Buckley-Leverett theory applied in Low-Salinity Water Flooding displacement

João Victor Correia Lopes[1], Luis Fernando Lamas[2], Damianni Sebrão[2]

[1]*PROBIC Scholar and undergraduate student of Santa Catarina State University - UDESC*
Av. Alameda Lourival Cesário Pereira, s/n - Nova Esperança, 88336-275, Balneário Camboriú - SC, Brazil
joaovictorcorreialopes@gmail.com
[2]*Dept. of Petroleum Engineering, Santa Catarina State University - UDESC*
Av. Alameda Lourival Cesário Pereira, s/n - Nova Esperança, 88336-275, Balneário Camboriú - SC, Brazil
luis.lamas@udesc.br, damianni.sebrao@udesc.br

Abstract. In offshore operations, due the amount of sea water, it is common to inject water in the wellbore as an EOR (Enhanced Oil Recovery) method to help maintain reservoir pressure and improve the oil production. However, it is necessary to evaluate the best method where it can improve the recovery factor and avoid spending a lot of money purchasing chemicals and equipments. The recovery factor is impacted by the interaction between the oil and the reservoir rock. The effect of the wettability is an example where the rock needs to be more water-wet than oil-wet to increase the recovery factor. Present studies indicate the injection of water with ion additions, also known as Low Salinity Water Flooding (LSWF), is efficient in wettability change and is cheaper than usual methods in the industry. This work aims to estimate the advance of water and LSWF displacement implementing Buckley-Leverett theory in numerical simulation with Python. Fractional flow, saturation profile, oil recovery factor and pressure drop are the outcomes that indicate higher oil production and lower decay when comparing LSWF to waterflooding.

Keywords: Enhanced Oil Recovery, Low Salinity Water Flooding, Buckley-Leverett theory

1 Introduction

According to Bordeaux-Rego et al. [1] waterflooding as a secondary oil recovery technique remains the most commonly used EOR method in the world. One can relate the success of waterflooding application to its relatively high efficiency in displacing light to medium-gravity crude oils and ease injection into oil-bearing formations. Additionally, water is inexpensive in comparison to other fluids used in Enhanced Oil Recovery (EOR) methods, such as CO2, polymer, and surfactant, making this process very attractive.

Enhanced Oil Recovery (EOR) in carbonate reservoirs can be a great challenge. Carbonate reservoirs are mostly oil-wet and naturally fractured. For this type of reservoirs, primary production is derived mainly from the high permeability fracture system which means that most of the oil will remain unrecovered in the low permeability matrix blocks after depletion. Further difficulties arise under high pressure and high temperature conditions (Gachuz-Muro and Sohrabi [2]).

Extensive laboratory studies and field tests across both clastic and carbonate rock systems have demonstrated enhanced oil recovery through flooding with low salinity water. The oil recovery can be improved during secondary or tertiary waterflooding by controlling the composition of the injected water (Collins et al. [3]). According to Sheng [4], the wettability alteration is the main mechanism as the pH changes from higher or lower than 9 which contributes to more oil displacement.

To model the oil production, the Buckley and Leverett [5] theory can be applied for a better understanding of the reservoir behavior when fluids are injected. Pope [6] creates an extension of the Buckley-Leverett theory, which enable simultaneous immiscible three-phase flow (the classical oil/water/gas flow problem) where can be modified to have the oil recovery with waterflooding as secondary method and LSWF as tertiary method.

In this context, the Buckley-Leverett theory is implemented in numerical simulation with Python, where the input datas is extracted from articles and is presented an evaluation of the best EOR method, comparing the recovery factor and pressure drop.

2 Methodology

A numerical simulation code is developed in Python, where the equations utilized is expressed in Pope [6] with more details. With the datas from Rosland [7] presented in Table 1, is created an array for normalized water saturation from 0 to 1 with *n* intervals, where the properties is calculated for each node.

