AN EXPERIMENTAL STUDY OF SURFACTANT SLUG ENHANCED WATERFLOODING: IS IT POSSIBLE TO USE LESS SURFACTANT AND ACHIEVE HIGH OIL RECOVERY?

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ABSTRACT

A novel EOR technique known as surfactant-slug enhanced waterflood (SSEW) technique is presented in this study. The underlying motivation for the development of this EOR method was to achieve high oil recoveries without using large quantities of surfactants by soaking the area around the injection or production well with an optimally concentrated surfactant slug prior to conducting a waterflood. The surfactant was left to soak in order to change the wettability in the well region and thus improve the conductance of the oil to the producing well. This study was aimed to evaluate the technical feasibility of the proposed improved waterflood method, and also its effectiveness when compared to a conventional waterflood and surfactant flood. This process can be used in any reservoir that is suitable for water injection. Two variations of this novel process were investigated where 0.2 pore volume (PV) of surfactant slug was injected in the area around the (1) production and (2) injection well and thus improving waterflood recovery from 47% to 55% and 67%, respectively. This proves that when surfactant is used efficiently a dilute solution is sufficient to significantly improve recovery. Therefore, a small investment of 10% (0.2PV) of the ideal surfactant solution can be used efficiently to net significant improvements in recovery. This study found that both variations of the improved waterflood method were technically feasible, and were more effective in improving oil recovery than a conventional waterflood. In addition, they accomplished the task of significantly improving oil recovery with only small quantities of surfactant.

INTRODUCTION

A previous experimental study by Ayirala [1] reported the development of mixed wettability using a nonionic surfactant (NEODOL™ 91-8), Yates oil, and Yates synthetic brine in a Berea core. At this mixed-wet state he was able to recover about 94% of the original oil in place (OOIP) after flooding the reservoir with 3500ppm surfactant solution for 2PV. Therefore, is it possible to achieve a considerable fraction of such extraordinary recoveries when using a fraction of the surfactant typically used? This study proposes the surfactant-slug enhanced waterflood (SSEW) method that combines the benefits of waterflooding and surfactant flooding [3]. The two variations of SSEW examined in this study are soaking the area around the production well and injection well prior to conducting a waterflood. The motivation behind this process is to favorably alter the wettability and decrease interfacial tension (IFT) either around the injection or production well. Treating the injection well may increase injectivity of the well, as treating the production well may improve the conductance of the oil to the producing well. Both variations are illustrated in Figure 1. The effectiveness of the SSEW process was compared to that of conventional waterflood and conventional surfactant flood.

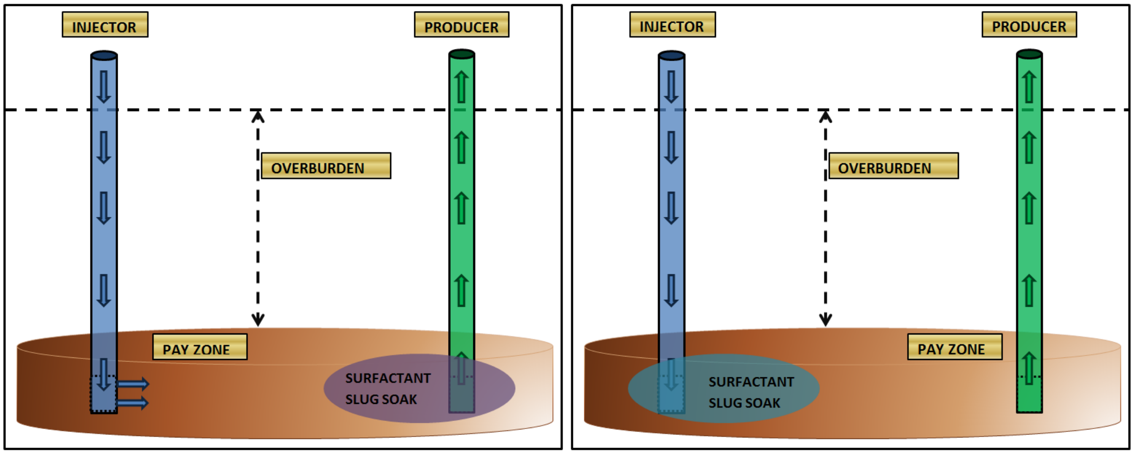


Figure 1: Surfactant-slug enhanced waterflood (SSEW) technique – the two figures illustrate the two variations of this process where the area around the producer (left) or that around the injector (right) is soaked with surfactant prior to waterflooding.

