

## MODELING WETTABILITY ALTERATION DURING LOW SALINITY WATERFLOODING IN SANDSTONE RESERVOIRS: A BRIEF REVIEW

Igor Oliveira de Freitas Campos<sup>a</sup>, Fernando Luiz Pellegrini Pessoa<sup>a</sup>, Gabriel de Veiga Cabral Malgaresi<sup>a</sup>

<sup>a</sup>Centro Universitário Senai Cimatec; Av. Orlando Gomes, 1845, Piatã; Salvador/BA.

**Abstract:** Low salinity waterflooding (LSW) is an emerging enhanced oil recovery (EOR) technique in which the salinity of the injected water is substantially reduced to improve oil production from sandstone reservoirs. While a significant number of laboratory tests have been carried out to investigate the impact of LSW in the literature, publications on modeling of this process are not so frequent due to the struggling in describe this phenomenon. Different approaches were proposed to model the wettability alteration during LSW, including salting-in, multiple ion exchange (MIE) and double layer expansion (DLE). In this paper a brief literature review is presented, describing the main mechanisms that have been proposed to explain the effects of wettability alteration during LSW, also gathering different mathematical models available in the literature.

**Keywords:** Low salinity waterflooding; Wettability alteration; Multiple ion exchange (MIE); Salting-in; Double layer expansion.

## MODELAGEM DA ALTERAÇÃO DA MOLHABILIDADE DURANTE A INJEÇÃO DE ÁGUA DE BAIXA SALINIDADE EM RESERVATÓRIOS ARENÍTICOS: UMA BREVE REVISÃO

**Resumo:** A injeção de água de baixa salinidade (LSW) é uma técnica emergente de recuperação avançada de petróleo (EOR), na qual a salinidade da água injetada é substancialmente reduzida para melhorar a produção de petróleo em reservatórios arenitos. Embora um número significativo de testes laboratoriais tenha sido realizado na literatura no intuito de investigar o impacto da LSW, as publicações sobre a modelagem deste processo não são tão frequentes devido à dificuldade para descrever esse fenômeno. Diferentes abordagens para modelar a alteração da molhabilidade durante a LSW foram propostas, o que inclui os mecanismos de *salting-in*, troca iônica (MIE) e a expansão da dupla camada elétrica (DLE). Neste artigo é apresentada uma breve revisão da literatura, descrevendo os principais mecanismos que foram propostos para explicar os efeitos da alteração da molhabilidade durante a LSW, reunindo também diferentes modelos matemáticos disponíveis na literatura.

**Palavras-chave:** Injeção de água de baixa salinidade (LSW); Alteração da molhabilidade; Troca iônica (MIE); *Salting-in*; Expansão da dupla camada elétrica.

## 1. INTRODUCTION 41

The current and prospective worldwide energy requirements have been driven most companies towards the maximization of the exploitation of mature oil reservoirs [1]. To maintain the reservoir pressure and be able to drive the oil into the production wells, waterflooding has been applied for many years as secondary recovery method [2]. During waterflooding operations, we have the formation of viscous fingering that is a product of displacing a high viscosity fluid by a low viscosity fluid [3]. This creates unswept zones that leave an amount of oil trapped in the reservoir, where part of the invading water, bypassing these zones, prematurely addresses the production well [4].

The amount of residual oil left in reservoirs after the secondary oil recovery is significant. Therefore, more efficient methods need to be used to improve the recovery of the oil still trapped in the fields, also called Enhanced Oil Recovery (EOR) [5]. Generally, EOR techniques are divided into four main groups: thermal, miscible flooding, microbial and chemical flooding. Each group uses different techniques based on the injection of fluids or other agents to modify certain physical and/or chemical properties, either in the fluids or in the reservoir, improving the oil recovery [6]. According to the EOR aforementioned classification, Low Salinity Waterflooding (LSW) is usually envisioned as a chemical EOR method consisting of injecting low salinity brine that is depleted of divalent cations compared to in-situ brine into the reservoirs, as demonstrated in numerous core-flooding experiments in sandstone rocks [7]. However, due to the complexity of crude oil-brine-rock interactions, the underlying mechanism of LSW has been debated in the literature for the past two decades [8]. To explain the increased oil recovery from LSW, several mechanisms have been proposed by several research groups [9-11]. Nowadays, three main mechanisms are considered as the principal mechanisms of LSW process, which are called wettability alteration, fines migration and interfacial tension [12].

