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Microemulsion flow in porous medium for enhanced oil recovery

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ABSTRACT

Injection of microemulsion is a chemical technique of enhanced petroleum recovery. With the implementation of this technique, oil recovery is enhanced by increasing the viscosity of the microemulsion systems, and reducing the interfacial tension between oil and water in a porous medium. In this work, injection assays have been carried out with fluids comprising microemulsion-based commercial anionic surfactants, oil from the Quiambina Field (mature field in the Brazilian State of Bahia) and brine (2% KCl). The experiments basically consisted of the injection of fluids into cylindrical plug samples from the Botucatu formation by means of conventional (injection of water or brine) and enhanced (injection of microemulsion) recovery techniques. During water and microemulsion flooding, samples were collected as a function of time, after which the volume of oil recovered was obtained. Parameters like mobility ratio, volume of displaceable oil, volume of displaced oil and displacement efficiency have been obtained as results. It was verified that lower mobility ratios were acquired with the injection of microemulsion than with injection of water, thereby favoring oil recovery. The volume of oil displaced by the microemulsion corresponded to 75% of the total displaceable oil, which is a much higher yield than that observed in conventional recovery procedures. The results showed that, when microemulsion flooding is applied, the displacement efficiency is 21.5%, whereas with the conventional method the efficiency is 41%. It could be concluded that the use of microemulsion in enhanced oil recovery is efficient to provide higher levels of extraction due to the higher viscosity of the microemulsion and to the decrease in the interfacial tension between the fluids in the porous medium.

1. Introduction

Enhanced oil recovery (EOR) techniques are used in physical situations where conventional methods fail, or would fail if they were to be implemented. Three categories are commonly known for general EOR techniques: thermal, miscible and chemical methods. Such classification is not unique, and there are a number of processes that may be included in more than one category.

This work particularly focuses on chemical methods, with the use of microemulsions as a recovery fluid. In chemical methods, it is assumed that the processes occur with a certain extent of chemical interaction between injected fluid and reservoir fluid, by injecting solutions of polymers or surfactants, microemulsions, and alkaline systems into the reservoir.

The first attempt to displace petroleum from reservoir rocks by microemulsion injection was carried out in 1963 by the *Marathon Oil Company*, which designed a process known as *Maraflood*® (Gurgel et al., 2008). The microemulsion contained brine, hydrocarbons, cosurfactant and a high concentration of surfactant. Later, Healy and Reed (1973) studied some properties of microemulsions by constructing ternary phase diagrams. Specially, viscosity, surface tension and resistivity were assessed for three different types of microemulsion systems in EOR. As a result, the authors could completely describe the phase regions for three distinct micellar configurations and demonstrated the consistency of the data based on the concepts proposed by Winsor (1948).

In microemulsion injection, a high concentration of surfactant is required to produce self-assembled structures, such as spherical droplets similar to micelles, that are able to solubilize or dissolve the oil in a reservoir. This process occurs by incorporating a certain amount of oil in the core of the droplets, thereby promoting miscibility in the overall system (Shindy et al., 1997). Surface tensions between oil and water are then reduced with the microemulsion injection into the reservoir, improving the oil recovery efficiency, also because of the relatively high viscosity of microemulsions (Glover et al., 1979; Austad and Strand, 1996; Shindy et al., 1997; Wellington and Richardson, 1997; Santanna et al., 2009).

Li et al. (2009) proposed a new type of flooding system, involving wormlike micelles, formed by the anionic surfactant sodium oleate (NaOA), in sodium phosphate (Na_3PO_4) solutions. Laboratory simulation flooding experiments were performed to

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investigate the effects of flooding with the wormlike micelle system. The results showed that the oil recovery was as high as 32.7%.

The mobility (λ_i) of a given fluid is defined by the ratio between its effective permeability (k_i) and its viscosity μ_i. For example, the mobility of oil samples (displaced fluid) can be given by Eq. (1) (Dake, 1998).

$$\lambda_o = k_o/\mu_o \quad (1)$$

The mobility ratio (M) can then be defined as

$$M = \lambda_i/\lambda_o \quad (2)$$

where λ_i is the mobility of the displacing fluid.

