EFFECT OF CAPILLARY NUMBER ON THE OIL RECOVERY USING OIL-WATER EMULSION INJECTION IN COREFLOODING EXPERIMENTS

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Abstract. *TheWater injection flooding is a common method to improve reservoir sweep and pressure maintenance. The heavy-oil-recovery efficiency is in part limited by the high water-to-oil mobility ratio. Several enhanced oil recovery methods are being developed as more efficient alternatives to water flooding. Dispersion injection, in particular oil-water emulsion injection, has been tried with relative success as an enhanced oil recovery method, but the technique is not fully developed or understood. If emulsion injection proves to be an effective EOR method, its use would bring the added benefit of disposing produced water with small oil content that could be modified to serve as the injected oil-water emulsion. The use of such methods requires a detailed analysis of the different flow regimes of emulsions through the porous space of a reservoir rock. If the drop size of the disperse phase is of the same order of magnitude as the pore size, the drops may agglomerate and partially block water flow through pores. This flow regime may be used to control the mobility of the injected liquid, leading to higher recovery factor. We have shown in recent experiments of oil displacement in a sandstone core that, the oil recovery factor could be raised from approximately 40 %, obtained with water injection only, up to approximately 75 % by alternating water and emulsion injection. Although these results clearly show the improvement in the recovery factor, the mechanisms responsible for the phenomenon have not been clearly elucidated. In this work, two sandstone cores were used to demonstrate the effect of flow rate (capillary number) on the mobility control by emulsion injection. Figure 1 shows a schematic representation of the experiment set-up. The experiments show that raising the flow rate by a factor of 10 (0.03 ml/min to 0.3 ml/min), the oil recovered factor decreases considerably.*

Keywords: *porous media, oil displacement, recovery factor, enhanced oil recovery*

1. INTRODUCTION

Water flooding is a 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 unswept. When the water injection becomes uneconomic, 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 production cost of emulsions would be much smaller than the cost of polymer solutions, because the emulsions could be prepared with native liquids from the reservoirs and the fluid-rock interaction would 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). In a previous paper (Guillén et al. 2007), was showed the efficiency of emulsions to improve the oil recovery. The goal of work was 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. At final stage of water and emulsion injection, the recovery factor was raised from 40% (just with water injection) to approximately 75% of the initial oil in place, Although these results clearly show the improvement on the recovery factor, the mechanisms responsible for the phenomenon are not clear. Toward to clarify there phenomenon, the work presented here attends the importance that flow rate have in the oil recovery throw emulsion injection process. When the flow rate is increased the capillary number is been also increased as is showed in "Eq. (1)" or more specifically for emulsions en "Eq. (2)".

$$Ca = \mu\, Q / A\, \sigma \tag{1}$$

Where μ is the viscosity, Q the flow rate, A the transversal area, and σ the surface or interfacial tension.

$$Ca = \frac{\mu_c\, \dot{\gamma}}{\sigma / R} \tag{2}$$

Where μ_c is the continuous-phase viscosity, $\dot{\gamma}$ the shear rate, and R the particle radius. When the capillary number is small (Ca$\rightarrow$ 0), the deformation of the droplets is negligible and the droplets can be treated as spherical. However, at high capillary numbers, the deformation of droplets from spherical shape can be quite significant. "Equation Eq. (2)" Under a steady macroscopic flow, the droplets of emulsions are subjected to two opposing effects: (i) a viscous stress of magnitude $\mu_c\, \dot{\gamma}$ that tends to elongate the droplet, and (ii) a stress of magnitude σ/R that tends to minimize the surface energy and hence tends to maintain the droplet in a spherical shape. Therefore, the equilibrium shape of the droplet is governed by the ratio of viscous stress to σ/R (Pal, 2001).

So, two sandstone cores with similar characteristics were used to understand the effect that different capillary numbers have on mobility control submitted to emulsion injection. The first with flow rate of 0,03ml/min and the second with 0,3ml/min. That means, the flow rate was raised over a factor of 10.

2. EXPERIMENTAL SETUP

Figure 1 sketch the experimental setup used to make the experiments. Two different types of injection liquids were used for both experiment, water and emulsions. Although, both experiments had the same conditions and parameters, with the only difference of the flow rate between them. A positive displacement pump controlled the flow rate fed into the porous media. To reduce the wear of the pump, only water flew through it. The water drives a piston installed in the storage cylinder to drive the injection liquid into the porous media. The two porous media used were cylinder sandstone. 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.