EXPERIMENTS

This project was based on Ayirala's [1] findings where he examined the effect of surfactants on relative permeabilities. Therefore, the same rock fluid systems were used, which included Berea sandstone, Yates oil, Yates synthetic brine, and decane (for non-reactive system). In addition, all corefloods were conducted under Yates reservoir conditions of 700psi and 82°F. A coreflood simulator [2] was used to generate relative permeability curves and fractional flow curves using the recovery and pressure data collected for the coreflood experiments. Each experiment was evaluated based on its recovery, pressure drop, fractional flow curves, saturations, and relative permeability. This study only reports measured recoveries.

SSEW Procedure

After initial conditions were established in the core, a surfactant slug of 0.2PV was injected in the area surrounding the production outlet (Figure 2) or around the injection inlet. The pressure rapidly increased as the slug was injected and thus the inlet or outlet valve, respectively, was opened to relieve the excess pressure. Consequently some oil was produced which prompted a new initial water saturation and oil in place to be calculated. Thereafter, the surfactant was left to soak for the required period of time, and lastly, waterflooding or surfactant flooding was initiated.

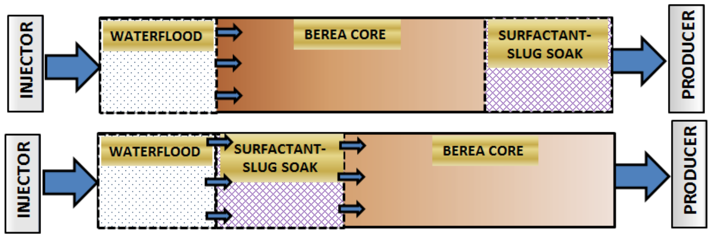


Figure 2: Schematic of an improved waterflood or improved LC surfactant flood in the core

The oil recoveries of both SSEW variations were compared to each other and to a waterflood and surfactant flood. Each coreflood was repeated 2-4 times and the results were found to be highly reproducible. For each coreflood, oil recovery and pressure drops versus time were recorded.

Experiment Design

This experimental study was divided into four sets of experiments where each set of experiments builds on the previous one. The first three sets were used to optimize different parameters of the proposed SSEW process. The first set of experiments determined the ideal surfactant concentration by conducting corefloods of different surfactant concentration. The concentration yielding the highest recovery and did not form viscous emulsions was considered to be ideal. The second set of experiments determined the ideal surfactant slug soaking period prior to a waterflood. After the initial conditions were achieved in the core, a 0.2PV surfactant slug was injected around the production well and soaked for 1 hour, 12 hours, and 24 hours in separate experiments. After the soaking period was completed, a waterflood was performed and the oil recovery was recorded. The third set of experiments investigated the effects of varying the surfactant slug size injected around the production well. After the initial condition was achieved in the core, a surfactant-slug of specified volume was injected, allowed to soak, after which a waterflood was carried out. The three surfactant slug volumes examined were: 0.1PV, 0.2PV, and 0.3PV. The last set of experiments examined different forms of the variations of SSEW proposed. The results were compared to a conventional waterflood, low concentration (1000 ppm) surfactant flood, and an ideally concentrated (3000 ppm) surfactant flood.

RESULTS

Set 1: Determination of an Ideal Surfactant Concentration

The objective of this set of experiments was to find the ideal surfactant concentration for the two examined rock fluid systems. The difference in both rock fluid systems is the oil type used and its influence on wettability. Decane is considered non-reactive because it does not interact with Berea thus the rock remains water-wet. Yates crude oil does have the potential of interacting with Berea rock and thus rendering the rock oil-wet or mixed-wet. Berea rock exhibited water-wet conditions for both reactive and non-reactive systems; however, when exposed to 3000ppm of surfactant, the wettability of the reactive system transitioned to a mixed-wet state. Figure 3 illustrates that the recoveries from the reactive case are higher than those in the non-reactive case. Higher surfactant concentrations were attempted; however, the surfactant formed thick emulsions that produced high pressure drops that are unfavorable. Therefore, those attempts are not included in this analysis. In addition, oil recovery significantly increases from 47% to 94% as the surfactant concentration is increased from 0ppm to 3000ppm in the reactive case. In the 0ppm flood, oil was not produced after breakthrough, while in the 1000ppm flood very little oil was produced after breakthrough. This behavior is indicative of water-wet conditions. However, in the 3000ppm flood a significant amount of oil was produced after breakthrough leading to very high oil recovery of 94%. The significant oil production after breakthrough that lead to low residual oil saturations indicate the core is neither oil-wet nor water-wet but rather mixed-wet as postulated by Salathiel [4]. This wetting state is formed in the presence of surfactant, where the water film initially coating the rock surface becomes unstable due to the extent of adsorption of surfactant molecules at the rock-water interface compared to that at the oil-water interface. Also, the orientation of surfactant molecules at these interfaces does add to the instability of the water film. This instability of the water film at the interface, results in oil-water-rock interactions forming a continuous oil-wet path for favorable displacement of oil which resulted in the gradual increase of recovery after breakthrough.

