OIL RECOVERY BY IONIC SURFACTANT AND SWEEP EFFICIENCY STUDY IN SANDSTONES

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Abstract. In this work, we have investigated the oil recovery performance, adsorption, sweep and displacement efficiency by ionic surfactants. In the adsorption and recovery assays, a surfactant aqueous solution at a concentration 30% above the corresponding critical micelle concentration (c.m.c.) was used to ensure micelle formation. The results obtained showed that the ionic surfactant recovered 89.0% of the original oil in place. High efficiency was provided both in the displacement assays, observed by oil recovery in core, and in the swept, due to the fact that the viscosity of the surfactant solution (3.0 cP) was close to that of the oil (2.9 cP).

Keywords: surfactant; enhanced oil recovery; adsorption; sweep and displacement efficiency

1. INTRODUCTION
When a fluid of lower viscosity, e.g. water, displaces one of higher viscosity, e.g. oil, in a porous medium, the displacement front between the fluids invariably becomes unstable. These interfacial instabilities, which are initiated by local heterogeneities in the porosity and permeability of the porous medium, result in fingering of the displacing fluid into the displaced fluid. This so-called viscous fingering phenomenon is responsible for premature breakthrough of the displacing fluid, thereby leading to a reduced displacement efficiency recovery of the displaced fluid. This has serious economic implications during secondary and tertiary recovery of oil from underground reservoirs by aqueous fluid injection.

Enhanced oil recovery or tertiary recovery (EOR) is designed for the remedy of relatively low recovery efficiencies relating to petroleum production processes. Surfactant flooding, one of the most promising techniques, has been granted much attention in recent years. During surfactant flooding lowering of the interfacial tensions helps recover additional oil by reducing the capillary forces (Zhang, 2005). It was observed that the response to the surfactant capillary imbibition recovery may be very different depending on the rock type and fluid properties, even if the same surfactant and concentration are used. For example, sandstone initially yields faster recovery with high interfacial tension (IFT) solution (brine with no surfactant addition), but the ultimate recovery becomes higher with decreasing IFT (Babadagli, 2005). Besides the enhancement of capillary imbibition and gravity drainage recovery by reduced IFT, wettability alteration by surfactant addition into brine can also be
expected depending on the rock and surfactant type. Ionic and nonionic surfactants have been employed for optimizing enhanced oil recovery techniques (Babadagli, 2006; Standnes, 2000).

In chemical flooding, surfactants are inevitably adsorbed on the surface of the reservoir rock through rock-oil-brine interactions. Surfactant adsorption from aqueous solution is a phenomenon of major importance in several applications, from ore flotation to paint technology, to enhanced oil recovery (Cases, 2002). It has been shown that the nature of the adsorption isotherm depends, to a large extent, on the type of surfactant used, the morphological and mineralogical characteristics of the rock, and the electrolytes present in solution. The adsorption of surfactants can be affected by the surface charge of the rock and fluid interfaces (Somasundaran and Zhange, 2006).

In this work, the performance of petroleum recovery and swept and displacement efficiency in arenite samples by ionic surfactant (IS) conducted in laboratory was investigated.

2. MATERIALS AND METHODS

2.1. Oil

The oil phase used was a petroleum and kerosene solution at a volume ratio of 2:3, respectively, viscosity of 2.9 cP and density of 0.8 g·cm⁻³ at 25°C. Petroleum samples were provided by Petrobras (Guamaré Production Site-Brazil) and collected from the Ubarana geological formation. These were obtained as raw samples, without the use of emulsifiers.

2.2. Brine

A 2% in weight KCl solution was used as aqueous phase in the saturation assays, with pH of 5.58, density of 1.03 g·cm⁻³ and viscosity of 1.0 cP at 25°C.

2.3. Surfactant

A specific property of surfactant solutions, either considered separately or in mixtures, is the concentration above which the first aggregates of monomers, known as micelles, are formed (Minssieux, 1989). Above this concentration, called critical micelle concentration (c.m.c.), the surfactant solutions display particular solubilizing properties used in many applications (Babadagli, 2003). The c.m.c. of the surfactant was determined by surface tension measurements (25°C) using a Surface Tensiometer (SensaDyne Instrument Div). The continuity break in the plots of surface tensions versus ln C corresponds to the c.m.c. value. From the curve used to obtain the c.m.c. value in distilled water, the area of the surfactant polar chain (S, in m²·mol⁻¹ or Å²·mol⁻¹) can be calculated from the Gibbs isotherm, according to equations 1 and 2:

\[ S = (1.66 \cdot 10^{-4}) \cdot (1/\Gamma) \]  
\[ 1/\Gamma = -RT \cdot [d(ln C)/d\gamma] \]

where: \( \Gamma \) is the excess surface concentration, in mol·m⁻²; \( \gamma \) is the surface tension, in mN·m⁻¹; the term RT is expressed in J·mol⁻¹ (R is the gas constant and T is the temperature in Kelvin) and \( d(ln C)/d\gamma \) is the slope of the curve before the c.m.c. value is reached. In this work, we have used SB, purchased from Gessy Lever, as an ionic surfactant. Some of their properties are listed in Table 1.