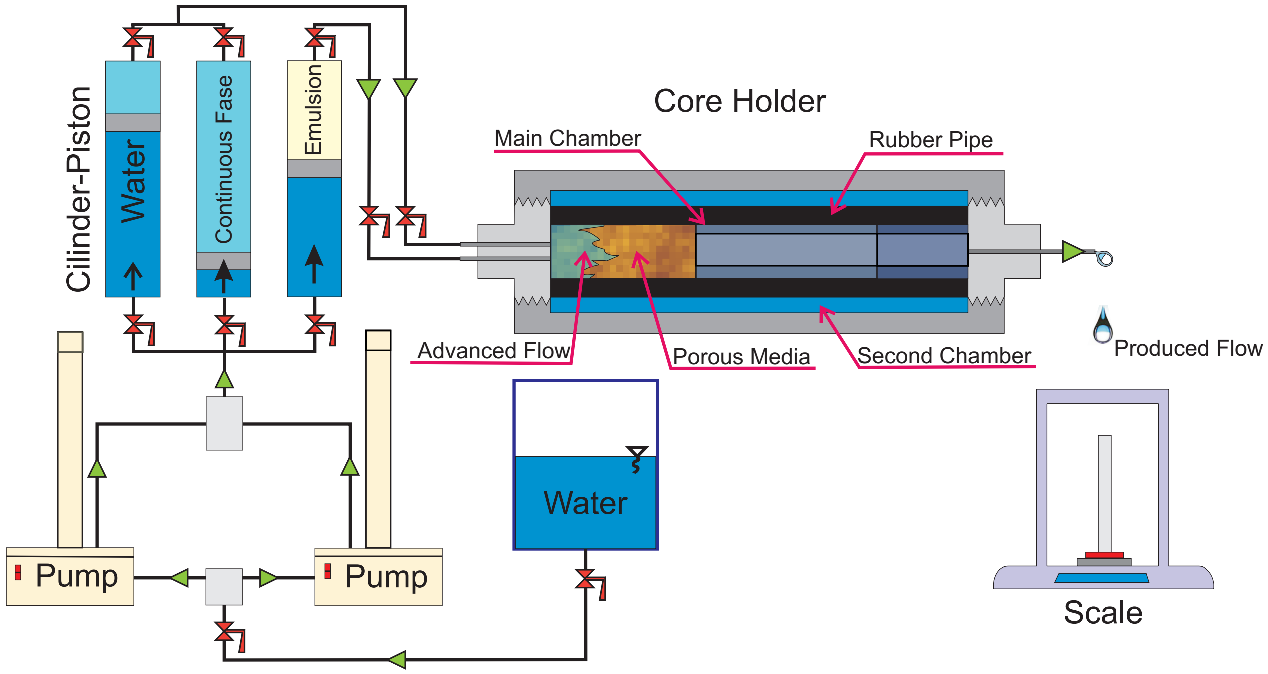

Figure 1. Schematic representation of experimental setup.

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 Tab. 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. Them, the experimental procedure was started. The porous sample was submitted to water injection and after that, the emulsion is injected to swept the remanent oil. As in our previous work, the produced liquid was weighted on a scale to determinate the oil fraction recovered during the entire experiment:

Table 1. Properties of the porous medias used at the experiments

Porous Media Properties			
Porous Media	Sandstone 1	Sandstone 2	–
Diameter	37.61	37.44	mm
Length	64.36	9.39	mm
Pore Size	60	60	μm
Porosity	25.3	25.6	%
Permeability	262.6	238.95	mD
Pore Volume	1809	2643	mm^3

$^{(1)}$: measured at 23^{o}C

The properties of the oils used to saturate the porous media and to prepare the emulsions are shown in Tab. 2. A 30% oil-in-water emulsion was prepared as the injection liquid. Its properties are presented in Tab. 3.

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 the Sandstone)	427(1)	0.9101(1)
Synthetic Oil (Emulsion Prepare)	1020(1)	0.9964(1)

(1): measured at 25^{o}C

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

Emulsion	Density (g/ml)	Drops Diamenter	Concentration
Oil-in-Water (saturate the Sandstone)	0.9992	50	30/70

(1): measured at 23^{o}C

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.

Both experiments kept the same procedure but with different behaviors due to the two different flow rates injection between them. In the first experiment as shown in Fig. 2 with Q=0.03ml/min, the oil was displaced from the porous sample by water injection until reached a plate of 34% in the recovery factor, the oil had not more recovered or had been too small when compared with the water utilized for this purpose, the injection pressure had also achieve a relative constant value near of zero. After that and approximately in the 15th pore volume injected of water, a cycle of emulsion was injected into the porous sample to improve the swept of remanent oil, was injected a volume of 0.3PV. The pressure then improved considerably, reaching a value of 8psi at the end of emulsion injection, and after that, the injection of water was restarted. Just after the water injection had started, the recovery factor started increasing, until it reached a new plateau of approximately 40%, and the pressure decreased until reach a new plateau of about 0.1psi. Then a new cycle of emulsion with 1PV was injected, the pressure rose abruptly until 24psi at the end of the emulsion injection and the water injection is restarted. The recovery factor was then increased to a new plateaus of 56% and the pressure decreased to 0.1psi. A third and final cycle of emulsion was then injected with 8.5PV elevating the recovery factor to value of 72% but the pressure increase was not so much. After emulsion injection, water was injected again and the recovery factor kept on 72% of the initial oil in place, and the pressure go back to 0.1psi. Is important remark that the flow is not stopped in anytime, just when a valve is closed an other is open to permit the flow of the other flow.

