**Exploitation and Optimization of Reservoir Performance in
Hunton Formation, Oklahoma**

QUARTERLY TECHNICAL PROGRESS REPORT

Submitted by

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Abstract

West Carney field – one of the newest fields discovered in Oklahoma – exhibits many unique production characteristics. These characteristics include:

- 1) decreasing water-oil ratio;
- 2) decreasing gas-oil ratio followed by an increase;
- 3) poor prediction capability of the reserves based on the log data; and
- 4) low geological connectivity but high hydrodynamic connectivity.

The purpose of this investigation is to understand the principal mechanisms affecting the production, and propose methods by which we can extend the phenomenon to other fields with similar characteristics.

In our experimental investigation section, we continue to describe the use of surfactant to alter the wettability of the rock. By altering the wettability, we may be able to recover additional oil through imbibition and gravity drainage process.

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Executive Summary

A significant amount of oil will still remain in the ground after the primary recovery is complete. In this report we present one possible technique of recovering additional oil by injecting surfactant in the reservoir. By altering the wettability of the rock and through gravity assisted drainage process, it is possible to recover additional oil from the reservoir. We validate our hypothesis using both experimental and simulation methods. Up to 50% of the initial oil in place can be recovered from fractured limestones in 50 days at the laboratory scale by surfactant-aided gravity drainage. As the interfacial tension increases, the oil recovery rate increases for a final wettability of 75° . Higher wettability alteration (towards water-wet) leads to faster oil recovery. This effect is larger at higher IFT. Gravity-driven flow is important at the later part of imbibition, capillarity-driven flow is important in the beginning and both these mechanisms are important in between.

Experimental

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Introduction

The objective of the third phase of this project is to test the feasibility of improved recovery in the Hunton reservoir. Because the reservoir is fractured and parts of the matrix may be oil-wet, a large amount of oil may be trapped in the matrix. Surfactant solutions can be introduced into the fractures which can diffuse into the matrix and change the wettability to moderately water-wet.¹ Then surfactant water can then displace the oil by gravity drainage. We have conducted this surfactant-aided gravity drainage process in low permeability limestone cores with permeability typical of the Hunton reservoir. We have developed a simulator to model this process mechanistically and investigated the sensitivity to interfacial tension reduction and wettability alteration. These results are described in this report.

Simulation Method

A single fracture block is simulated for surfactant brine imbibition process. A cylindrical matrix block is considered, as shown in Fig. 1. This is similar to the laboratory experiments done in cylindrical cores. The core is discretized in radial (r) and axial (z) directions. In this simulation, surfactant brine surrounds the fracture block and the surfactant diffuses into the matrix. The surfactant then alters the IFT between oil and brine and also changes the wettability of the rock. This leads to further imbibition of the surfactant brine solution and oil recovery.

Fig. 1: Illustration of simulation problem.

The features of the matrix block are given in Table. 1. The surfactant surrounding the core as shown in Fig. 1 is taken to be at 0.05 wt % and it lowers the IFT to a final value of 0.01 mN/m and changes wettability to a final value of 75°, in the base case. The IFT and wettability are altered inside the porous media as function of surfactant concentration. The changes in IFT and wettability lead to changes in capillary pressure and relative permeability.²

Table 1	
Properties of the core used for imbibition	
Porosity	22.0 %
Permeability(mD)	7
S_{or}	25.0 %
S_{wr}	27.5 %
$k_{r_{wet}}^0$	0.1
n_{wet}	4.5
$k_{r,nw}^0$	0.9
n_{nw}	2.25
IFT reduction	30 to 0.01 mN/m
Surfactant Conc.	0.05 wt %
Wettability alteration	160^0 to 75^0

Table 1: Material properties

Results and Discussion

Recovery from an oil-wet core by using surfactants depends on various parameters. The important parameters which are analyzed by the simulator are the ability of the surfactant to alter wettability and to lower interfacial tension. The results of these simulations are discussed in this section.

