Introduction

Low-salinity waterflooding (LSWF) is an attractive IOR/EOR solution for both of sandstone and carbonate reservoirs. By injecting brine with modified composition and typically with reduced salinity (compared to the reservoir resident water), the wettability of the reservoir rock can be altered toward a more water-wetting state and/or the residual oil saturation can be decreased (Bartels et al. 2019; Mahani et al. 2015; Mahani et al. 2016; Morrow & Buckley 2011).

Although the process of designing LSWF appears to be simple and straightforward, there are important aspects which should be considered for a successful field operation. Among them is physical dispersion which can occur during any miscible flooding process (Brigham et al. 1961; Sorbie & Mackay 2000). Once the low salinity (LS) brine is injected into a reservoir, which already contains brine with higher salinity (either as initial formation brine or as high salinity (HS) brine injected prior to low salinity injection), these brines with different salinities are mixed at the displacement front and the performance of LSWF could be significantly affected (Attar & Muggeridge 2018). Mixing is enhanced by the small scale heterogeneity and can result in deceleration of oil recovery, therefore a higher volume of low salinity brine should be injected to compensate for it (Attar & Muggeridge 2018; Jerauld et al. 2006). This would negatively impact the project economics.

In this paper, the aim is to address (in-situ) mixing by adding (a small amount of) polymer to the LS brine and assess the resulting reduction of the physical dispersion. In this regard, sandpack flooding experiments were designed and executed. The ability of polymer to control mixing was monitored and evaluated by measuring the effluent brine salinity as function of pore-volume (PV) injected and comparing the inferred dispersivity under different salinity gradients and polymer concentrations.

Methodology

The sandpack experiments were performed at ambient condition. The physical properties of the sandpack is presented in Table 1. Two different grain sizes of sand (SiO$_2$) were used in all of the performed tests to arrive at the desirable porosity and permeability. Four sandpack tests were performed and the design of these tests are presented in Table 2.

<table>
<thead>
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<th>Table 1. The properties of the fabricated sandpack</th>
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<td>Length (cm)</td>
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<td>Diameter (cm)</td>
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<td>Porosity (fraction)</td>
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<td>Permeability (Darcy)</td>
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In tests #1 and #2, the HS brine was composed of 100,000 ppm NaCl while in tests #3 and #4, 40,000 ppm NaCl solution was used as the HS brine. 2,000 ppm and 4,000 ppm NaCl brine was used as LS brine. 200 ppm HPAM polymer was also added to the LS solution in two of the performed tests (test #2 and #4). In order to visually track the salinity front during the flooding, the LS brine was dyed blue using a food coloring agent (5 vol%). The possible impact of coloring agent on the conductivity of the brines was investigated and accounted for in the calculations.

<table>
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<th>Table 2. The design of performed sandpack experiments</th>
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<td>Test No. HS</td>
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The flooding experiments started with injecting HS to the porous medium at a fixed injection rate of 0.2 cc/min (equivalent to 4.5 ft/day displacement velocity). Using an electrical conductivity (EC) meter, the salinity of the effluent brine was continuously monitored and recorded. Once the salinity (conductivity)
of the effluent brine was stabilized and equal to the salinity of HS, LS was injected. The same injection rate was used for LS injection and the value of EC was recorded versus time. Once the salinity of the effluent was reduced to the EC value of LS, injection was ceased. Thereafter the salinity profiles (or breakthrough curves) were fitted with an analytical advection-dispersion model (Eq. 1-3) to calculate the “apparent” dispersivity (α) of the system (Green & Willhite 1998):

\[ C_B = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{L - ut}{2\sqrt{D}t} \right) \right] \]  
\[ C = C_{HS} - C_B (C_{HS} - C_{LS}) \]  
\[ D = ua \]  

where \( C, C_{HS} \) and \( C_{LS} \) designate brine salinity, salinity of HS brine and LS brine salinity respectively. \( L, u, t \) and \( D \) are sandpack length, interstitial velocity, time and dispersion coefficient, respectively.