It is known that the oil recovery efficiency decreases with increasing mobility ratio, because the injected fluid tends to displace the oil banks due to its higher mobility. Preferential paths are then created between injected and producing wells (Ahmed, 2006). When $M<1$, a favorable condition is established and the displacement is little different from the case when $M=1$. However, if $M>1$, the mobility ratio becomes unfavorable, and instabilities on the displacement front promote the appearance of viscosity “fingers” or channeling, considerably changing the nature of the displacement phenomenon (Salama and Kantzas, 2005).

Due to capillary effects, only part of the oil can be displaced. This fraction is called displaceable volume or mobile oil (Ahmed, 2006), and is given by the following expression:

$$V_{DL} = V_p(S_o - S_{or}) \quad (3)$$

where V_{DL} is the volume of displaceable oil, V_p is the porous volume, S_o is the oil saturation and S_{or} is the residual oil saturation.

Considering the convention water injection technique, the volume of water that invades the porous medium must be equal to the volume of displaced or produced oil. As a result, the volume of oil displaced by the conventional method (V_{DCM}) can be given by

$$V_{DCM} = V_{pinvw}(S_w - S_{wi}) \quad (4)$$

where V_{pinvw} is the volume of the porous medium that is invaded with water, S_w is the water saturation and S_{wi} is the initial water saturation.

When microemulsions are used in EOR applications, the volume of microemulsion that invades the porous medium must be equal to the volume of both oil and water that are displaced and consequently produced. In this case, the volume of water displaced by the enhanced method (V_{WDEOR}) can be given by

$$V_{WDEOR} = V_{pinvmicro}(S_w - S_{wi}) \quad (5)$$

where $V_{pinvmicro}$ is the porous volume that is invaded with microemulsion. Similarly, the volume of oil displaced by the enhanced method (V_{ODEOR}) is

$$V_{ODEOR} = V_{pinvmicro}(S_o - S_{or}) \quad (6)$$

Fig. 1 shows a typical curve of oil recovery by water injection into a reservoir, with a plot of recovered oil volume versus injected water volume. The linear section of the curve reflects the fact that the amount of injected water can displace the same volume of oil in the reservoir. The inflexion point indicates the transition from a linear to a non-linear behavior, and is commonly referred to as the *curve inflexion* or *breakthrough* (Ahmed, 2006). From this point on, the volume of produced oil is not proportional to the amount of injected water, and a fraction of the oil is retained within the reservoir. Ultimately, some water also starts to be produced together with oil.

The displacement efficiency is a measure of the reduction in oil saturation in the region that is invaded by the displacing fluid. One of the methods used in the study of fluid flow in porous medium is the complete displacement model or piston-like displacement. In this model, it is assumed that only the displacing fluid moves in the region of the reservoir that it invades. Therefore, the displacing fluid expels the fluid that was originally stored in the reservoir as it flows, like a piston, and the displacement efficiency (DE) is the ratio between the displaceable oil volume and the porous volume, as in Eq. (7) (Ahmed, 2006).

$$DE = V_p(S_o - S_{or})/V_p = S_o - S_{or} \quad (7)$$

2. Materials and methods

2.1. Chemicals

The chemicals used to prepare the microemulsion systems were a commercial anionic surfactant (soap) derived from fatty