Effect of IFT Reduction

The oil recovery from an oil-wet core starts by diffusion of the surfactant molecules into the porous media, and when the surfactant reaches the oil-water interface, it reduces the interfacial tension between the two phases. This reduction in the IFT leads to decrease in the macroscopic bond number N_B^{-1} . This reduction leads to imbibition of water into the rock surface thereby displacing the oil by buoyancy forces. The extent of recovery depends on the decrease in the IFT between the two phases but also depends on the extent of wettability alteration by the surfactant. Consider three cases: A) Surfactant which alters the wettability of the porous media to water-wet in nature. In this case, the primary mode of oil recovery is by capillary forces. A reduction in IFT

in this case reduces the capillary forces, thereby slowing the rate of recovery. B) Surfactant which does not alter the wettability of the porous media, or alters wettability slightly where the final state is still oil-wet in nature. In this case the primary mode of oil-recovery would be by buoyancy forces, and hence a decrease in IFT can lead to increase in the rate of recovery, as more area of the porous media can be invaded by decrease in IFT. C) Wettability is altered to an intermediate wet regime. In this case, any reduction in IFT causes no reduction in the capillary forces, and no change to buoyancy forces, hence the recovery should be independent of IFT. The recoveries also depend on the permeability of the porous medium. The effect of IFT and permeability for 75° final contact angle is shown in the following.

In this case, surfactant is assumed to alter the wettability of the porous medium as a function of surfactant concentration (as explained in earlier section) from initial state of 150° contact angle to a final state of 75° contact angle. The dimension of the core is 0.04 m in diameter and 0.1 m in length. Note that the permeability is 7mD. The IFT for the system is varied from 30mN/m (implying no decrease in IFT), 1 mN/m, 0.1 mN/m (as would be the case for cationic surfactants) and 0.001 mN/m (as would be the case with some anionic surfactants). The recovery rates for these cases are shown in Fig. 2.

Fig. 2: Recovery rates for a 7 mD core

As expected a decrease in IFT leads to decrease in the rate of recovery, because for water-wet case decreasing IFT decreases the capillary pressure which is the driving force for recovery. As the IFT is reduced the effect of permeability reduction becomes more and more prominent. In case of IFT of 0.001 mN/m, the 0.1 mD and 7 mD curves are recalibrated with capillary dimensionless group and gravity dimensionless group to 150 mD curve. For example, for 0.1 mD the time is readjusted by multiplying the original time by (0.1/150) to match the 150 mD time with gravitational scaling, and multiplied by $(0.1/150)^{1/2}$ to match 150 mD time with capillary scaling. Fig. 3 shows the calibration of the gravitational scaling. Fig. 3 shows that at later times with recovery > 60%, all the plots match to a single curve, indicating that the major mechanism of recovery after 60% of oil is recovered is by gravitational means.

Fig. 3: Scaling of 0.001 mN/m IFT reduction and 75° final contact angle curve with gravitational scaling group to match 150 mD curve.

Fig. 4 shows the calibration of the capillarity scaling. At earlier times with recovery < 20%, all the plots match to a single curve, indicating that the major mechanism of recovery before 20% of oil is recovered is by capillary forces. In the region of 20% recovery to 60% recovery, neither of

the dimensionless groups work as both capillarity and gravity are equally important in this regime.

Fig. 4: Scaling of 0.001 mN/m IFT reduction and 75° final contact angle curve with capillary scaling group to match 150 mD curve.

Effect of Wettability Alteration

The effect of wettability on oil recovery depends on the extent of IFT reduction, in principle. The simulations in the previous subsection can be used to plot the recoveries for a given IFT and permeability with varying contact angle. In general, as the contact angle decreases, meaning surfactant alters wettability towards water-wet regime, for a capillary driven process (high IFT surfactants), the capillary pressure becomes a higher positive value, hence more water-wet rock increases the rate of recovery. For a low IFT system, as the contact angle decreases, the capillary pressure becomes a negative value, but because of low IFT, the capillary pressure is still a low value. On the other hand as the wettability becomes more towards water-wet regime, oil phase becomes non-wetting, hence its relative permeability increases, which leads to increased oil

recovery. From these arguments, it can be seen that irrespective of IFT reduction a decrease in contact angle, going towards more water-wet regime increases the rate of oil recovery.