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 additional oil recovery [13]. Multiple mechanism can contribute to wettability alteration during LSW, for instance salting-in mechanism, multiple ion exchange (MIE) mechanism and double layer expansion (DLE) [14].

Based on the complexity of the aforementioned wettability alteration mechanisms, this work aims to understand, explain and present main LSW models controlled by wettability alteration available in the literature.

## 2. METHODOLOGY

This paper presents a literature review of different approaches to modeling the mechanism of wettability alteration, which controls the effects of the low salinity waterflooding in sandstone reservoirs. These mechanisms are called salting-in, multiple ion exchange and double layer expansion. Firstly, we searched at literature the three main mechanisms that are suggested as controlling for the change in the wettability. Then we evaluated numerous papers that have been published in the past 20 years to better understand the phenomenological explanations for each mechanism. Subsequently, different model approaches to describe salting-in mechanism were investigated. Then, the correlations commonly used in each model were organized in level of technology readiness. Subsequently, the main approach that is used currently in many papers to model the multicomponent ion exchange (MIE) was studied. Finally, we chose two main models approaches to describe the last mechanism, double layer expansion (DLE).

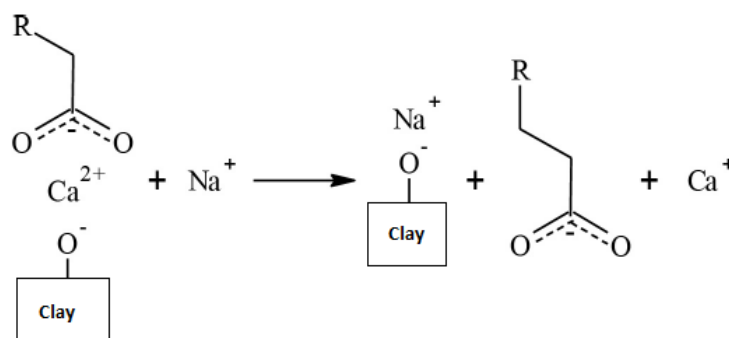
### 3. RESULTS AND DISCUSSION

Different physicochemical mechanisms have been proposed to explain wettability alteration as one of the primary causes of oil recovery enhancement by LSW flooding in sandstone rocks. These mechanisms are classified as salting-in, multiple ion exchange (MIE) and double layer expansion (DLE) [14].

The salting-in mechanism is related to a disturbance in the equilibrium between the phases through the injection of low salinity water into the reservoir, which changes the solubility of polar components in water. As the salt concentration in the system decreases, it leads to an increase in the solubility of organic material in the porous media. In general, the organic material is adsorbed on the clay surface through a loose bond, and due to the salting-in effect, it desorbs from the clay, thus contributing to change the wettability to a more water-wet system [15].

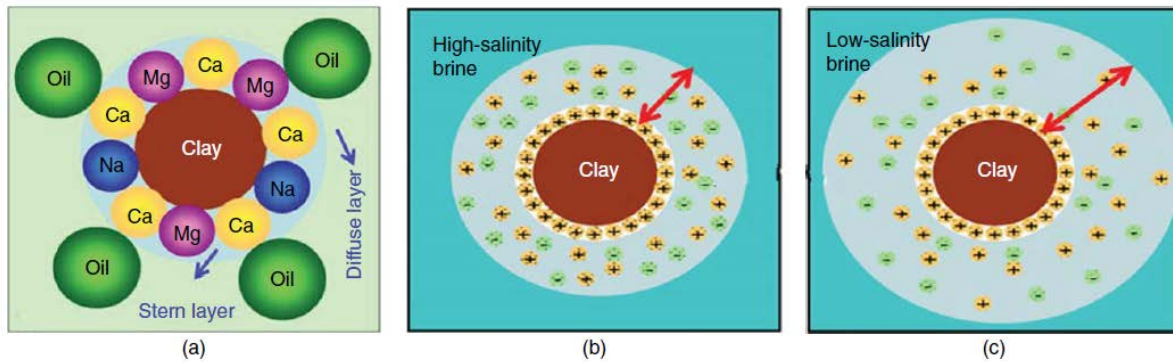
In contrast to the first mechanism, [10] proposed that the multiple ion exchange (MIE) is the main mechanism responsible to control the change in wettability. The MIE mechanism states that the wettability alteration is the result of the ion exchange, which affects the interactions between the clay minerals and the surface-active components in the crude oil controlled by the presence of divalent ions such as  $Ca^{2+}$  and  $Mg^{2+}$ . This mechanism is shown in Figure 2, where the divalent ion acts as a bridge between the negatively charged clay surface and the carboxylic material, and the organic material is removed by cationic ion exchange at the surface.

