OIL DISPLACEMENT BY OIL-WATER EMULSION INJECTION IN COREFLOODING EXPERIMENTS

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Abstract. *Water injection is a common method to improve reservoir sweep and maintain its pressure. The efficiency of oil recovery in the case of heavy oils is limited by the high mobility ratio between the injected water and oil. A method for reducing the problem related to the high viscosity ratio is polymer injection. However, fluid-rock interactions, the large volume and the associated cost of polymer may make this technique not applicable in the case of giant fields. Different enhanced oil recovery methods are being developed and studied as alternatives to polymer injection.*
Dispersion injection, in particular oil-water emulsion injection, has been tried with relative success as an enhanced oil recovery method, but the techniques are not fully developed or understood. The use of such methods requires a complete analysis of the different flow regimes of emulsions inside the porous space of a reservoir. Most analyses of flow of emulsion in a porous media use a macroscopic description. This approach is only valid for dilute emulsion in which the size of the disperse phase features is smaller than the pore throat. If the drop size of the disperse phase is of the same order of magnitude of the pore size, the drops may agglomerate and partially block the flow through pores. This flow regime may be used to control the mobility of the injected liquid, leading to higher recovery factor.
In this work, experiments of oil displacement in a rock sample by water and emulsion injection were performed. The results show that by alternating water and emulsion injection, the oil recovery factor could be raised from approximately 40 %, obtained with water injection only, up to approximately 75 %.

Keywords*: Emulsion, enhanced-oil recovery, porous media, coreflooding, recovery factor*

1. INTRODUCTION

Oil is generally brought to the surface from the reservoir by using different flow-driving mechanisms, from primary to tertiary processes, depending on the development stage of the field. Primary recovery methods use the initial potential energy available in the reservoir. Examples include fluid expansion, solution-gas driver or water influx from aquifer. These mechanisms typically lead to recovery fractions between a fifth and a third of the original oil in place. To increase the amount of oil recovered beyond primary production, economically viable secondary recovery processes can follow primary recovery exploitation plans, once the economic limit of the latter has been reached. Water flooding is a sensible conventional secondary oil recovery method, often used in field development plans, whether for pressure maintenance or oil displacement. Pressure maintenance is a way to assist insufficient primary water drive by injecting water into the edges of the oil column (edge aquifer) or in the bottom aquifer. In its well-patterned strategy (displacement), the method basically consists of injecting water through injection wells to drive the oil towards production wells. The application of this method is responsible for more than half of the world oil production, but the process has limited sweep efficiency, often leaving a considerable amount of oil in the reservoir. This is the result of an unfavorable mobility ratio between oil and water and the action of interfacial tension between the two liquid phases. Waterflooding is also affected by reservoir heterogeneity, which is typically linked to large contrasts in absolute permeability, such as the so-called “thieves-zones”, i.e. high permeability layers between injectors and producers that leave lower permeability layers upswept. This situation can be mitigated with the use of blocking agents. These agents increase the effectiveness of injection fluids in sweeping low permeability zones, hence helping to recover some of the remaining oil. Emulsions can be used to selectively block porous media, and consequently improve the efficiency of displacing fronts.

Several laboratory studies have been carried out to understand emulsion flow in porous media. McAuliffe (1973) determined properties of oil-in-water emulsions and studied their flow through porous media, to show that emulsions could be used as selective blocking agents for oil recovery in waterflooding experiments. He also showed that oil–in-water emulsions displace oil more efficiently than water alone. Later, Soo e Radke (1984) studied the flow of dilute emulsions through porous media and determined the final reduction in permeability. They measured droplet size distributions, both at the outlet and at the inlet of the porous sample and determined how the distribution changed as a result of filtering. They used a glass micro-model to prove that permeability reduction is caused by a capture mechanism similar to that observed in particle filtration processes. Kambharatana (1993) mentions the lack of good physical and mathematical descriptions for the flow of emulsions through porous media. In his work, he observed that viscosity changes of emulsions in porous media have a similar behavior trend as that seen in the viscosimeter, for the shearing rates of interest. Kambharatana confirmed that emulsion drops were captured according to a filtration process.

Emulsion injection as an alternative chemical recovery method is not a mature technology, but has been used successfully in some field trials. In the recovery of heavy oil, emulsions may provide an effective mobility control when the oil is displaced through the porous media (Bragg, 1999). In case this proves technically viable, the use of emulsions would bring some advantages relative to polymer injection. The cost of production of emulsions would be much smaller than the cost of polymer solutions and, because the emulsions could be prepared with native liquids from the reservoirs, the fluid-rock interaction could be minimized.

