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Evaluation of low salinity waterflooding models controlled by wettability alteration

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Abstract

Low salinity waterflooding (LSW) is an emerging cost-effective and environmentally friendly enhanced oil recovery (EOR) technique in which the salinity of the injected water is substantially reduced to improve oil production from sandstone reservoirs. Since the discovery of the potential of LSW, numerous studies have been reported focusing on analysis of the mechanisms behind the LSW technique, and several physicochemical mechanisms have been proposed to explain the oil recovery enhancement by LSW. In this paper, in order to analyze the performance of the main mechanisms that describe the wettability alteration during LSW, a comparative analysis was conducted. Seven proposed models were selected and implemented in a one-dimensional simulator and their results were compared to experimental data. The majority of models showed good agreement with experimental data, except one model due to selection of a modify Brooks-Corey correlation, in which was not able of capture the shape of relative permeability curves, leading to unrealistic results. Despite its simplicity, the interpolation approach does not capture the impact of water composition changes, because only salt concentration is controlling the mobility change. The work demonstrated that the MIE model, when well-calibrated, can be the basis of modeling wettability alteration during LSW.

Keywords

Multiple Ion Exchange; Double Layer Expansion; EOR.

Introduction

Enhanced Oil Recovery (EOR) methods have been used worldwide to improve oil production. The injection of a low salinity water has shown promising results for increasing the amount of oil recovered in reservoirs compared to conventional waterflooding methods [1-2]. In the past two decades, several papers were published aiming to understand and model the complex chemical interactions between crude oil-brine-rock (COBR) in the system [3]. Despite the knowledge acquired, the main mechanism behind it is still debated in the research groups and several mechanisms have been suggested in this period to explain the effects of LSW [4].

Nowadays, three main mechanisms are considered strong candidates to describe the effects behind the additional oil recovery due to low salinity water injection, which are called wettability alteration, fines migration and interfacial tension [5]. Wettability alteration mechanism describes that LSW would change the wettability toward less oil-wet or more water-wet states contributing to a more favorable condition which results in addition oil recovery [6]. In order to model the mechanism of wettability alteration, different physicochemical approaches have been proposed which are classified as salting-in, multiple ion exchange (MIE) and double layer expansion (DLE) [7].

Based on the complexity of modeling the COBR system, this paper aims to study and compare the performance of the available models in the literature developed to predict the wettability alteration due to low salinity waterflooding in a sandstone reservoir.

Methodology

A review was conducted to identify different phenomenological approaches used to model low salinity injection into a sandstone reservoir. Three main approaches were selected, and then a further review was carried out to find the main proposed models that describe the change in wettability during LSW. In the models selection, the publication period and mechanism were used as screening criteria.

Subsequently, the selected models were implemented in a one-dimensional simulator of multiphase flow in porous medium, in which was developed to solve a system of partial differential equations formulated from a two-phase Buckley-Leverett model, coupled with continuity equations for different ions in water. In the simulations, the effect of gravity and temperature change was neglected. In order to evaluate the performance of the models, their results were compared with coreflooding experiment results taken from the literature [8].

To corroborate the performance evaluation, a residual analysis was performed. Initial conditions, operational conditions, fluid reservoir properties and compositions are defined based on the experimental data. A set of two relative permeability curves representing high and low salinity behavior extracted from the experiment were used as input parameter in the simulations.
Table 1 summarizes the average petrophysical properties of the sandstone corefloods, crude oil characteristics and parameters used in the simulations. The water compositions are presented in Tab. 2.

Table 1. Petrophysical properties, oil and water characteristics and simulation parameters [8].

Properties	**Sandstone Coreflood**
Length (cm)	5.1
Porosity (%)	25.6
Initial water saturation (%)	23
Oil viscosity (cp)	83
Water viscosity (cp)	1
Injection rate (cm^3/min)	0.15
Clay content (%)	0.094
CEC (mol/m^3)	160
S_{or}^{HS}/ S_{or}^{LS}	0.22/0.12
k_{rw}^{HS} / k_{rw}^{LS}	0.053/0.052
n_w^{HS} / n_w^{LS}	1.2/1.2
n_o^{HS} / n_o^{LS}	2/2

Table 2. Experimental water composition used in the first case study [8].