Table 1. Input datas

Parameter	HS	LS
$k_{rw_0}[-]$	0.3	0.4
$k_{ro_0}[-]$	0.75	0.9
$S_{wc}[\%]$	0.15	0.15
$S_{wi}[\%]$	0.15	0.15
$S_{or}[\%]$	0.3	0.15
$n_w[-]$	2	2
$n_o[-]$	3	3
$\mu_w[Pa{\cdot}s]$	3×10^{-4}	3×10^{-4}
$\mu_o[Pa{\cdot}s]$	6×10^{-4}	6×10^{-4}

Where, the first column is the input parameters and is composed by maximum water relative permeability (k_{rw_0}), maximum oil relative permeability (k_{ro_0}), connate water saturation (S_{wc}), initial water saturation (S_{wi}), residual oil saturation (S_{or}), Corey's water parameter (n_w), Corey's oil parameter (n_o), water viscosity (μ_w) and oil viscosity (μ_o). The values are demonstrated in the other two columns as HS is the high-salinity water and LS is the low-salinity water.

For the pressure drop calculation, the equation is obtained from Darcy's Law for the total (constant) flow as demonstrated in eq. (1).

$$\frac{q}{A} = -\frac{k}{\mu}\frac{\partial p}{\partial x}. \tag{1}$$

Where, for two phase flow the eq. (1) can be expressed in eq. (2).

$$\frac{q}{A} = -\left[\frac{kk_{ro}}{\mu_o} + \frac{kk_{rw}}{\mu_w}\right]\frac{\partial p}{\partial x}. \tag{2}$$

Rearranging terms and isolating the pressure, the eq. (2) results in eq. (3).

$$\partial p = -\frac{q}{Ak}\frac{\mu_w}{\frac{k_{ro}\mu_w}{\mu_o} + k_{rw}}\partial x. \tag{3}$$

Changing the variable x for dimensionless condition, where $x_D = x/L$ and integrating eq. (3), the integrals are obtained as expressed in eq. (4).

$$\int_{p_{in}}^{p_{out}} \partial p = -\int_0^1 \frac{1}{\frac{k_{ro}\mu_w}{\mu_o} + k_{rw}}\partial x_D. \tag{4}$$

The left term in eq. (4) can be replaced by $\Delta p = (p_{in} - p_{out})$, where the pressure drop in dimensionless condition is presented by eq. (5).

$$p_D = \int_0^1 \frac{1}{\frac{k_{ro}\mu_w}{\mu_o} + k_{rw}} \partial x_D. \tag{5}$$

3 Results and Discussions

3.1 Waterflooding

Figure 1 presents the oil displacement behavior as the water is injected in the wellbore pushing the oil in horizontal direction to the produced well.

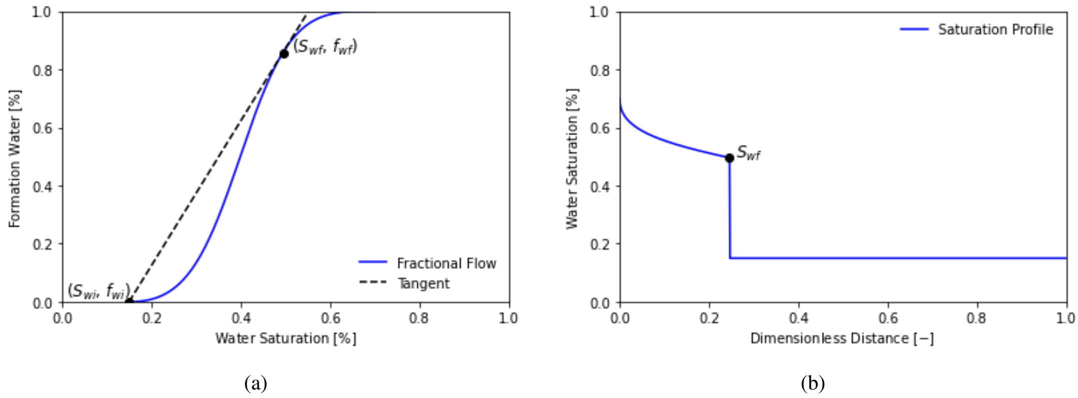


Figure 1. (a) Fractional flow of water and (b) saturation profile

For the fractional flow presented in Fig. 1(a), the initial condition is when formation water (f_w) is zero and water saturation (S_w) is S_{wi}. As the oil is being produced the water front advances increasing water saturation. The point where the tangent touches the "S" curve is the limit of the water-oil contact, where f_w is 0.86% and S_w is 0.49%. Figure 1(b) presents the shock front for a dimensionless time (t_D) of 0.1 where the water have swept the reservoir in 25% of total dimensionless distance (x_D).