One of the difficulties in developing emulsion injection technologies for EOR relates to the lack of fundamental knowledge about the flow of emulsions through porous media. Blockage of the pores by the discontinuous phase, as one of the controlling mechanisms, is a function of several parameters involved in the physics of the flow. In this sense, it is important to find a rational way to establish a relationship between pressure drop and flow rate, depending upon variables such as emulsion viscosity, viscosity ratio between the continuous and discontinuous phase and mean droplet size/mean pore-throat size ratio. A detailed observation of these phenomena at the microscopic scale was presented by Cobos et al. (2006).

The goal of this work is to study the recovery of oil in a sandstone plug by the injection of water and different emulsions in coreflooding experiments. The oil recovery factor and the injection pressure were recorded during the experiments for different fluid displacement protocols.

2. EXPERIMENTAL PROCEDURE

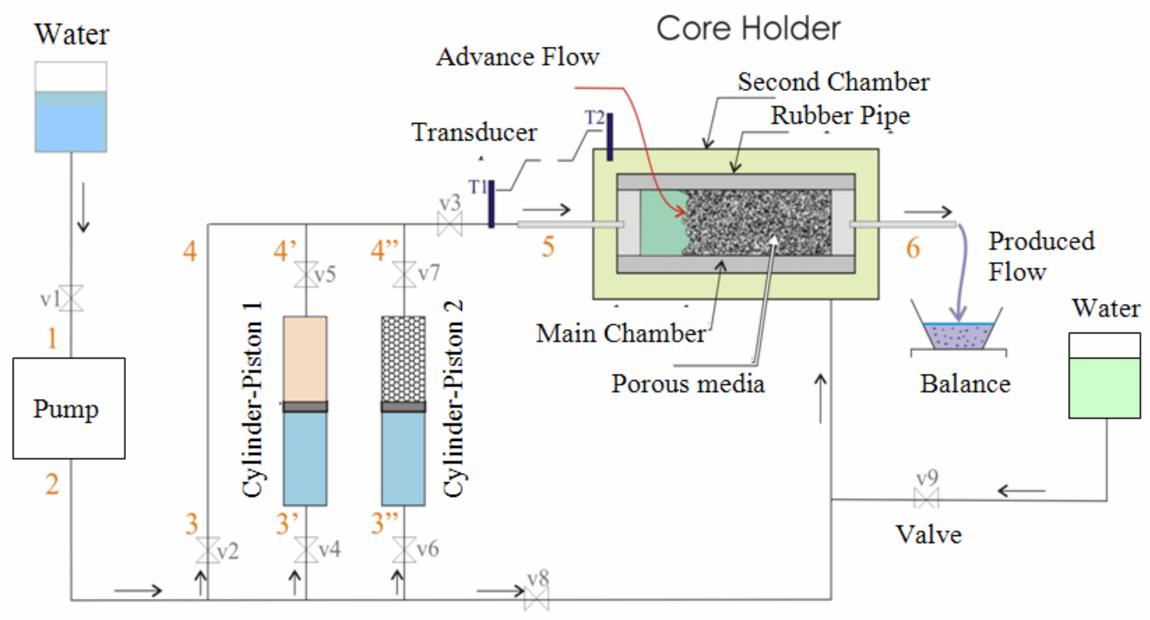

Figure 1. Schematic representation of experimental setup, (*i*) 3-4 when water is injected, (*ii*) 3'-4' when oil is injected, and (*iii*) 3"-4" when emulsion is injected.

The experimental setup used in the analysis is sketched in Fig.1. Two different types of injection liquids were used, water and emulsions. Each of the liquids was stored in a cylinder. The positive displacement pump controlled the flow rate fed into the sample. To reduce the wear of the pump, only water flowed through it. The water drives the piston installed in each of the storage cylinder to drive the injection liquid into the porous media, as indicated in Fig.1. A core-holder was used to store the porous media. The core-holder is divided into two concentric cameras separated by a rubber tube. The main camera lodges the porous media and the secondary camera is used to create the confining pressure. Two pressure transducers were installed to measure the injection pressure and the confining pressure.