Figure 1: The multicomponent ion exchange (MIE) leading to oil release [16].



The third mechanism is called double layer expansion (DLE) and was suggested by [11]. In this approach, the clay surface is surrounded by two layers of ions, where the first layer is called the stern layer that contains only monovalent and divalent cations. The second layer is called the diffuse layer and is where negative components might be present, which could result in an attachment with the cations leading to an oil-wet state. By injecting low salinity water into the reservoir, the double layer expands, due to a reduction in ionic strength that leads to decrease in the screening potential of the cations. This in turn yields increased electrostatic repulsion between the clay surface and the oil, which overcome the bonding force and cause oil desorption leading to a more water wet state, as shown in Figure 3.

Figure 2:(a) Schematic of electric double layer and oil components adsorbed to the divalent ion through the double layer; (b) the thickness of double layer during high salinity waterflooding; (c) the thickness of double layer during low salinity waterflooding [17].



There are numerous papers that have been reported experimental studies about the potential of LSW, but relatively few modeling works can be found in the literature [18]. One of the earliest studies on LSW modeling was presented by [19] where it described salting-in mechanism. This new model for LSW was developed with some modifications of a traditional water flooding model. In this model, the interpolation technique is applied and makes relative permeability and capillary pressure curves salinity-dependent between two salinity thresholds. The salt was modeled as an additional single-lumped component in the aqueous phase, and the interpolation parameter is defined as a function of residual oil saturation, which depends on the salinity. Eqs (1) to (5) present the [19]'s model formulation:

$$k_{rw} = \theta k_{rw}^{HS}(S^*) + (1 - \theta) k_{rw}^{LS}(S^*) \quad (1)$$

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

$$P_c = \theta P_c^{HS}(S^*) + (1 - \theta) P_c^{LS}(S^*) \quad (3)$$

$$\theta = (S_{or} - S_{or}^{LS}) / (S_{or}^{HS} - S_{or}^{LS}) \quad (4)$$

$$S^* = (S_o - S_{or}) / (1 - S_{iw} - S_{or}) \quad (5)$$

where the subscripts *HS* and *LS* indicate high and low salinity, respectively. The shape of the relative permeability and capillary pressure curves is assumed to be linearly dependent on salinity between the thresholds and to be constant beyond.

Differently from [19], [20] proposed a model that does not interpolate between two sets of relative permeabilities through an interpolating parameter. However, the calculated residual oil saturation, which is a function of salinity, is then used directly in the Brooks-Corel model to change the relative permeabilities. In contrast to [19], who did not formulate the correlation between residual oil saturation and salinity, [20] proposed that residual oil saturation is a function of salt concentration, as can be seen in the equations below:

$$k_{rw} = \left( \frac{S_w - S_{iw}}{1 - S_{iw}} \right)^{2+\varphi} \quad (6)$$

$$k_{ro} = \left( \frac{S_o - S_{or}(X_c)}{1 - S_{iw}} \right)^2 \left[ 1 - \left( \frac{S_w - S_{iw}}{1 - S_{iw}} \right)^\varphi \right] \quad (7)$$

$$S_{or}(X_c) = S_{or1} + \frac{X_c - X_{c1}}{X_{c1} - X_{c2}} (S_{or1} - S_{or2}) \quad (8)$$

where  $S_{or1}$  is the residual oil saturation at low salt mass fraction,  $X_{c1}$ , and  $S_{or2}$  is the residual oil saturation at high salt mass fraction,  $X_{c2}$ .

Based on those models, several approaches have been proposed in the literature to model wettability alteration. [21] introduced three models, the first is similar to [20]'s model, where residual oil saturation is assumed to be the only salinity-dependent parameter. In the second model, water relative permeability equation is also modified to depend on salinity, in addition to the residual oil saturation. The last model introduces the oil relative permeability exponent as a function of salinity. [22] used a different correlation to model the oil relative permeability, along with the third model of [21]. The equation brings two new parameters that are obtained using curve fitting technique and are also related to salt concentration. In this approach, the results showed that oil relative permeability curve should be adjusted due to low salinity water flooding and water relative permeability curve will be fixed. Table 1 shows the evolution of the different models for the salting-in mechanism.