Ion	**Initial water (IW)**	**Sea water (SW)**	**50% SW**	**Low salinity water (LSW)**
Na^+	0.87648	0.61332	0.30666	0.06133
Cl^-	1.44134	0.58951	0.29476	0.05895
Ca^{2+}	0.31188	0.01871	0.00936	0.00187
Mg^{2+}	0.12343	0.18515	0.09257	0.01851
SO_4^{2-}	0.00052	0.02082	0.01041	0.00208

Results and Discussion

In order to understand the incremental oil recovery by LSW, while several researchers initially focused on experimental studies, Jerauld et al. [9] were the first to present a model describing the displacement of low salinity waterflooding. Their general approach is to model LSW by making the relative permeability and capillary pressure curves salinity-dependent between two salinity thresholds. The salt is modeled as an additional single component in the aqueous phase, and the interpolation parameter is defined as a function of residual oil saturation, defined as

$$\theta = \frac{S_{or} - S_{or}^{LS}}{S_{or}^{HS} - S_{or}^{LS}} \quad (1)$$

where S_{or} are input values as a function of salinity, and the superscripts *HS* and *LS* indicate high and low salinity thresholds, respectively. The transition from an initial high salinity state towards a low salinity state controlled by the abovementioned parameter is based on the following equations:

$$k_{rw} = \theta k_{rw}^{HS} + (1-\theta) k_{rw}^{LS} \quad (2)$$
$$k_{ro} = \theta k_{ro}^{HS} + (1-\theta) k_{ro}^{LS} \quad (3)$$

Concomitantly, Tripathi and Mohanty [10] introduced three different approaches to model LSW, where they correlated different parameters with salt concentration to capture distinct wettability change conditions. The first model is similar to the model proposed by [9], in which S_{or} is assumed to be the only salinity-dependent parameter. In the second model, the end-point water relative permeability is altered due to the change in salinity, in addition to the change in S_{or}. The last model introduced the Corey's exponents and the S_{or} as a function of salinity. In contrast to [9], who did not formulate the correlation between residual oil saturation and salinity, [10] proposed that residual oil saturation is a function of salt concentration, as shown in Tab. 3.

Table 3. Evolution of the low salinity waterflooding modeling process based on wettability alteration.

Authors	**Models**
Tripathi and Mohanty (2008)/ Type I [10]	$S_{or}(C_s) = S_{or}^{LS} + \frac{C_s - C_s^{LS}}{C_s^{HS} - C_s^{LS}}(S_{or}^{LS} - S_{or}^{HS})$ (4)
Tripathi and Mohanty (2008)/ Type II [10]	$k_{rw}(C_s) = k_{rw}^{LS} + \frac{C_s - C_s^{LS}}{C_s^{HS} - C_s^{LS}}(k_{rw}^{LS} - k_{rw}^{HS})$ (5)
Tripathi and Mohanty (2008)/ Type III [10]	$n_i(C_s) = n_i^{LS} + \frac{C_s - C_s^{LS}}{C_s^{HS} - C_s^{LS}}(n_i^{LS} - n_i^{HS})$ (6)
Wu and Bai (2009) [11]	$k_{rw} = \left(\frac{S_w - S_{iw}}{1 - S_{iw}}\right)^{2+\varphi}$ (7) $k_{ro} = \left(\frac{S_o - S_{or}(X_c)}{1 - S_{iw}}\right)^2 \left[1 - \left(\frac{S_w - S_{iw}}{1 - S_{iw}}\right)^{\varphi}\right]$ (8) $S_{or}(X_c) = S_{or1} + \frac{X_c - X_{c1}}{X_{c1} - X_{c2}}(S_{or1} - S_{or2})$ (9)
Omekeh et al. (2011) [12]	$H(\beta_{Ca}, \beta_{Mg}) = \frac{1}{1 + rm(\beta_{Ca}, \beta_{Mg})}$ (10)
Korrani (2014) [14]	$\theta = \frac{TIS_{max} - TIS(x,t)}{TIS_{max} - TIS_{min}}$ (11)