The pressure drop presented in Fig. 2 indicates the pressure to time, representing the reservoir pressure while water is injected.

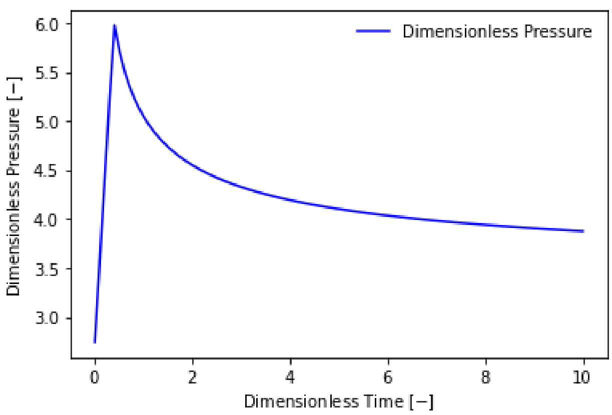
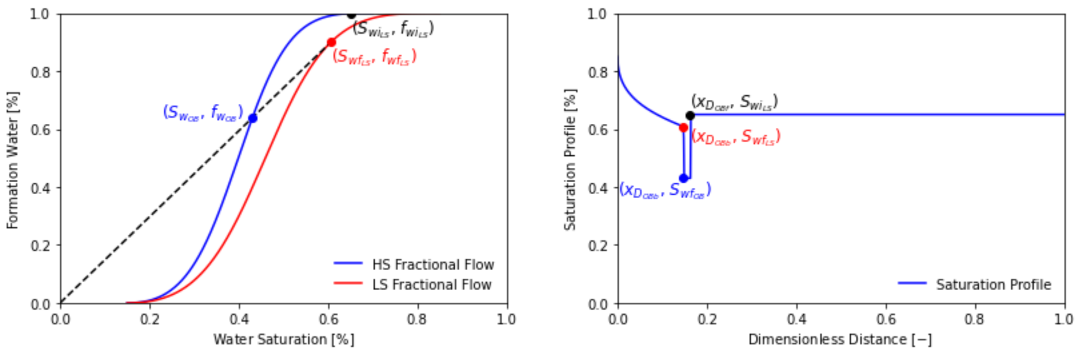


Figure 2. Waterflooding pressure drop

The first peak where the water start pushing the oil with a dimensionless pressure (p_D) of 5.97 begins to decrease while the oil bank is displaced reaching a p_D of 3.87 with a t_D of 10.

3.2 Low Salinity Water Flooding

The LSWF is used as tertiary EOR method after the waterflooding. The difference between those methods is observed in Fig. 3, where the fractional flow in Fig. 3(a) is composed by two "S" curves which the LS curve is displaced in front of the HS curve indicating a sweeper reservoir by the low-salt water front.

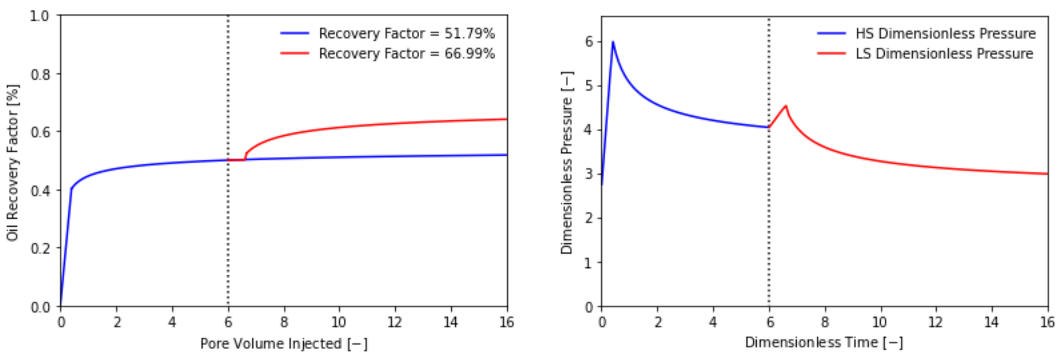


(a) (b)