Table 1: Models considering salting-in mechanism

Authors	Wettability alteration correlation
<i>First model</i> Tripathi and Mohanty (2008)	$S_{or}(X_c) = S_{or}^{LS} + \frac{X_c - X_c^{LS}}{X_c^{LS} - X_c^{HS}} (S_{or}^{LS} - S_{or}^{HS}) \quad (9)$
<i>Second model</i> Tripathi and Mohanty (2008)	$k_{rw}(X_c) = k_{rw}^{LS} + \frac{X_c - X_c^{LS}}{X_c^{LS} - X_c^{HS}} (k_{rw}^{LS} - k_{rw}^{HS}) \quad (10)$
<i>Third model</i> Tripathi and Mohanty (2008)	$n_o(X_c) = n_o^{LS} + \frac{X_c - X_c^{LS}}{X_c^{LS} - X_c^{HS}} (n_o^{LS} - n_o^{HS}) \quad (11)$
Shojaei, Ghazanfari and Masihi (2015)	$K_{ro} = k_{ro}^0 \frac{(1 - S_w^* + h_0)^{m_0} + a_0(1 + S_w^*)}{(1 + h_0)^{m_0} + a_0} \quad (12)$ <p>where <math>S_w^* = \frac{S_w - S_{wc}}{1 - S_{wc}} \quad (13),</math></p> $a_o(X_c) = a_o^{LS} + \frac{X_c - X_c^{LS}}{X_c^{LS} - X_c^{HS}} (a_o^{LS} - a_o^{HS}) \quad (14),$ <p>and <math>m_o(X_c) = m_o^{LS} + \frac{X_c - X_c^{LS}}{X_c^{LS} - X_c^{HS}} (m_o^{LS} - m_o^{HS}) \quad (15)</math></p>

In contrast to the aforementioned authors, [23] proposed a model to describe the wettability alteration, which is controlled by the MIE mechanism. In general, the model is formulated such that the total release of divalent cations, such as  $Ca^{2+}$  and  $Mg^{2+}$  from the rock surface gives rise to a change of relative permeability functions, thus mobilizing more oil. Hence, the following interpolation equation is proposed.

$$k_{ri}(S_i, \beta_{Ca}, \beta_{Mg}) = H(\beta_{Ca}, \beta_{Mg}) k_{ri}^{HS} + [1 - H(\beta_{Ca}, \beta_{Mg})] k_{ri}^{LS} \quad (16)$$

where the subscript  $i = w, o$  and  $H(\beta_{Ca}, \beta_{Mg})$  is defined by Eq. (17) below.

$$H(\beta_{Ca}, \beta_{Mg}) = \frac{1}{1 + rm(\beta_{Ca}, \beta_{Mg})} \quad (17)$$

Eq. (17) is a weighting function representing the wetting state and works such that when  $H(\beta_{Ca}, \beta_{Mg}) = 1$ , no adsorption of divalent cations from the clay surface occurs, implying that  $k_{ri}(S_i, \beta_{Ca}, \beta_{Mg}) = k_{ri}^{HS}$ . This reflects the initial high salinity wetting state. Then, as desorption of divalent cation takes place, it follows that  $m(\beta_{Ca}, \beta_{Mg})$  starts to increase, whereas  $0 < H < 1$  in case of desorption of at least one of the divalent cations. Nevertheless, when all ions have been desorbed, it follows that  $H(\beta_{Ca}, \beta_{Mg}) = 0$ , resulting in a low salinity state. Moreover, the constant  $r$  represents the extent in which the divalent cations desorbed leads to a specific change of wetting state. In other words, it describes how fast  $H(\beta_{Ca}, \beta_{Mg})$  is approaching the low salinity state simultaneously as  $m(\beta_{Ca}, \beta_{Mg})$  increases.

Nowadays, different researchers have been using this approach to model the cation exchange accoupling with other mechanisms. For instance, [16] introduced a detailed chemical reaction model that captures both multiple ion exchange and double layer expansion effects. Nevertheless, other researchers such as [17] suggested an approach to model the double layer expansion effect as the only mechanism contributing to the change in wettability. Similar to the aforementioned mechanisms, the authors also proposed that the relative permeability equation is calculated with an interpolating parameter as a function of the total ionic strength, as shown in the equation below.

$$\theta = \frac{TIS_{max} - TIS(x, t)}{TIS_{max} - TIS_{min}} \quad (18)$$

where  $TIS_{max}$  is the total ionic strength greater than which no wettability alteration occurs and  $TIS_{min}$  is the value at which maximum wettability alteration occurs.