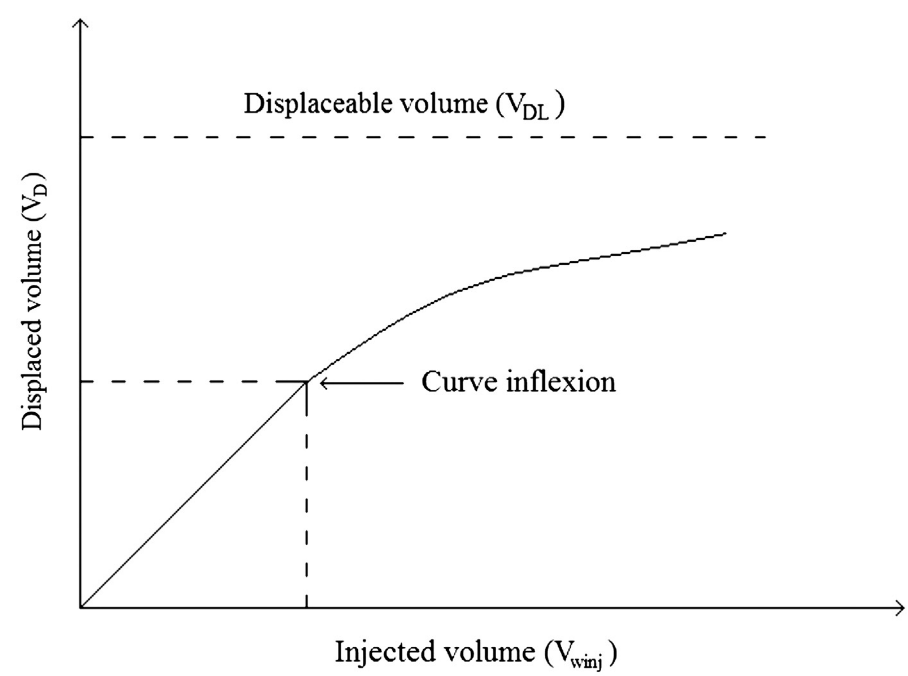

Fig. 1. Volume of displaced oil as a function of volume of water injected.

acids (20–30% of vegetable oil and 70–80% of animal fat, in mass percentages); isoamyl alcohol ($C_5H_{11}OH$, from Merck), used as cosurfactant; pine oil, used as oil phase without previous purification; and distilled water. The petroleum sample used was acquired from the Quiambina field, a mature field located in the Brazilian State of Bahia, and was kindly supplied by the Field-School Project. Also, 2% KCl brine solution was used in conventional injection assays.

2.2. Microemulsion

Phase behavior studies were performed in order to construct the phase diagrams of the systems tested at room temperature (26 °C), and to determine the extent of the microemulsion regions. A pseudoternary system comprising distilled water, vegetable oil and a fixed cosurfactant/surfactant ratio of 0.5 was investigated.

The phase boundaries in the diagram were named according to the Winsor classification (Winsor, 1948; Friberg and Bothorel, 1987). In these systems, the oil phase was added to the cosurfactant/surfactant mixture, and the resultant solution was titrated with water until the Winsor regions were detected. The volume of added water was recorded to determine the extent of each region. The pseudoternary phase diagram was thereby constructed by plotting the points with the corresponding amounts of water, oil, surfactant and cosurfactant used in the experiments.

After constructing the phase diagram, one point was selected within the microemulsion region to represent the overall composition of that system. The microemulsion was then prepared with a mechanical stirrer, and all components were added at the same time, and allowed to mix for about 30 min.

2.3. Fluid injection assays

The fluid injection assays were carried out basically by injecting fluids in sandstone cylindrical plugs from the Botucatu formation (Santanna et al., 2009), as seen in Fig. 2. This apparatus has already been successfully used in surfactant flooding experiments (Curbelo et al., 2007). The plugs were isolated with resin and their dimensions were 3.8-cm diameter and 8.7-cm length. Before being submitted to the resin application, the plugs had been calcined at 700 °C for 12 h, with the objective of removing all humidity and improving permeability.

The injection assays involved the following steps: (1) in order to determine the absolute permeability and the porosity of the plug, brine (2% KCl solution) was injected at a constant flow rate of 0.2 mL/min, through the plug; (2) once the plug was saturated with brine, oil with a viscosity of 9 cP was injected at a constant flow rate of 0.2 mL/min; (3) with the purpose of determining the mobility ratio (Eq. (2)), the volume of displaceable oil (Eq. (3)), the volume of displaced oil (Eq. (4)) and the displacement efficiency (Eq. (7)) in the conventional method, brine was injected again, after plug saturation, at a constant flow rate of 0.2 mL/min. The volumes of oil and water were measured in graduated tubes; and (4) similar to the 3rd step, microemulsion with a 32 cP viscosity was injected at a constant flow rate of 0.2 mL/min with the objective of calculating the parameters for an equivalent EOR method, namely the mobility ratio (Eq. (2)), the volume of displaceable oil (Eq. (3)), the volume of displaced water (Eq. (5)), the volume of displaced oil (Eq. (6)) and the displacement efficiency (Eq. (7)). The collected samples initially contained water and oil. The volumes of oil and water were also measured in graduated tubes, and the samples were collected at previously defined time intervals. After some time, oil started to be produced mixed with the microemulsion, and from this point this amount of oil was not determined. Finally, totally clear microemulsion samples were collected, with no oil residues.