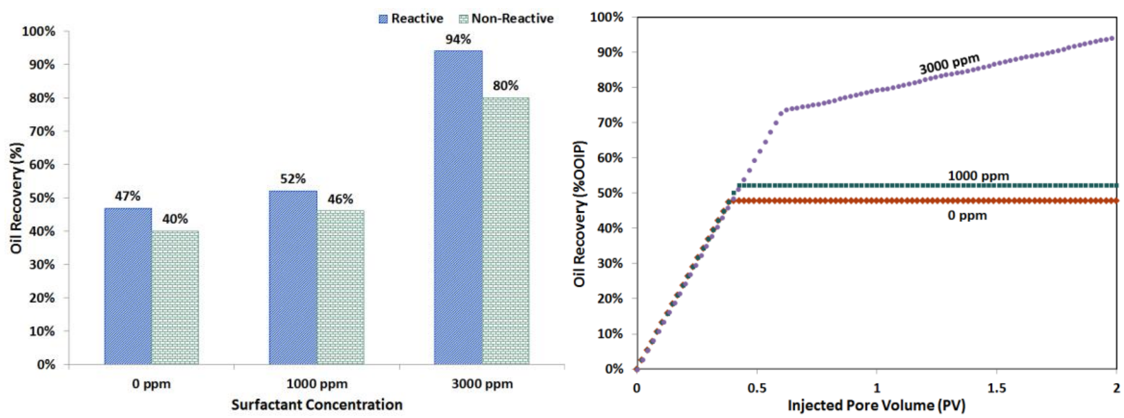


Figure 3: Recovery factors of the reactive and non-reactive cases

Sets 2 and 3: Determination of Ideal Surfactant-Slug Soaking Time and Size

Using the ideal surfactant concentration of 3000ppm and a slug size of 0.2PV, the effect of surfactant-slug soaking time on oil recovery was investigated. Figure 4 illustrates that the soaking period does influence the amount of oil recovered. The ideal soaking time was determined to be 12 hours for a 0.2PV surfactant-slug.

The effects of varying the surfactant slug size were then examined using a concentration of 3000ppm and 12 hour soak time. The results presented by Figure 4 indicate that no increment in recovery was observed at 0.1PV which can be attributed to the volume of surfactant not being sufficient to effectively alter the wettability and/or IFT of enough of the rock and thus influence the recovery. In the case of 0.2PV and 0.3PV slug sizes, production was increased by 8% and 15%, respectively. The larger the surfactant slug size, the larger the area whose wettability is altered and therefore, higher recovery.

As indicated by the above results, the size of surfactant slug soaked has a significant effect on the recovery. A conventional waterflood and an ideal surfactant flood (3000ppm) where the fluid was injected for two pore volumes (PV) resulted in a recovery of 47% and 94%, respectively. Thus, if the core is treated with pore volumes between 0 and 2PV, the recoveries are expected to fall between 47% and 94%. The observed results in this section followed this hypothesis well.

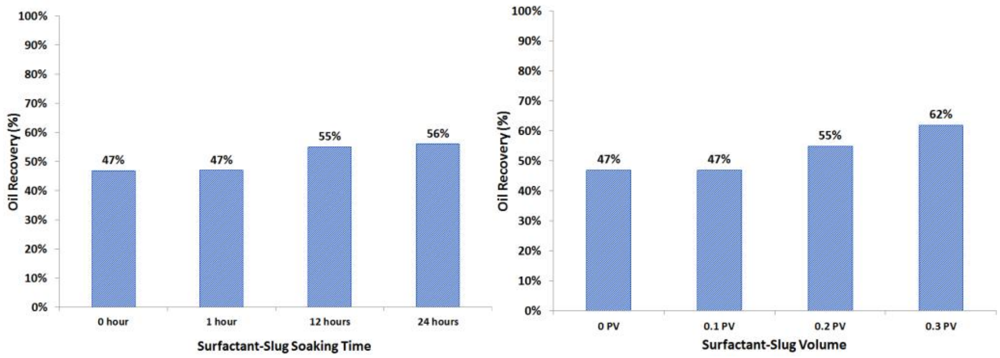
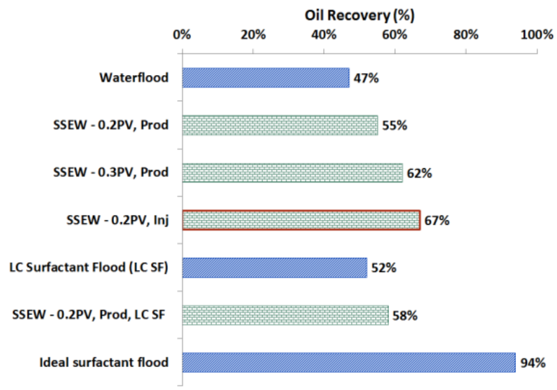