Subsequently, [24] improved the model by changing the interpolating parameter as a function of a dimensionless number, called wetting film stability number, as shown in the following equation.

$$\theta = \max\left(\min\left(\frac{SN(x, t) - SN_{min}}{SN_{max} - SN_{min}}\right), 0\right) \quad (19)$$

where  $SN_{max}$  and  $SN_{min}$  are minimum wetting film stability number, wherein wettability begins to change to a more oil-wet state and maximum wetting film stability number above which no further change to rock wettability occurs. This model has a restriction that  $SN_{min}$  cannot be set below 0.1 and  $SN_{max}$  above 2.0. For the dynamic modeling of wettability alteration, the wetting film stability number can be calculated by the following equation.

$$SN = 0.09\epsilon_r^{1.5}\psi_{oil/brine}\psi_{brine/rock}\sqrt{\frac{T}{I}} \quad (20)$$

where  $\epsilon_r$  is the relative electrical constant of water,  $T$  is temperature in Kelvin,  $I$  is the solution total ionic strength, and  $\psi_{oil/brine}\psi_{brine/rock}$  is the oil/brine and rock/brine zeta potential wherein the multiplication of the two parameters represents the electrostatic force.

#### 4. CONCLUSION

The brief studies concerning the different approaches to model wettability changes showed that despite the selected mechanism, the proposed models have a similar way of modeling the wettability by assuming an interpolating parameter that modifies the relative permeability and capillary pressure curves. Each model has a unique combinations of weighting functions which differentiates the various methods, however there are still many points to be investigated. Thus, a thorough comparison of the approaches through a simulation analysis is required. Therefore, this paper shows that there are numerous approaches to model the effects of LSW in a sandstone reservoir by only one proposed mechanism, hence, to advance in this area of research, a more complete evaluation contemplating all three main mechanisms is needed.

#### Acknowledgments

The authors thank PRH27.1, ANP/FINEP, Centro de Competências em Soluções Integradas Onshore and SENAI/CIMATEC for the financial support and for research incentives.

#### 5. REFERENCES

- <sup>1</sup>DRUETTA, P.; RAFFA, P.; PICCHIONI, F. Chemical enhanced oil recovery and the role of chemical product design. **Applied Energy**, v. 252, n. May, 2019.
- <sup>2</sup>MOHSENATABAR FIROZJAI, A.; SAGHAFI, H. R. Review on chemical enhanced oil recovery using polymer flooding: Fundamentals, experimental and numerical simulation. **Petroleum**, v. 6, n. 2, p. 115–122, 2020.
- <sup>3</sup>KARGOZARFARD, Z.; RIAZI, M.; AYATOLLAHI, S. Viscous fingering and its effect on areal sweep efficiency during waterflooding: an experimental study. **Petroleum Science**, v. 16, n. 1, p. 105–116, 2019.
- <sup>4</sup>BLUNT, M. J. **Multiphase Flow in Permeable Media Multiphase Flow in Permeable Media**, 2017.
- <sup>5</sup>SHALABI, E. W. AL; SEPEHRNOORI, K. **Low Salinity and Engineered Water Injection for Sandstone and Carbonate Reservoirs**. 2017.
- <sup>6</sup>SATTER, A.; IQBAL, G. M. Enhanced oil recovery processes: thermal, chemical, and miscible floods. **Reservoir Engineering**, p. 313–337, 2016.
- <sup>7</sup>SNOSY, M. F.; ABU EL ELA, M.; EL-BANBI, A.; SAYYOUH, H. Comprehensive investigation of low-salinity waterflooding in sandstone reservoirs. **Journal of Petroleum Exploration and Production Technology**, v. 10, n. 5, p. 2019–2034, 2020.
- <sup>8</sup>KATENDE, A.; SAGALA, F. A critical review of low salinity water flooding: Mechanism, laboratory and field application. **Journal of Molecular Liquids**, v. 278, p. 627–649, 2019.
- <sup>9</sup>TANG, G. Q.; MORROW, N. R. Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery. **Journal of Petroleum Science and Engineering**, v. 24, n. 2–4, p. 99–111, 1999.
- <sup>10</sup>LAGER, A.; WEBB, K. J.; BLACK, C. J. J.; SINGLETON, M.; SORBIE, K. S. Low salinity oil recovery - An experimental investigation. **Petrophysics**, v. 49, n. 1, p. 28–35, 2008.
- <sup>11</sup>LIGTHELM, D.; GRONSVELD, J.; HOFMAN, J.; BRUSSEE, N.; MARCELIS, F.;