The porous media was first fully saturated with water in order to measure the porous volume. The properties of the porous sample used in the experiments are shown in Table 1. Mineral oil was then injected into the porous media displacing the water until the irreducible water saturation is obtained. After the porous sample was saturated with oil, three different tests were performed:

1. Oil recovery by water injection at different flow rates;
2. Oil recovery by injection of emulsions with different drop size distribution;
3. Oil recovery by alternated injection of water and emulsion.

Table 1. Properties of the porous media used in the experiments.

POROUS MEDIA		
Rock Sample	Sandstone	
Diameter	37.7	mm
Long	70.55	mm
Porosity	27.3	%
Permeability	193	mD
Pore Volume	20.03	mm^3

(1) : measured at 25°C.

The results of these experiments are compared to determine the effect of emulsion injection on the recovery factor and injection pressure.

The properties of the oils used to saturate the porous media and to prepare the emulsions are shown in Tab.2. Two different oil-water emulsions with 30% volume concentration of oil were prepared as injection liquid. Their properties are presented in Tab.3. The main difference between the emulsions is the average size of the drops. Emulsion 1 had an average drop diameter of 5 μm and emulsion 2, of 20 μm. Both emulsions tested were shear-thinning, as indicated in Fig.2. The viscosity value presented in Tab.3 represents the viscosity at a characteristic shear rate. The viscosity of the emulsion with smaller drop (emulsion 1) was higher than the viscosity of the emulsion with larger drops (emulsion 2).

Table 2. Properties of the oil used to saturate the porous media and the oils used.

Oils	Viscosity (mPa-s)	Density (g/ml)
Mineral Oil (Saturate to Rock)	410[1]	0.9101
Synthetic Oil (Emulsion Prepare)	1000[1]	0.998

(1) : measured at 25°C.

Table 3. Properties of the emulsions used in the experiments.

EMULSIONS	Viscosity (mPa-s)	Density (g/ml)	Drops Diameter (μm)	Concentration (--)
Emulsion 1	300[(1)(2)]	0.9992	5	30/70
Emulsion 2	120[(1)(2)]	0.9992	20	30/70

(1) : measured at 25 °C.

(2) : for shear rate $\overset{\circ}{\gamma} = 0.0544\, 1/s$.

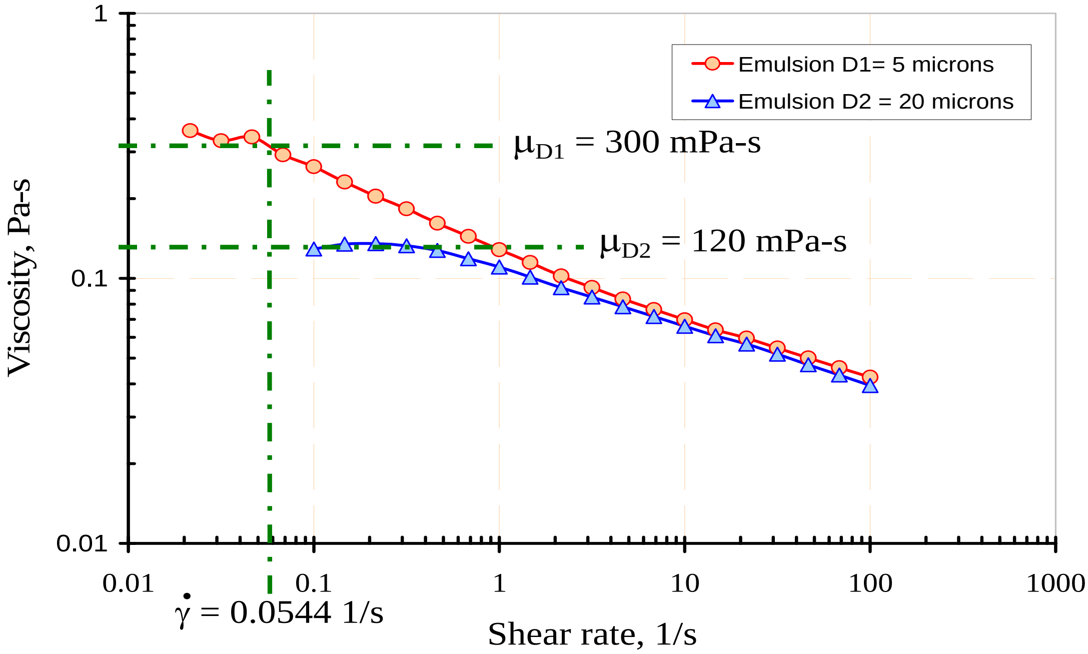

Figure 2. Variation of the viscosity with respect to the shear rate for the two emulsions: D_1 = 5 μm and D_2 = 20 μm

3. RESULTS

The amount of oil produced during the experiments is presented here as a recovery factor, defined as the ratio of volume of oil recovered to the volume of oil inside the porous space at the beginning of the experiment. To make a correct comparison, oil volumes ought to be compared at the same conditions. In the results presented here, the conditions of comparison were atmospheric pressure and ambient temperature.