The second experiment as shown in Fig. 3. with Q=0.3ml/min, the oil recovery factor achieved a value of 21% throw water injection, the injection pressure had also achieve a relative constant value of 4psi, (its shows a bigger pressure that the first experiment due to bigger flow rate). After that and approximately in the 20th pore volume injected of water, the first cycle of 0.3PV of emulsion was injected into the porous sample. The pressure then improved until value of 28psi at the end of emulsion injection, and after that, the water injection was restarted. After the water injection had started, the recovery factor started increasing, reaching a new plateau of approximately 24.5%, and the pressure decreased until reach a new plateau of about 4psi. Then a new cycle of emulsion with 1PV was injected, the pressure had risen abruptly until 46psi at the end of the emulsion injection when the water injection was restarted. The recovery factor was then increased but not significantly to a new plateau of 26% and the pressure decrease to 7psi. A third and final cycle of emulsion was then injected with 4PV but did not see any recovery factor improved, and the pressure increase drastically to more than 100psi. After emulsion injection, water was injected again and the recovery factor kept on 26% of the initial oil in place, and the pressure go back to 15psi.

The experiments show that raising the flow rate by a factor of 10 (0.03 ml/min to 0.3 ml/min), the oil recovered factor decreases considerably.

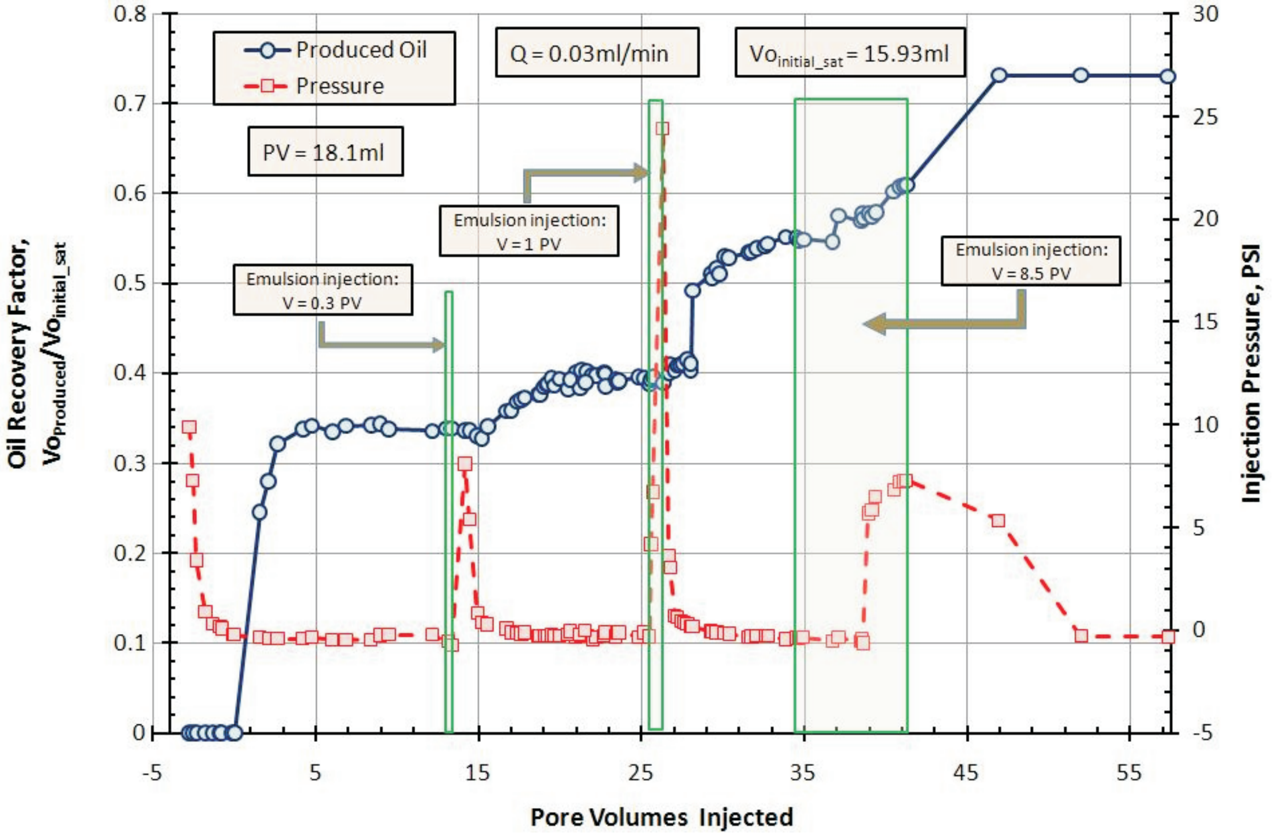

Figure 2. Recovery Factor throw Alternated water and emulsion injection at low Ca in a Sandstone.