The permeability of the plugs and the effective oil and water permeabilities were determined with Darcy's equation, used in the study of fluid flow in porous media (Ahmed, 2006).

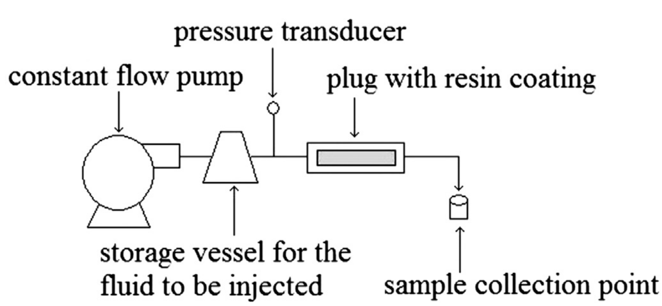

Fig. 2. Fluid injection system.

3. Results and discussion

3.1. Phase diagram

The pseudoternary phase diagram was constructed in order to mark the boundaries of the microemulsion region, as shown in Fig. 3 (Dantas et al., 2006; Dantas Neto et al., 2008; Santanna et al., 2009), where very well-defined microemulsion regions (WIV and viscous WIV) are observed.

One point belonging to the viscous microemulsion (viscous WIV) region was selected to be used in the microemulsion preparation, with the following composition: 15.3% surfactant, 7.7% cosurfactant, 18% oil phase and 59% aqueous phase. All concentrations are given in mass percentages.

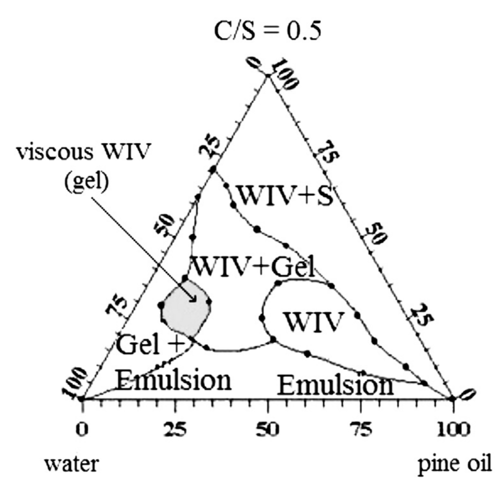

Fig. 3. Pseudoternary system comprising distilled water, commercial surfactant (*S*), pine oil, isoamyl alcohol (*C*), with *C*/*S* ratio=0.5, constructed at 26 °C (Dantas et al., 2006).

Table 1
Properties of the plug.

Plug	
Porosity (%)	11.35
Porous volume (cm^3)	9.76
Absolute permeability (mD)	2.59

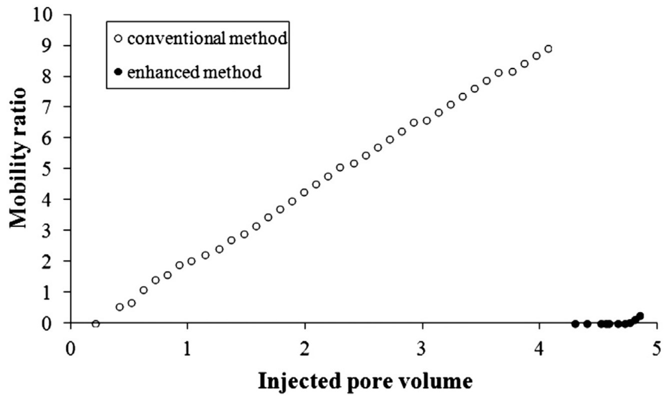

Fig. 4. Mobility ratio of the injected fluids.

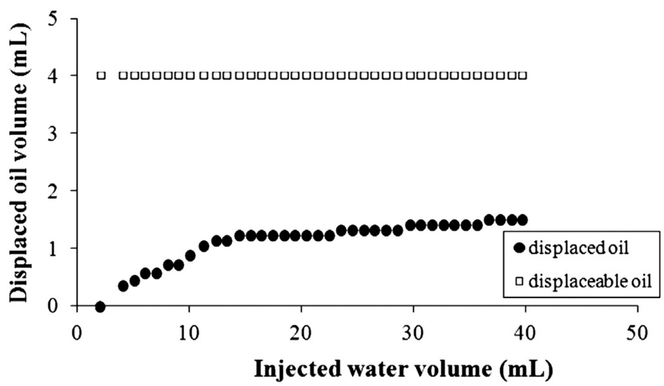

Fig. 5. Volume of displaced oil as a function of injected water volume by the conventional method.