Figure 4: Left figure shows recovery factors achieved by varying the soaking time of the surfactant-slug prior to conducting a waterflood. Right figure shows recovery factors achieved by varying the surfactant-slug size prior to conducting a waterflood

Set 4: Comparison of SSEW, Conventional Waterflood, and Surfactant Flood

In this section, two variations of SSEW were tested and their results were compared to the conventional waterflood and surfactant floods and the results are illustrated by Figure 5. Soaking the production and injection well with 0.2PV of an ideally concentrated surfactant slug prior to conducting a waterflood, improved the oil recovery from 47% to 55% and 67%, respectively. This indicates that treating the injection zone is more effective than treating the production zone prior to a waterflood. When the surfactant slug is injected around the production well it displaces the oil away from the production well. In addition, the only means to improve recovery is by the surfactant altering the wettability of the soaked area and also by allowing time for the surfactants to diffuse to the rest of the core. The surfactant diffuses from the production side to the injector side (backwards), therefore, requiring a longer soaking period for the surfactant to be dispersed throughout the entire core. On the other hand, when the surfactant slug is injected from the injector side the oil is displaced towards the production well. The injected surfactant slug alters the wettability of the soaked zone. Secondly, when the waterflood displaces the surfactant slug from the injection zone to the production well the whole core is exposed to surfactant.

In addition, it was observed that flooding the core with a low concentrated (1000ppm) surfactant solution (instead of water) after soaking the well with an ideally concentrated surfactant slug increased the recovery by 11% when compared to a waterflood, and by 5% when compared to a conventional SSEW where the production zone is soaked. All in all, it is clear that the SSEW technique does not produce as high recoveries as those observed by an ideally concentrated surfactant flood. However, this process does significantly increase the oil recovery of a waterflood by a significant amount while using a small fraction of the surfactants used in an ideally concentrated surfactant flood.



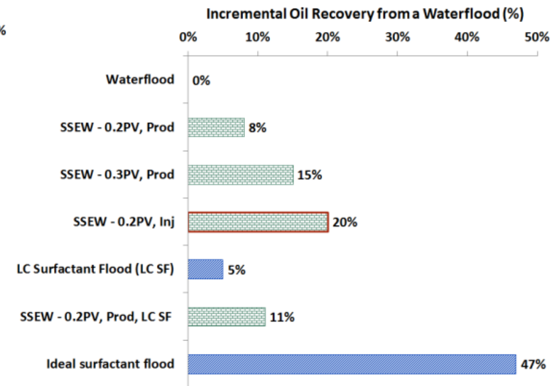


Figure 5: Comparison in the oil recovered by SSEW technique versus conventional waterflood, low concentrated (1000ppm) surfactant flood, and ideally concentrated (3000ppm) surfactant flood.

CONCLUSION

The objective of this study was to evaluate whether the proposed improved SSEW technique was technically feasible, and also to determine its effectiveness when compared to a conventional waterflood. The experimental results clearly established that the SSEW method is feasible and is more effective than a conventional waterflood especially when the area around the injection well is treated with a surfactant soak. Therefore, it is possible to increase oil recovery by using a small fraction of surfactant typically used in a traditional surfactant flood. Using 0.2PV of ideally concentrated surfactant oil recovery was increased from 47% to 52% and 67% using the first and second SSEW variations, respectively. To exploit these findings in the field, upscaled laboratories studies and simulations are needed to provide a clearer understanding of the benefits and challenges of the SSEW technique. As the challenges are realized, modifications maybe made to this process for it to be suitable for field implementation. All in all, this project did establish that it is feasible to use a fraction of surfactants typically used in a conventional surfactant flood, to significantly improve the waterflood process.

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