2.4. Viscosity

The viscosity of the surfactant was determined using a Brookfield Viscometer – Brookfield Engineering Labs., which is based on the rotacional variation of a sensor of the concentric-type cylinder (spindle - CP48) submerged in a fluid (sample). The sample was submitted to sufficient torque so as to maintain

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>Molecular mass (g/mol)</th>
<th>c.m.c. (mol/L) (distilled)</th>
<th>c.m.c. (mol/L) (2% KCl solution)</th>
<th>S (Å²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS</td>
<td>286.1</td>
<td>7.34 x 10⁻³</td>
<td>5.94 x 10⁻³</td>
<td>17.36</td>
</tr>
</tbody>
</table>
the rotation of the spindle that is submerged in the sample. The concentration used was 30% above the c.m.c., which was the first concentration used in the recovery tests. Thus, this study was carried out to verify the dependence of the surfactant solution behavior (viscosity) with temperature and time, since, in oil recovery processes, the surfactants are submitted to high temperatures in the oil wells (approximately 70°C).

2.5. Adsorbent

The solid adsorbent was a sample of sandstone from the Açú geological formation, in Brazil. This sample is similar to the ones observed in the petroleum formation. The cores used (Figure 1) were coated with resin and had the following dimensions: 3.8 cm diameter, 8.7 cm length and an average porosity of 24%. Before coating with resin all cores were roasted at 700°C during 18 hours, to remove humidity and increase permeability. Two fluid distributors were attached in the core plug. These were covered with two core ends connected with the injection and production line, respectively. The core plug, distributors and core ends were joined with a coating of resin.

The system employed in the petroleum recovery tests is schematically shown in Figure 2.

Before each experiment, the core was evacuated with a vacuum pump, and the pore volume was determined by N2 injection. The following steps were followed during the recovery tests:

1. Injection of KCl-brine (30 psi): the absolute permeability (K) was measured at this point.

2. Flooding of the core with an oil phase until cease of further brine production: the oil permeability at irreducible water saturation was determined before starting water injection.

3. Water injection, during which the core effluent was collected in 10 mL test tubes in the fraction collector. The volumes of oil and brine produced were determined in each tube. This step refers to the Conventional Recovery Method.

4. Surfactant solution injection, performed after the three steps mentioned above, during which the core plugs were saturated with the oil
and water phases. This step aimed to recover the remaining oil that was trapped in the pores of the rock due to the high interfacial tensions between oil and water. This step refers to the Special Recovery Method or Enhanced Oil Recovery.

2.6. Adsorption Tests

The surfactant adsorption in the rock-reservoir is one of the main disadvantages for technical and economical viability. In view of this, the relevance of this study is highlighted, whereby surfactant flooding process is used in enhanced oil recovery, for the determination of the surfactant amount that is adsorbed on the rock, before reaching the reservoir. The adsorption was determined by continuous surfactant injection (at concentrations 30% above the c.m.c.) in the core during the recovery process. This particular investigation, performed at room temperature, was concluded when the sample concentration at the exit of the core reached the value of the initial concentration injected, corresponding to saturation. The difference between initial and final concentration of samples determined the surfactant mass (in grams) adsorbed in the rock.

2.7. Oil recovery

Petroleum recovery tests were carried out through fluid displacement in the porous medium, whereby two methods were used: conventional method (CM) and special method (SM). The recovery factor (RF) regarding the amount of oil recovered was determined by two methods (equation 3):

$$RF_{total} = RF_{CM} + RF_{SM} = \frac{V_{CM} + V_{SM}}{V_{total \ injected}}$$

where: $RF_{total}$ is the total recovery factor (%), $RF_{CM}$ is recovery factor calculated with the conventional method (%), $RF_{SM}$ is the recovery factor by the special method (%), $V_{CM}$ is the oil volume recovered by the conventional method (mL), $V_{SM}$ is the oil volume recovered by the special method (mL), and $V_{total \ injected}$ is
the total oil volume in the plug before recovery.