This section shows the effect of contact angle variation for a given IFT reduction and permeability of the core. Only IFT of 1 mN/m and 0.001 mN/m results are shown to explain the results for a cationic surfactant and anionic surfactant system. Fig. 5 shows the effect of contact angle for a surfactant which lowers IFT to 0.1 mN/m for different permeabilities. We can see that as the surfactant alters wettability to water-wet regime, the rate of oil recovery increases. The effect of wettability alteration becomes more important as the permeability decreases.

Fig. 5: Effect of wettability alteration for a surfactant which lowers IFT to 1 mN/m for 7 mD porous media.

Fig. 6 shows the effect of contact angle for a surfactant which lowers IFT to 0.001 mN/m for different permeabilities. This is a representative of anionic surfactant, and we can see that as the surfactant alters wettability to water-wet regime, the rate of oil recovery increases. The effect of wettability alteration becomes more important as the permeability decreases.

Fig. 6: Effect of wettability alteration for a surfactant which lowers IFT to 0.001 mN/m for 7 mD porous media.

Conclusions

Up to 50% of the initial oil in place can be recovered from fractured limestones in 50 days at the laboratory scale by surfactant-aided gravity drainage. As the interfacial tension increases, the oil recovery rate increases for a final wettability of 75°. Higher wettability alteration (towards water-wet) leads to faster oil recovery. This effect is larger at higher IFT. Gravity-driven flow is important at the later part of imbibition, capillarity-driven flow is important in the beginning and both these mechanisms are important in between.

References

1. Seethepalli, A., Adibhatla, B., and Mohanty, K. K., "Physicochemical Interactions during Surfactant Flooding of Fractured Reservoirs," *SPE J.*, **9** (4), 411-418 (December, 2004).
2. Adibhatla, B., Sun, X., and Mohanty, K. K., "Numerical Studies of Oil Production from Initially Oil-Wet Fracture Blocks by Surfactant Brine Imbibition," SPE 97687, SPE International Improved Oil Recovery Conference, Kuala Lumpur, Malaysia, 4-6 December, 2005.

Engineering and Geological Analysis

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One of the biggest difficulties we found in examining the recoveries from reservoirs which are de-watered is the fact that the recoveries of oil and gas are extremely low during the early depletion phases. However, as the pressure is reduced, the recoveries increase significantly. This is in contrast to typical oil reservoirs where the recovery during the early depletion is a lot higher and as the pressure declines, the incremental recovery becomes very small. Intuitively this is not surprising since in a de-watering project the expansion energy is largely consumed in producing water in early stages and, only after we recover significant quantities of water, the expansion energy is used to recover additional gas and oil. We need to develop a better procedure to explain this behavior. Currently, we are developing a better material balance procedure to explain this behavior. We will have the details of the method as well as validation of this method using field data in the next report.

Technology Transfer

1. Adibhatla, B., Mohanty, K.K.: "Oil Recovery from Fractured Carbonates by Surfactant-Aided Gravity Drainage: Laboratory Experiments and Mechanistic Simulations," SPE 99773, paper presented at the SPE/DOE IOR Symposium, Tulsa, OK, April 22-26, 2006.

Conclusions

Based on the material presented in this report, the following conclusions may be drawn:

- Use of surfactants can help us to change the wettability of the rock. If we can change the wettability of the rock from moderately oil wet to water wet, additional oil can be recovered using imbibition process
- The feasibility of surfactant displacement as a potential recovery process is validated using both simulation and lab studies.