**Results & Discussion**

As mentioned earlier, the degree of mixing/dispersion during LSWF process could be evaluated by comparing the value of dispersivity from different tests. The visual inspection indicates that the length of mixing zone can be reduced significantly by adding polymer. **Fig. 1** and **Fig. 2** compare the advancement of the dyed LS brine through the porous medium in absence and presence of 200 ppm HPAM in the LS at two PVs. In the case of polymer-free LS brine (see **Fig. 1**), mixing of LS (dyed blue) and HS resident brine is high (as they are miscible phases) and an extended transition zone from high-salinity to low-salinity region is observed. Comparing the length of mixing zone in 0.14 PV and 0.72 PV shows that this transition (mixing) zone grows with time (theoretically with square root of time). Conversely, when 200 ppm of HPAM is added to the LS brine, the front becomes sharper and less dispersed because mixing of HS and LS is lessened and the length of transition zone is significantly reduced. Even after 0.72 PV injection of LS, the mixing of brines with different salinities has been controlled, as such the breakthrough of the LS has been delayed. Less dispersion of LS into HS implies that the pore-scale occupancy of LS or displacement efficiency has increased. Dispersion control by adding polymer is believed to be rooted in viscosity increase. Once 200 ppm of polymer is added to the LS brine, the viscosity of brine increases 2 to 3 times (as a function of shear rate) which help reduce viscous instabilities at the LS and HS contact line.

![0.14 PV](image1) ![0.72 PV](image2)

**Fig. 1.** Dyed LS brine displacing the resident high salinity brine in the sandpack in absence of polymer (flow direction in from right to left).

![0.14 PV](image3) ![0.72 PV](image4)

**Fig. 2.** Dyed LS brine displacing the resident high salinity brine in the sandpack in the presence of polymer (flow direction in from right to left).

Based on the above observations, it can be qualitatively concluded that augmenting LS with polymer reduces the degree of mixing between HS and LS brines and the front becomes sharper. Further analysis was conducted to quantify the changes in dispersivity based on fitting the analytical advection-dispersion solution to the experimental data. The salinity profiles corresponding to tests in Table 1 have been presented in **Fig. 3-4.** The dispersivity of the test #1 was estimated to be 0.0069 ft and the
associated Peclet number is 118.9. Once polymer is added to the same brine (i.e. in test #2), the dispersivity is reduced to 0.0018 ft. and Peclet number is increased to 455.7. The significant decrease of dispersivity is due to the fact that mixing of high- and low- salinity brines are lowered thanks to the presence of polymer. Comparison of test #3 and test #4 also shows a similar effect and the dispersivity has decreased from 0.0041 ft. in test #3 to 0.0012 ft. in test #4. In this case, the Peclet number has increased from 200.1 to 683.5. The dispersivity has been reduced more than three times in both cases which proves the concept of mixing control by polymer.

![Graph](image)

**Fig. 3.** Dimensionless salinity profile during tests #1 & 2.

Another aspect that could be pointed out is the impact of salinity gradient on the dispersivity of the salt in porous medium. Comparison of test #1 and test #3 shows that dispersivity depends on salinity gradient. A higher salinity gradient resulted in greater mixing of brines. In test #1, the salinity of HS brine is 50 times of the LS and the estimated dispersivity is 0.0069 ft. On the contrary, in test #3, the salinity of HS brine is 10 times of the LS and the estimated dispersivity is 0.0041 ft. Since The operating conditions including temperature and injection flow rate were similar in all experiments, this effect is attributed to the salinity gradient of HS and LS. Comparing the impact of salinity gradient on the dispersivity of test #2 and test #4 where polymer was added to LS, reveals a similar trend. The
dispersivity of test #2 and test #4 were estimated to be 0.0018 ft. and 0.0012 ft., respectively. Therefore, the higher is the salinity gradient, the larger the dispersivity becomes.

Conclusions

Sandpack experiments were performed to evaluate the possible positive impact of adding polymer to the low salinity brine on the degree of physical dispersion during the LSWF. It was observed that the salt dispersion can be suppressed by adding polymer to the LS brine. Dispersivity was reduced by 70% after adding 200 ppm of HPAM polymer, implying that the length of mixing zone can be diminished. Thus, a significantly lower volume of LS brine would be required to displace the HS brine and establish LS in the pores which is a prerequisite for low salinity effect. Moreover, the salt dispersion was found to be higher when the salinity gradient imposed in the system increased; both in absence and presence of polymer. While understanding of the dependency of dispersivity to salinity gradient requires further investigation, it is believed to be related to the salinity dependency of brine viscosity and polymer solution rheology and polymer interaction with porous medium. To account for these complexities not captured in the analytical solution of the advection-dispersion equation, detailed calculations and analysis using numerical simulation will be carried out.

References