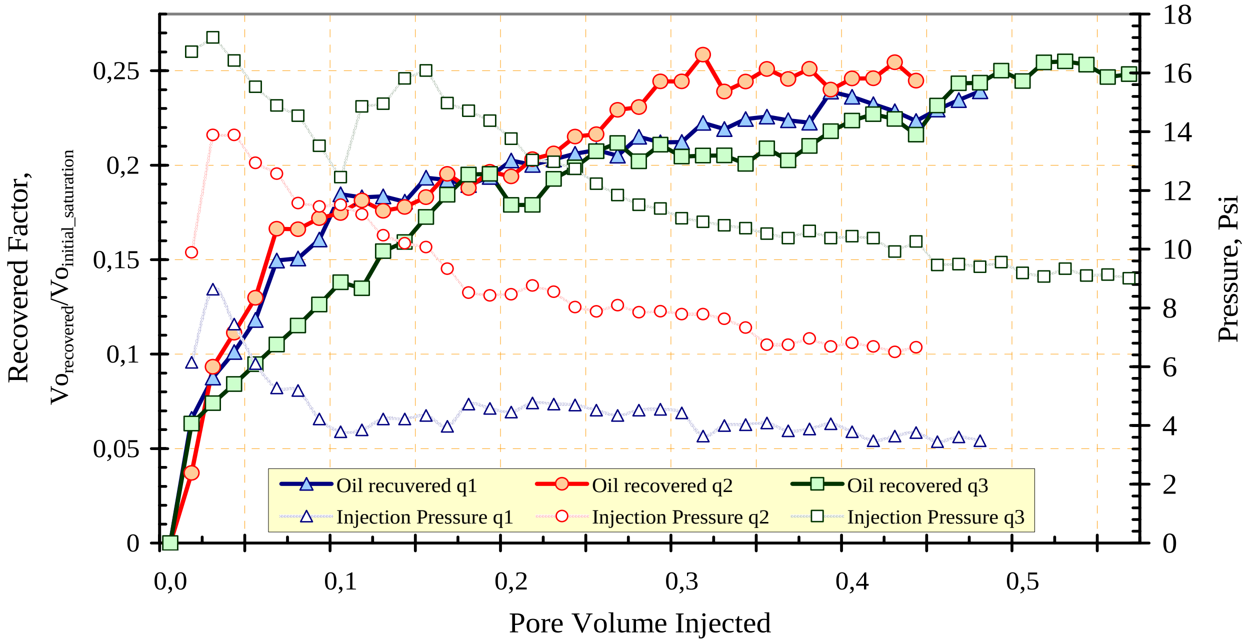

Figure 3. Oil recovered fraction, by three water injection flow rates q1, q2 and q3, and their injection pressures.

As mentioned before, first the oil was displaced by water injection. The recovery factor and the injection pressure as a function of time at three different water flow rates, e.g. q_1 = 0.005 ml/min, q_2 = 0.010 ml/min and q_3 = 0.015 ml/min, are shown in Fig.3. Notice that the time scale represents the fraction of the pore space injected, obtained by calculating Vi/Vϕ ratio, where, Vi is the volume of oil injected and Vϕ is the pore volume. The experiment proceeded until the volume of water injected was approximately 60% of the porous volume. The recovery factor at the end of the experiments was approximately 25% and it was not a function of the injection flow rate. This value of the recovery factor under waterflooding is relatively low, but can be explained on the basis of short-time injection period, as will be seen in later results, and mainly due to poor mobility ratio. The viscosity ratio, oil/water, is unfavorable for oil recovery by waterflooding. This indicates that the fingering mechanism that creates pools of oil inside the sample that were not swept is dominated by capillarity, not by viscous effects. As expected, the injection flow rate varied linearly with the water flow rate, as indicated in Fig.3.