Subsequently, Wu and Bai [11] proposed a model that calculated residual oil saturation as a function of salinity directly on Corey's modified model to change relative permeabilities rather than using an interpolating technique. Differently from the aforementioned models, the equation of salt transport through porous medium considers advection, diffusion, and adsorption processes.
Afterward the models begin to increase their complexity by adding different processes or using

empirical approaches. For instance, [8] used a different correlation to model the oil relative permeability, in which there are two new parameters that are obtained using curve fitting technique and are also related to salt concentration.

Following, Omekeh et al. [12] conducted a core-flood experiment using several brines with different ion compositions, and then proposed a more robust model that is controlled by multiple ion exchange. In general, the model is formulated such that the total release of divalent cations from the rock surface gives rise to a change of relative permeability functions, increasing the amount of oil recovered. Then, [13] developed a mechanistic model which considered that ionic exchange process promotes mineral dissolution of the rock surfaces and changes the ionic composition of formation water, and consequently altered the wettability. Different researchers have been using this approach to model cation exchange accoupling with other mechanisms. Nevertheless, Korrani [14] suggested that double layer expansion effects are the only mechanism contributing to the change in wettability. Table 3 shows that the authors also proposed a similar approach to model LSW, whose relative permeability equations are calculated with an interpolation technique using a parameter as function of ionic strength.

The abovementioned models were evaluated by comparing its results against a low salinity coreflooding experiment taken from literature, considering LSW in sandstone cores [8]. The parameters used in the simulations are illustrated in Tab. 1-2.

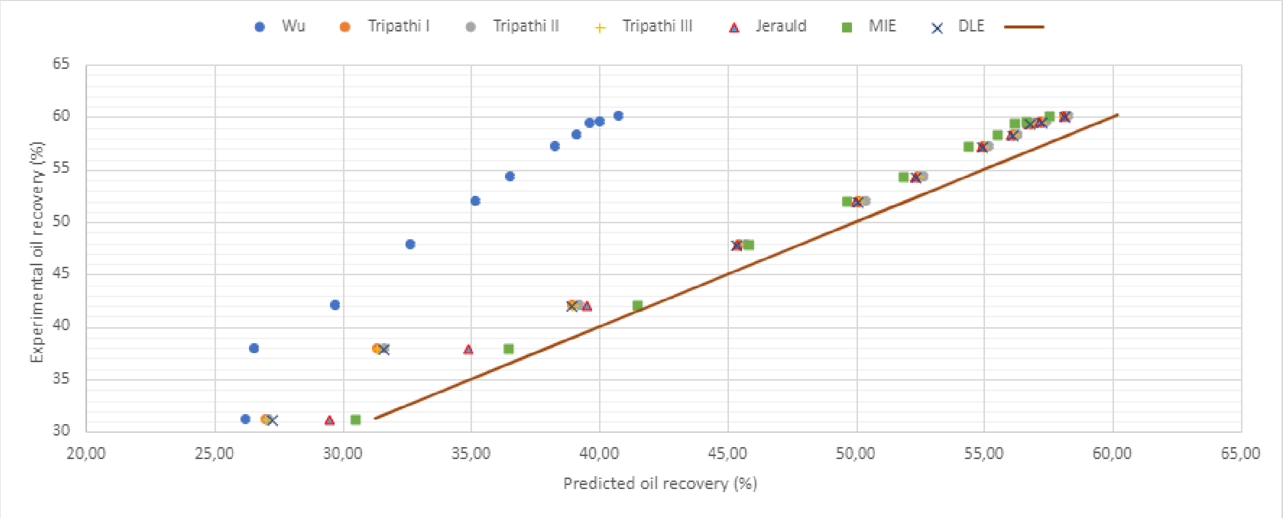

Figure 1. Comparison of experimental and predicted oil recovery from implemented models.