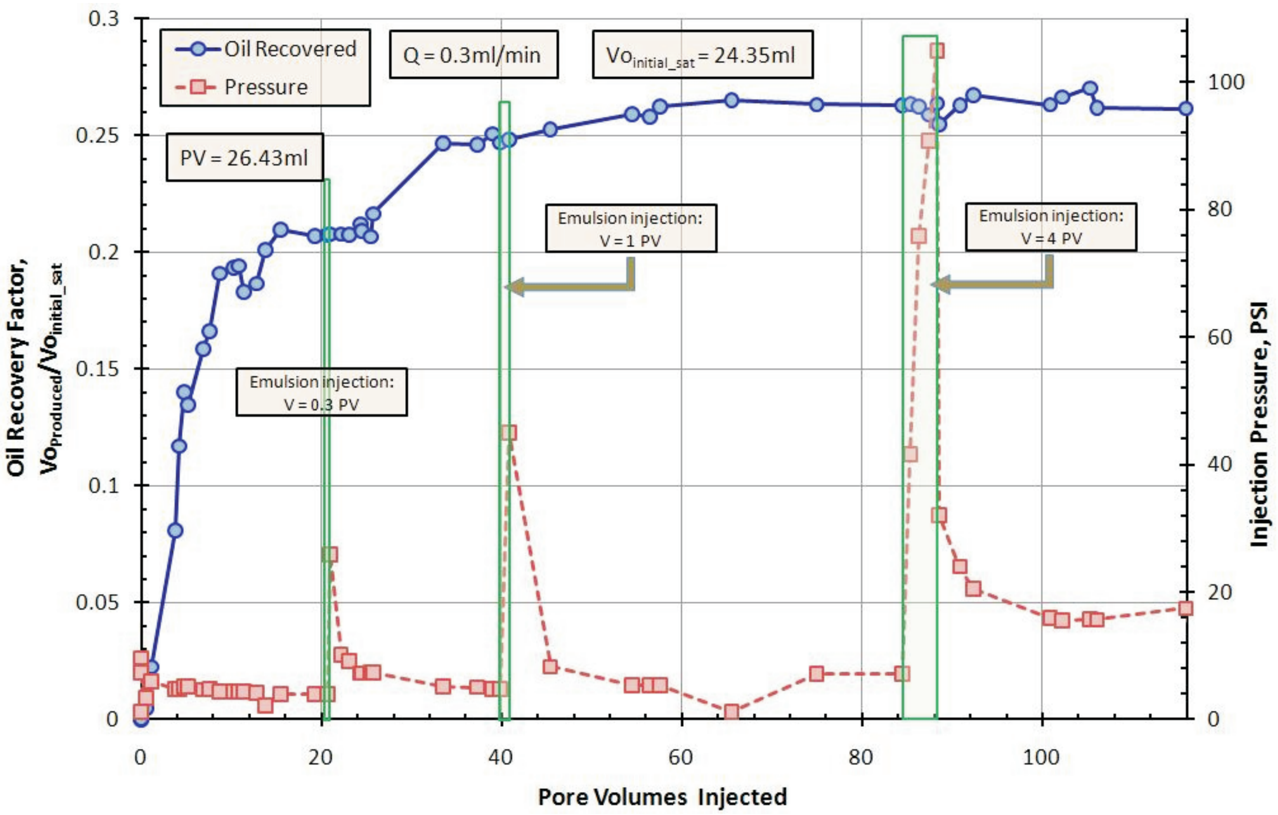

Figure 3. Recovery Factor throw Alternated water and emulsion injection at high Ca in a Sandstone.

4. ACKNOWLEDGEMENTS

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5. FINAL REMARKS

The experiments reported here illustrate that, with an apropriate Ca, the emulsion injection can be considerate as a great alternative in EOR method. It raised the oil recovery factor from 34%, obtained by water injection, up to 73%, obtained with alternate water and emulsion injection. The results also showed that the mechanism responsible for the improvement of 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. 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. The appropriate flow rate permitted an adequate control of mobility of the injected liquid, leading to higher recovery factor.

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