In the second set of experiments, two different emulsions were injected in the porous sample saturated with oil. The injection flow rate of both emulsions was q_3 = 0.015 ml/min. The recovery factor and the injection flow rate during the experiments are presented in Fig.4. It is important to notice that when the volume injected was approximately 60 % of the porous volume, the recovery factor with emulsion 1 was close to 40%, and with emulsion 2, close to 35%, both much larger than the 25% recovery factor obtained with water injection. The injection pressure was close to 30 psi, much larger than that of water injection, close to 9 psi. An interesting phenomenon can be observed when comparing the injection pressure with the two different emulsions. The pressure is higher when emulsion 2 is injected, although it has a smaller viscosity. This proves that the viscosity of the emulsion, a macroscopic property, does not control the flow of emulsion inside the porous space. The characteristic geometry of the porous space is the same order of magnitude of the drop diameter. In this case, a continuous approach is not adequate. The injection pressure when emulsion 2 is used is higher because of the larger drop diameter of this system.

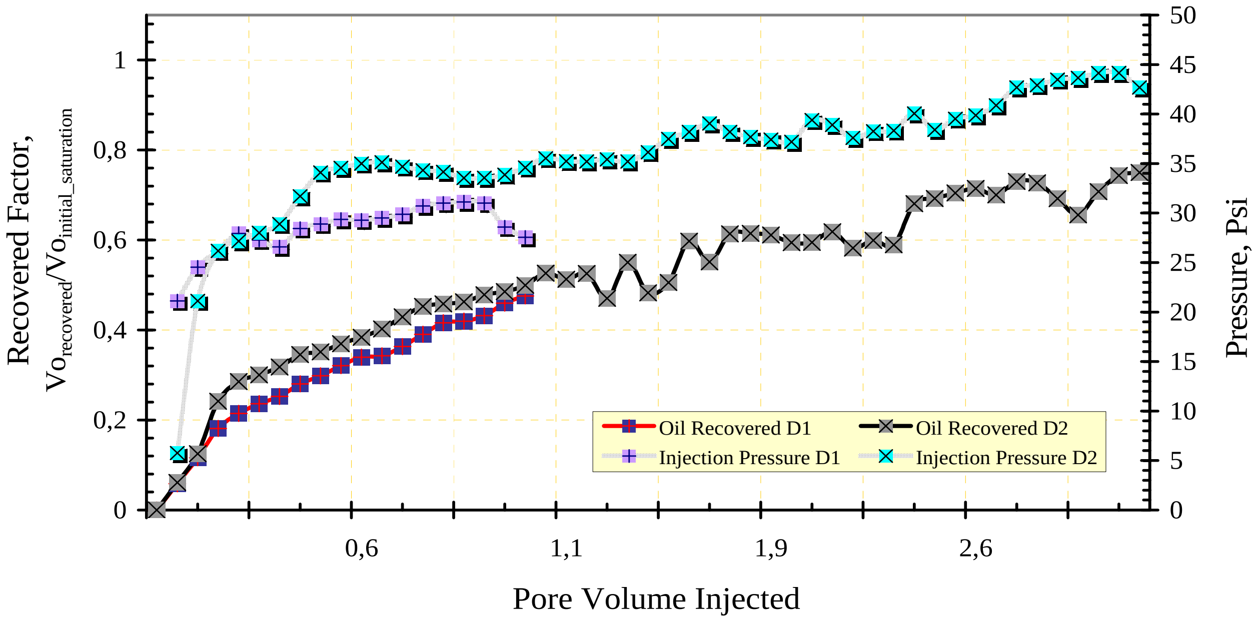

Figure 4. Oil recovered fraction, by emulsion injection of average drops D1 & D2, and their injection pressure.

In the third set of experiments, the oil was displaced from the porous sample by alternate injection of water and oil-water emulsion 2, with an average drop diameter D_2 = 20 μm. The experiment started with injection of water of approximately 3.5 times the porous volume. The recovery factor had reached a plateau of approximately 40% and the injection pressure had also reached a constant value of 30 psi. At this point, a volume of 30% of the porous volume of emulsion was injected, and after that, injection of water was restarted. Just after the water injection has restarted, the recovery factor started increasing, until it reached a new plateau of approximately 45%. The injection pressure rises abruptly after the emulsion is injected. It keeps rising for a short while after the water injected is resumed but starts falling just after that, until it reaches a new plateau of 22 psi. A second cycle of emulsion injection followed, with a volume of 60% of the porous volume. The recovery factor started rising just after the start of the emulsion injection.