3.2. Fluid mobility

Table 1 lists the main properties of the porous medium (plug) used in the injection experiments.

The permeabilities of the fluids were determined by carrying out the fluid injection steps, both in conventional and enhanced recovery techniques. The mobility ratio could then be determined using the viscosities of the fluids, as shown in Fig. 4. It can be seen that water, in the conventional recovery method, has a much higher mobility ratio than the microemulsion, in the EOR method. It is known that lower oil recovery efficiencies are observed with increasing mobility ratios, in that the displacing fluid moves through the porous medium more easily than oil (which is the displaced fluid), even by-passing the oil itself. Consequently, less oil is produced or its production is ceased. In view of this, and also due to fact that microemulsions have low mobility ratios ($M < 1$), the microemulsion induces the oil phase to move with a velocity that can be higher or equal to its own flow rate. As a result, the oil will not be surpassed or by-passed by the microemulsion, and will be ultimately extracted from the well.

In Fig. 5, the dependence of the volume of recovered oil with the injected water volume is shown for the conventional method (black dots). A linear section is evident, which means that the amount of injected water could displace the same volume of oil in the plug up to a certain extent. From approximately 12 mL of injected water, which corresponds to little more than one injected porous volume, the curve inflexion point is indicated, from which there is no direct proportionality between injected water volume and produced oil volume. Some fraction of the total oil content is retained in the plug and a certain amount of water starts to be produced. In the enhanced method, a maximal displaced (or recovered) oil volume of 1.5 mL was produced, which is rather lower than the volume of displaceable oil (4 mL).

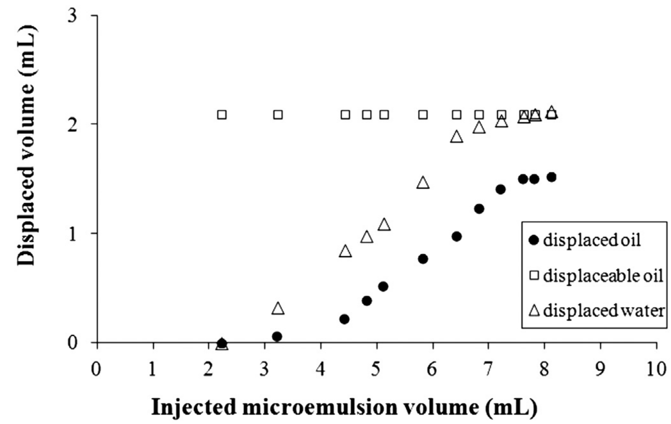

Fig. 6. Volumes of displaced oil and water as a function of injected microemulsion volume in the enhanced method.

On another departure, the efficiency of the enhanced method is demonstrated in Fig. 6, where the volumes of displaced oil and water are related to the volume of injected microemulsion. Similarly, a linear section is also seen, representing the proportionality between the volumes of injected and recovered fluids. In this case, oil and water are produced together because the plug was saturated with them. Besides, the viscosities of these fluids are lower than that of the microemulsion, and they are displaced by the microemulsion without being by-passed, for possessing lower mobility ratios (Fig. 4). Therefore, the displacement of oil and water is favored in the porous medium, a phenomenon that is further enhanced with the reduction of interfacial tensions between oil and water, promoted by the microemulsion. However, from approximately 7.5 mL of injected microemulsion, which corresponds to less than one injected porous volume, the inflexion point is detected on the curve, indicating that the volume of produced oil is not proportional to the volume of microemulsion, and some fraction of the oil is retained. As a result, a certain amount of microemulsion is produced, up to a maximal displaced oil volume of approximately 1.5 mL. This amount of recovered oil is much closer to the volume of displaceable oil (2 mL). It is also observed that the volume of displaced water is higher than that of oil, which is a consequence of the fact that the initial water saturation in the plug (54.92%) is higher than the initial oil saturation (24.59%).

