisms are not exclusive, for instance, multi-ion exchange releases the polar component, consequently changing the surface wettability. Moreover, none of these mechanisms alone stand up to all cases that showed the LSE, for example, no fine production and pressure increase were observed in some tests showing a positive LSE [35]. There are always evidences and counter-evidences to each of these mechanisms [36,16].

The absence of a universal mechanism for LSE arises from the complex nature of interactions among brine, crude oil and rock, each of which consists of several properties that could strongly effect the LSE. The total salinity and divalent cation concentration of the connate brine and the injected brine; the acid number (AN), base number (BN) and polar component content (Polar) of crude oil; and the clay content and initial wettability of the rock have all been proposed as possible parameters to affect the LSE. However, to disentangle these parameters for independent investigation of their roles requires elaborated experimental designs and sophisticated analytical techniques. This is still very challenging, especially considering that there could be synergistic effects among these parameters.

Several literature reviews have tried to illustrate the dominant EOR mechanisms for LSE. Sheng [36] and Al-Shalabi and Sepehrnoori [4] summarized laboratory and field observations along with discussion of all the mechanisms proposed in the literature, and concluded that wettability alteration is probably the most plausible explanation for LSE, although the wettability change itself is an outcome of other root causes. They also pointed out that high incremental oil recovery is not realistic in field due to the fact that field tests cannot inject as many pore volumes as laboratory studies. Myint and Firoozabadi [25] discussed the wettability alteration during LSWF by primarily focusing on the effect of DLE on the thickness and stability of the thin brine films on the rock surface. They concluded that DLE provides a qualitative but incomplete explanation for the LSE. Jackson et al. [16] collected LSWF data on sandstones from 37 publications and discussed major EOR mechanisms by providing both supporting and contrary evidences. They identified MIE, local pH increase and DLE as the most probable mechanisms. Moreover, suggestions are made upon acquiring a complete set of parameters from experiments and an urgent need of measuring zeta potential, which is a common feature of these three mechanisms. By holding wettability alteration as the main cause of LSE, Ding and Rahman [9] reviewed and analyzed the leading mechanism of wettability alteration, i.e. DLE, in terms of DLVO (Derjaguin-Landau-Verwey-Overbeek) and non-DLVO forces in the oil, brine and rock system. Surface force measurements, such as atomic force microscopy, are suggested to describe the microscale interactions among oil, brine and rock. All in all, the working conditions and EOR mechanisms proposed for LSE have been well summarized and examined in these literature reviews, yet none of them systematically linked all experimental conditions with the oil recovery outcomes, or linked all experimental observations of incidental changes with EOR mechanisms using data available.

Starting from extracting sandstone core flooding data from secondary and tertiary LSWF experiments published up to date, this study aims at understanding the sufficient and necessary conditions for LSWF to yield a positive oil recovery from a statistical point of view. Initial conditions are then correlated to the incremental oil recovery factors measured in the tertiary flooding experiments, in both single and combinatorial manners. Correlation coefficient and adjusted coefficient of determination are adopted to indicate the strength or goodness of the relationships. Furthermore, incidental parameters that accompany the LSWF process are quantified against incremental recovery factors to further understand the existing mechanisms. For simplicity, linear regressions were carried out in most cases. Finally, we sorted all existing mechanisms and identified the hierarchical order of cause and effect among them. We compiled nearly 200 groups of tertiary flooding data by reviewing over 200 publications (listed in the supplementary excel). Although the database may not fully represent a global description of LSWF in sandstone, it was collected in an unbiased manner (all literature that contain quantitative analyses that are available to us) and summarizing these data in a systematic manner would help clarify the current experimental findings and identify gaps for further investigation.

2. Data compiling

2.1. Secondary and tertiary recovery factors

LSWF experiments are typically conducted in two modes: secondary and tertiary. Secondary mode usually compares HSWF and LSWF experiments with cores of similar properties, while tertiary mode applies LSWF after a secondary HSWF on the same core. Also, secondary and tertiary modes represent different injecting strategies for an oilfield: one represents LSWF from the beginning of secondary recovery, while the other represents LSWF after secondary HSWF.

Both secondary and tertiary recovery results are compiled from sandstone/sand pack flooding tests that have been published to date, including over 500 groups of results from 66 papers (Supplementary Material). Secondary recovery factors are defined as the incremental recovery factor in %OOIP (directly reported or converted from original references) for secondary LSWF compared to those in secondary HSWF. In total there are 157 incremental secondary recovery factors extracted, ranging within [−5.4, 28.4], with the mean of 7.01 and the standard deviation of 6.89 in %OOIP. Fig. 1 shows the frequencies of the secondary recovery factors, which have been rounded to their nearest integers. Likely due to core heterogeneity and possibly negative effects of LSWF under certain circumstances, some tests yielded negative incremental values. Most of the incremental secondary recovery factors from LSWF range between 0 and 20, with decreasing frequencies at higher recovery factors.

Tertiary recovery factors (RF) achieved by LSWF are defined as the incremental oil recovery in %OOIP of post-secondary flooding. A total of 202 tertiary recovery factors are extracted from literature. The tertiary recovery factors range within [0, 16.2], with the mean of 4.98 and the standard deviation of 4.27 in %OOIP. The average tertiary recovery factor is lower than that of the incremental secondary recovery factors. The frequencies of the rounded tertiary recovery factors are shown in

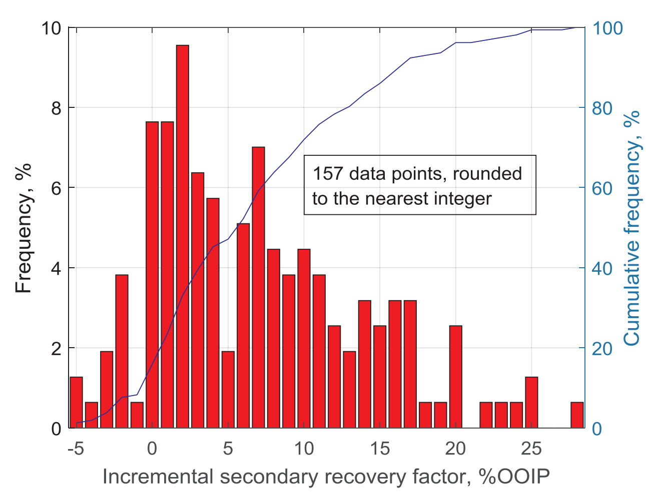

Fig. 1. Frequency of incremental secondary recovery factors compiled from publications.