Immediately after the emulsion injection, the injection of water was resumed. It continued until the recovery factor reached a new plateau, now of approximately 70%. A third and final cycle of emulsion injection elevated the recovery factor to approximately 75% of the initial oil in place.

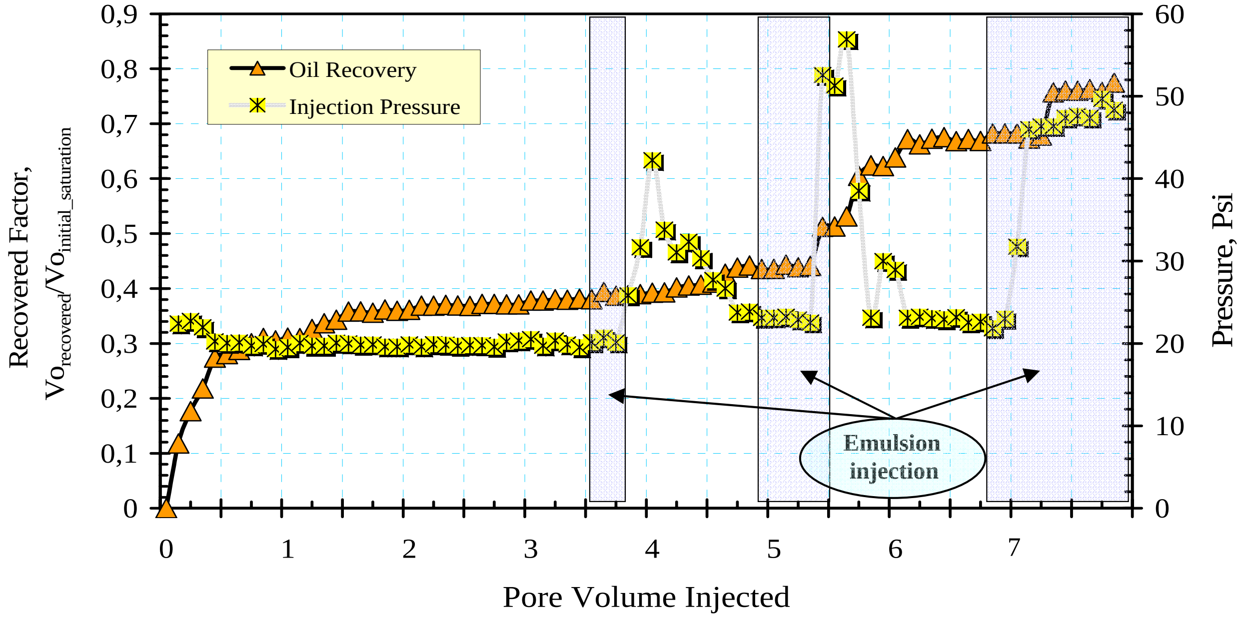

Figure 5. Results of oil recovered fraction, by alternate water and oil-water emulsion injection of average drop diameter D_2 , and their respective results of injection pressure.

The alternate injection of water and emulsion led to high recovery factor avoiding the high injection pressure during the entire experiments. The injection pressure rose each time emulsion was injected, but it went down once water injection was resumed. The explanation is that for the emulsion to flow through the porous media, a high injection pressure was necessary. However, once the emulsion was in place and water injection was resumed, the emulsion remained stationary, blocking the porous space and diverting the water that followed to regions of the porous space that has never been swept.

3. FINAL REMARKS

The experiments reported here illustrate the potential of emulsion injection as an EOR method. It raised the oil recovery factor from 40%, obtained by water injection, up to 75%, obtained with alternate water and emulsion injection.

The results also show that the mechanism responsible for the improvement on the recovery factor is not associated with the higher viscosity of the emulsion, but related to the pressure gradient necessary to flow an oil drop through a pore throat with a diameter of the same size of the drop.

In order to apply this method, several basis questions still need to be addressed. The first is that the emulsion that is going to be injected has to have the appropriate micro structural properties in order to block the desired regions of the porous space. To answer this question, complete understanding of how oil drops flow through constricted passages is essential. This subject is been investigated by experimental visualization and measurements and theoretical modeling of emulsion flow through constricted glass capillaries. The second question that needs to be addressed is the stability and cost of the emulsions.

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