Figure 1 shows a comparison between experimentally observed and model-based prediction of oil recovery values. The straight line represents an ideal situation, where the model matches the experimental data perfectly. It can be observed that the model proposed by [11] performs poorly, which is indicated by the high slope of the fitted curve. This can be related due to selection of a modify Brooks-Corey correlation, which is used for calculating the relative permeability of the COBR system, instead of using power-law expressions, often referred to as generalized Brooks-Corey relations [7].

A modification of the equations was also suggested, where only oil relative permeability equation is salinity dependent. Those choices led to unrealistic results, first because the Brooks-Corey equation did not capture the shape of the relative permeability curves and the end-points permeability due to lack or poorly fitted parameters. Second, the proposed modifications did not explain the changes in water relative permeability due to decrease in salinity, which is not in agreement with the experimental data.

In contrast, the results of the other proposed models showed less variation with the experimental data, as depicted by Fig. (1). Comparing the slopes of the fitted curves, the Jerauld's model is the best fit followed by MIE model, with slope of 0.9978 and 1.088, respectively. Nevertheless, the residual analysis slightly indicated that MIE model had a better performance than Jerauld's model, with sum of residuals 64.50 and 65.31, respectively. The predicted values based on MIE model have a standard deviation of 2.677, which indicates less dispersion of the data around the regression line compared to the Jerauld's model. This model stands out by presenting better results before the breakthrough, which occurs between 0.5 and 1 PVI. The simulation of MIE model was conducted without any tuning or model calibration. For instance, the cation exchanger capacity (CEC) used in the simulations was not available in the experimental data. Therefore, sensitivity analyses are needed to adjust the simulation parameters to yield better results, particularly by decreasing the difference between predicted and experimental oil recovery values.

Despite good results, Jerauld's model is not able to capture the impact of water composition changes that may affect the velocity of low salinity waterfront. The MIE and DLE mechanisms were proposed to capture these contributions. In particular, DLE mechanism uses the ionic strength of the injected water to control mobility changes rather only salt concentration, thus capturing the impact of water composition. The fitted curve based on DLE model has a slope of 0.9044 and standard deviation of 3.550, which shows that despite good performance this approach still requires improvement to better predict LSW behavior.

Analyzing the models proposed by [10], the type II model had the best performance, where the difference from the type I and III is related to the salinity dependence of the end-points relative permeability, in which had more impact on oil recovery than a Corey exponent as function of salinity or just residual oil saturation, as proposed by [9,11]. This approach allowed a proper adjustment to the interpolation parameter, thus capturing the LSW behavior well.

Conclusions

We presented a simulation study for the modeling of low salinity waterflooding in sandstone reservoirs. The models were successfully benchmarked against experimental data, except the model proposed by [11], due to selection of a modify Brooks-Corey correlation, in which was not able of capture the shape of relative permeability curves, leading to unrealistic results. For this reason, it was not possible to evaluate the contribution of the dispersion term. Despite its simplicity, the model proposed by [9] had better performance, nevertheless, it does not capture the impact of water composition changes, because in this approach only salt concentration is controlling the mobility change. The work demonstrated that the MIE model, when well-calibrated, can be the basis of modeling wettability alteration during LSW. Yet, an analysis is required with different mechanisms coupled to MIE mechanism, due to the increase in residuals between predicted and experimental oil recovery values when the injection of water is above 1 PVI, which is probably the effect of different phenomena occurring simultaneously.

As a final consideration, our study suggests that different approaches with coupled mechanisms should be implemented and tested to analyze how those models capture the complex behavior of COBR system and the effect of different phenomena occurring simultaneously.

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Responsibility Notice

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