Figure 3. (a) Fractional flow and (b) average water saturation

With the tangent line starting in zero, is possible to have one touch in each "S" curve obtaining the water and low-salt fronts. The blue point indicates the oil bank saturation, where f_{wOB} is 0.64% and S_{wOB} is 0.43%, the black point indicates the initial water saturation with $f_{wi_{LS}}$ of 0.99 and $S_{wi_{LS}}$ of 0.65, and the red point indicates the limit of low-salt water with $f_{wf_{LS}}$ of 0.90% and $S_{wf_{LS}}$ of 0.61%. Figure 3(b) demonstrates the saturation profile with t_D of 0.1, where it models the back ($x_{D_{OBb}}$) and front ($x_{D_{OBf}}$) of the oil bank in LSWF and represents the low-salt water displacing the oil bank in 10% of the total distance.

For evaluation and point the best EOR method, Fig. 4 presents the oil recovery factor and pressure drop curves analyzing the secondary and tertiary method.



(a) (b)

Figure 4. (a) Recovery factor and (b) pressure drop

Figure 4(a) presents the oil recovery factor, where the tertiary method starts after the water injection of 6 pore volumes. The increase of 15.2% in oil recovery is done after 16 pore volumes of low-salt water. LSWF also contributes for decreasing the pressure drop as demonstrated in Fig. 4(b) reaching a p_D of 3.0 with a t_D of 16.

4 Conclusions

The numerical simulation code built with Python for the application of Buckley-Leverett theory simulate the injection of EOR methods utilized in carbonate rocks in oilfields over the world. This work demonstrates the difference between water and low-salinity water in oil displacement and the increase of water saturation, also influenced by the wettability change where low-salt water presents many other mechanisms which contributes to the rock to be more water-wet than oil-wet.

Even waterflooding being the most common EOR method in the world, due the easy application and over-abundance of seawater, the LSWF presents better results in oil recovery factor with increment of 12.5% in oil production and the pressure drop of LSWF is lower than waterflooding also indicating more oil displaced.

Acknowledgements. The authors express gratitude for PIC&DTI/UDESC program and appreciate the support provided by the SMART Research Group throughout the discussions and research that went into this article.

References

[1] F. Bordeaux-Rego, M. Mehrabi, A. Sanaei, and K. Sepehrnoori. Improvements on modelling wettability alteration by engineered water injection: Surface complexation at the oil/brine/rock contact. *Fuel*, vol. 284, pp. 118991, 2021.

[2] H. Gachuz-Muro and M. Sohrabi. Smart water injection for heavy oil recovery from naturally fractured reservoirs (spe-171120-ms). *Society of Petroleum Engineers - SPE Heavy and Extra Heavy Oil Conference*, vol. Latin America 2014, LAHO 2014, 2014.

[3] I. R. Collins, J. W. Couves, M. Hodges, E. K. McBride, C. S. Pedersen, P. A. Salino, K. J. Webb, C. Wicking, and H. Zeng. Effect of Low Salinity Waterflooding on the Chemistry of the Produced Crude Oil. *SPE Improved Oil Recovery Conference*, vol. Day 4 Tue, April 17, 2018. D041S012R002, 2018.

[4] J. Sheng. Critical review of low-salinity waterflooding. *Journal of Petroleum Science and Engineering*, vol. 120, 2014.

[5] S. E. Buckley and M. C. Leverett. Mechanism of fluid displacement in sands. *Transactions of the AIME*, vol. 146, n. 01, pp. 107–116, 1942.

[6] G. A. Pope. The application of fractional flow theory to enhanced oil recovery. *Society of Petroleum Engineers Journal*, vol. 146, n. 20, pp. 191–205, 1980.

[7] F. A. Rosland. Modelling of water-oil flow in reservoirs including effects from gravity, capillary pressure and water rock chemistry. Master's thesis, Universitetet i Stavanger, Norway, 2013.