LINDE, H. VAN DER. Novel waterflooding strategy by manipulation of injection brine composition. **71st European Association of Geoscientists and Engineers Conference and Exhibition 2009: Balancing Global Resources. Incorporating SPE EUROPEC 2009**, v. 2, n. Figure 1, p. 1313–1335, 2009.

<sup>12</sup>NGUYEN, N.; DANG, C.; GORUCU, S. E.; NGHIEM, L.; CHEN, Z. The role of fines transport in low salinity waterflooding and hybrid recovery processes. **Fuel**, v. 263, n. July, p. 116542, 2020.

<sup>13</sup>ROSTAMI, P.; MEHRABAN, M. F.; SHARIFI, M.; DEJAM, M.; AYATOLLAHI, S. Effect of water salinity on oil/brine interfacial behaviour during low salinity waterflooding: A mechanistic study. **Petroleum**, v. 5, n. 4, p. 367–374, 2019.

<sup>14</sup>ESMAEILI, S.; MAAREF, S. Investigating the effect of transient flow behavior from HSW to LSW on oil recovery in low-salinity water flooding simulation. **Journal of Petroleum Exploration and Production Technology**, v. 9, n. 2, p. 1495–1515, 2019.

<sup>15</sup>REZAEIDOUST, A.; PUNTERVOLD, T.; STRAND, S.; AUSTAD, T. Smart water as wettability modifier in carbonate and sandstone: A discussion of similarities/differences in the chemical mechanisms. **Energy and Fuels**, v. 23, n. 9, p. 4479–4485, 2009.

<sup>16</sup>KUZNETSOV, D.; COTTERILL, S.; GIDDINS, M. A.; BLUNT, M. J. Low-salinity waterflood simulation: Mechanistic and phenomenological models. **Society of Petroleum Engineers - SPE Asia Pacific Enhanced Oil Recovery Conference, EORC 2015**, p. 537–555, 2015.

<sup>17</sup>KORRANI, A. K. N.; JERAULD, G. R.; SEPEHRNOORI, K. Mechanistic modeling of low-salinity waterflooding through coupling a geochemical package with a compositional reservoir simulator. **SPE Reservoir Evaluation and Engineering**, v. 19, n. 1, p. 142–162, 2016.

<sup>18</sup>KORRANI, A. K. N. **Mechanistic Modeling of Low Salinity Water Injection**. 2014.

<sup>19</sup>JERAULD, G. R.; LIN, C. Y.; WEBB, K. J.; SECCOMBE, J. C. Modeling low-salinity waterflooding. **SPE Reservoir Evaluation and Engineering**, v. 11, n. 6, p. 1000–1012, 2008.

<sup>20</sup>WU, Y. S.; BAI, B. Efficient simulation for low-salinity waterflooding in porous and fractured reservoirs. **SPE Reservoir Simulation Symposium Proceedings**, v. 1, n. 2008, p. 126–138, 2009.

<sup>21</sup>TRIPATHI, I.; MOHANTY, K. K. Instability due to wettability alteration in displacements through porous media. **Chemical Engineering Science**, v. 63, n. 21, p. 5366–5374, 2008.

<sup>22</sup>SHOJAEI, M. J.; GHAZANFARI, M. H.; MASIHI, M. Relative permeability and capillary pressure curves for low salinity water flooding in sandstone rocks. **Journal of Natural Gas Science and Engineering**, v. 25, p. 30–38, 2015.

<sup>23</sup>OMEKEH, A.; FRIIS, H. A.; FJELDE, I.; EVJE, S. Modeling of ion-exchange and solubility in low salinity water flooding. **SPE - DOE Improved Oil Recovery Symposium Proceedings**, v. 2, p. 990–1002, 2012.

<sup>24</sup>KORRANI, A. K. N.; JERAULD, G. R. Modeling wettability change in sandstones and carbonates using a surface-complexation-based method. **Journal of Petroleum Science and Engineering**, v. 174, p. 1093–1112, 2019.