3.3. Displacement efficiency

The saturation of the residual oil obtained by the conventional and EOR methods along the injection assays are represented in Fig. 7. The plug had an initial oil saturation (S_{oi}) equal to 65.57%. After brine injection, corresponding to the 3rd step of the conventional process, the oil saturation (S_{orCM}) was reduced to 24.59%. When microemulsion was injected, in the 4th step, the oil saturation (S_{orEOR}) changed from 24.59% to 3.07% with only 0.8 injected porous volume.

From the oil saturation results, the displacement efficiency via both conventional and EOR methods can be calculated (Eq. (7)), and the results are shown in Fig. 8. When the conventional method is employed, the maximal efficiency of oil displacement was 41%, which means that 62.5% of the original oil in place (OOIP) could be recovered. This is due to the higher oil viscosity (9 cP), as compared to the brine viscosity (1 cP). Therefore, brine is more easily displaced through the porous medium, creating preferred paths and leaving part of the oil within the porous medium ($M > 1$).

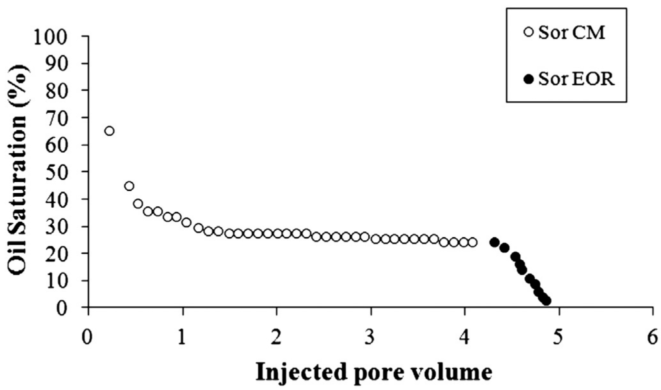

Fig. 7. Oil saturation versus injected porous volume in the conventional (◇) and EOR (◆) methods.

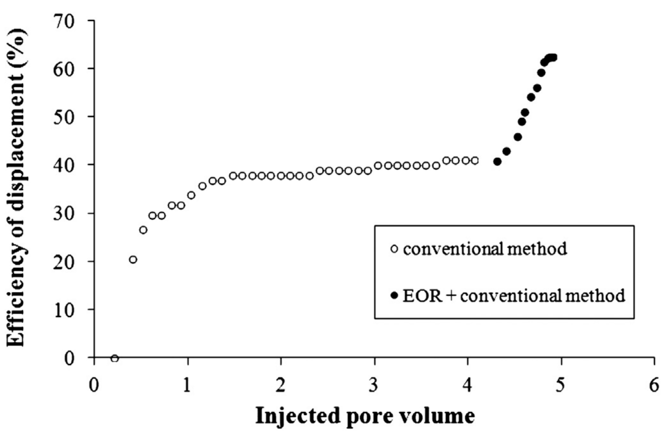

Fig. 8. Efficiency of displacement versus injected porous volume by conventional and EOR methods.

On the other hand, when the EOR method is performed the maximal efficiency in oil displacement is 21.5%, which accounts for 87.5% of recovered OOIP (Fig. 8). This demonstrates the efficiency of microemulsions in oil recovery, a direct effect of the higher microemulsion viscosity (32 cp). In effect, the microemulsion has lower mobility in the porous medium (Fig. 4), reducing the interfacial tensions between oil and water. As a result, oil is more easily displaced.

4. Conclusions

In this work, it has been demonstrated that the injection of microemulsions as part of enhanced oil recovery techniques can produce lower mobility ratios ($M<1$) as compared to water injection in conventional methods ($M>1$). Since the microemulsion could move with the same velocity, or even less rapidly, than the fluids that were stored in the porous medium (water and oil), a higher displacement efficiency was acquired. In the experimental apparatus developed for this investigation, the volume of oil displaced by the microemulsion was 1.5 mL, which corresponds to 75% of the total displaceable oil. If only water is injected, the absolute volume of displaced oil was also 1.5 mL, which corresponds to only 37.5% of the displaceable oil in this case. As to the displacement efficiency, an increase in efficiency of about 21.5% was observed with the use of microemulsions, with a recovery of 87.5% of the original oil in place. This increase was justified in part by its higher viscosity, as compared to the other fluids within the medium, and by the reduction in the interfacial tension between oil and water in porous medium.

Acknowledgments

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