2.8. Sweep Efficiency
This study was realized in an arenite porous medium (pore volume of 22.58 and porosity of 0.25) with dimensions of 12 cm x 12 cm x 0.7 cm (Figure 3). The porous medium was sealed with an epoxy resin and six points were fixed, as well as an injector well and five producer wells.

3. RESULTS AND DISCUSSION

3.1. Viscosity
Figure 4 shows the variation of the surfactant viscosity with shear rate. The surfactant presented higher viscosity, 0.003 Pa-s, at 30°C. At 40°C, its viscosity varied between 0.002 and 0.003 Pa-s. In the other temperatures, 50°C to 70°C, its viscosity varied between 0.001 and 0.002 Pa-s.

3.2. Oil recovery and adsorption
The surfactant concentrations injected, at 30 psi, varied between 30% and 50% above the c.m.c. During the second injection step, 8.0 mL of oil (original oil in place, OOIP) remained in the core. After the saturation steps, 3.2 mL of oil (residual oil, RO) stayed in the core awaiting recovery. The recovery factors for each injected concentration are shown in the Table 2.

Figure 5 shows the recovery factors for each concentration used.

In the surfactant flooding process, it was possible to observe that, from the 3.20 mL of RO in the core, 2.30 mL were recovered. Table 3 presents recovery data of residual oil (PRF) and total recovery (TRF) by the surfactant solution used.

During the oil recovery process with saturation of surfactant, it was possible to detect when the surfactant saturates the rock by an adsorption mechanism (Figure 6).

From the results shown in Figure 6, it is possible to observe that the beginning of surfactant saturation was reached when an approximate injected pore volume of 12 mL was used. The ionic surfactant molecules

<table>
<thead>
<tr>
<th>Concentration (g/mL)</th>
<th>Partial recovery factor (%)</th>
<th>Injected pore volume</th>
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<tbody>
<tr>
<td>0.0027 (30% ↑ c.m.c.)</td>
<td>71.00</td>
<td>7.47</td>
</tr>
<tr>
<td>0.0032 (50% ↑ c.m.c.)</td>
<td>0.00</td>
<td>5.10</td>
</tr>
<tr>
<td>Total = 71.00%</td>
<td>Total = 12.57</td>
<td></td>
</tr>
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</table>

Figure 3. Recovery factor for surfactant IS.
develop electrostatic interactions with the substratum ions and, for this reason, the adsorption process is fast and provides good recovery factors.

3.3. Sweep Efficiency

This test was performed in order to verify the surfactant sweep efficiency in the rock. The saturation steps followed are shown in Figures 7 through 9.

These results showed that the ionic surfactant was efficient both in the displacement assays (Figure 2), as indicated by the oil recovery in the core plug, and in the swept (Figure 3). This was mainly due to the fact that the viscosity of the surfactant solution (3.0 cP) was close to that of the oil (2.9 cP). Plus, as expected, the interfacial tension between oil and brine was largely reduced, which allowed for higher recovery factors than those obtained in process that use polymers (Sabhapondit, 2003).

4. CONCLUSION

The main objective of this paper was to study the oil recovery factor obtained by an ionic surfactant and its adsorption in the porous medium, whereby the interferences that cause low recoveries were examined, such as high interfacial tension and low viscosity of the injected fluid (surfactant). From the results gathered, it was possible to conclude that:

The adsorption of surfactant at solid-liquid interfaces depends on the surfactant nature and the rock surface. There is an apparent correlation of the adsorption density between ionic surfactant and the porous medium, because these surfactant types presented higher affinity with the rock ions.

The optimum surfactant concentration was found to be 30% above the c.m.c. of the surfactant used, since above this concentration (e.g. 50%) there was no increase in the recovery factor.

The ionic surfactant was effective in enhanced oil recovery. The addition of the ionic surfactant decreased the interfacial tension between the oil phase and brine and increased the solution viscosity to 3.0 cP (brine). Higher oil recovery rates were observed for the IS (89.0%).

ACKNOWLEDGMENT

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<table>
<thead>
<tr>
<th>Surfactant</th>
<th>Recovered RO volume (mL)</th>
<th>PRF (%)</th>
<th>TRF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS</td>
<td>2.30</td>
<td>71.00</td>
<td>89.00</td>
</tr>
</tbody>
</table>

Table 3. Oil recovery factor for ionic surfactant.

Figure 4. Adsorption of surfactant in the oil recovery process.
REFERENCES

Figure 5. First saturation step

Figure 6. Second saturation step

Figure 7. Sweep efficiency by surfactant solution