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EFFECT OF VISCOSITY RATIO ON TERTIARY RECOVERY EFFICIENCY BY INJECTION OF NEWTONIAN FLUIDS IN A POROUS MEDIA

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Abstract. *The application of tertiary recovery methods to increase the recovery factor of oil fields, specially in heavy oil reservoirs, has increased considerably due to the fact that the efficiency of primary and secondary oil recovery methods do not exceed 30%. Among these methods, the injection of chemicals can be cited, but to apply these methods, it is important to understand the phenomenology of liquid-liquid displacement occurring within a porous medium. In this work, the influence of the viscosity ratio on tertiary recovery method was evaluated. Using an experimental approach, different Newtonian solutions were used to displace another Newtonian fluid that fills the pores of a specific porous medium. It was shown that the lower the viscosity ratio, the greater the displaced liquid fraction recovered.*

Keywords: *tertiary recovery, porous medium, liquid-liquid displacement.*

1. INTRODUCTION

Displacement of a liquid through the injection of a fluid into a porous medium is a frequent problem in a variety of applications, such as oil field operations.

Today, much of the energy consumed by the world's population comes from oil, which is a source of non-renewable energy. Due to the increasing demand for energy consumption and raw materials in the industries, the demand for oil has been focused on deep and ultra-deep waters. Therefore, understanding the problem of fluid flow in porous media is of utmost importance in order to maximize the amount of oil recovered.

At the beginning of production, many wells are able to raise the oil to the surface or even to a stationary production unit because it has sufficiently high energy. This energy is called primary energy and is related to the mechanisms of production by gas in solution, by water inflow and gas cap. Over the time, the energy contained in the reservoir undergoes a depletion process due to the decompression of the fluids and the resistance associated with viscous and capillary forces (Musse, 2009). The oil fields produced using the primary production mechanisms have low recovery factors and, consequently, much of the oil is retained in the reservoir.

In order to increase the amount of recovered oil, the secondary recovery methods were developed and implemented, which consists in recovering the energy of the reservoir through the injection of native fluids from the reservoir itself. Among them can be cited the injection of water.

There are reservoirs, specially those that have very viscous and heavy oils, that present low recovery factor, when using primary and/or secondary methods. Therefore, tertiary recovery methods, or advanced recovery methods, have been developed, such as polymer injection (Musse, 2009; Veloso, 2014).

There are several numerical and experimental studies related to the flow of fluids in porous media in the literature, both single-phase and multi-phase in nature. Among these works, we can mention those that aim to study the behaviour of the flow of a fluid contained in a porous medium when it is displaced by another fluid.

In porous media, because they have channel dimensions equivalent to or smaller than those of a capillary tube that interconnects the pores, capillary effects should be considered. Therefore, to better understand the phenomenology of the flow in porous media, during the accomplishment of the bibliographic research, studies related to the flow in capillary tubes were studied.

Soares et al. (2015) carried out numerical and experimental studies on immiscible displacement of a viscous liquid using another viscous liquid inside a capillary tube. However, in addition to analyzing the behaviour of the liquid film thickness through the deposited geometric mass fraction, the authors also studied the behaviour of the displacement efficiency. These parameters were investigated for various capillarity numbers (Eq. 1) and the viscosities ratio (Eq. 2).

$$Ca = \mu_2 U / \sigma \quad (1)$$

$$N\mu = \mu_2 / \mu_1 \quad (2)$$

In the above equations, μ_1 is the viscosity of the displacing fluid, μ_2 is the viscosity of the displaced fluid, U is the characteristic velocity of the flow and σ is the interfacial tension between the two liquids.

Although the influence of viscosity ratio on liquid displacement has been already evaluated in capillary tubes, the effect of viscosity ratio on the liquid displacement, and therefore on the tertiary recovery efficiency, needs more investigation. This work, evaluates the influence of the viscosity ratio on tertiary recovery method. Using an experimental approach, different Newtonian solutions were used to displace another Newtonian fluid that fills the pores of a specific porous medium.

2. METHODOLOGY

The material used to compose the porous medium was quartz sand. The characterization tests necessary to obtain the characteristics of the porous were the real grain density, particle size analysis, compaction curves, maximum and minimum void indices and permeability. Before the performance of the tests, the sand was kept for a minimum of 12 hours in an oven at 100 °C for drying.

The test for obtaining the specific mass of the grains was performed according to the NBR 6508/84 - Grains of soil passing through the 4.8 mm sieve: Determination of specific mass. The actual specific mass of the grains used was 2.68 g/cm³. The procedure for the granulometric analysis of the sand was performed according to the NBR 7181/84 - Soil: Granulometric analysis. The tests involved the stages of fine screening and sedimentation. Coarse screening was not necessary because the diameters of the grains fit as fine or average grains.

Based on the grain size, the average grain diameter was determined in order to determine the Reynolds number, the characteristic length and the deformation rate. For every two screens, the average diameter of the grains left in a given sieve was the arithmetic mean between the passing diameter of the current screen and the previous screen. For example, particles diameter retained in the 1 mm sieve, since the previous sieve used was 2 mm, was considered 1.5 mm. This procedure was repeated for all the sieves used in the test.

To obtain the maximum void index, the NBR 12004/90 - Solo was applied: Determination of the maximum void index of non-cohesive soils. The procedure consisted of carefully inserting the sand into a mold using a funnel to achieve the lowest possible material compaction. The apparent specific mass of dry soil (ρ_{apparent}) was measured under the lowest compaction condition, which presented a value of 1.437 g/cm³. From this parameter and the specific grain mass (ρ_{grains}), the maximum void index was calculated by applying Eq. 3. The maximum void index (I_v) was 0.865.

$$I_v = (\rho_{\text{grains}} / \rho_{\text{apparent}}) - 1 \quad (3)$$

The minimum void index was obtained by applying the NBR 12051/91 - Soil: Determination of the minimum void index of non-cohesive soils. Compaction tests were done by adding different water contents in different soil samples, seeking a compaction curve. For different moisture content grades, the apparent specific mass of the dry soil was obtained. From these points, the compaction curve was generated and the humidity corresponding to the maximum apparent specific mass of the dry soil was obtained. From the maximum specific mass of the dry soil, which was equal to 1.683 g/cm³, and the grain density, the minimum void index was obtained using Eq. 3. The minimum void index was 0.592.

The absolute porosity (ϕ) is also related to the volume of voids. It is defined as the ratio between the void volume and the porous medium volume (V_t), given by the sum of the volume of solids (V_s) and the volume of voids (V_v), Eq. 4.

$$\phi = I_v / (I + I_v) \quad (4)$$

Since the sand is cementless, the absolute porosity and effective porosity are equivalent, i.e., all pores are interconnected to each other. To ensure that in each test the characteristics of the porous media are constants, it was always prepared under the condition of maximum compactness.

To finish the characterization of the porous medium, a specimen was prepared with the sand in question to obtain soil permeability. To obtain this parameter, the permeability test was performed following the NBR 13292/95 - Soil - Determination of the permeability coefficient of granular soils at constant load. The soil was prepared and compacted in

such a way that the minimum voids were obtained, i.e., the soil in its maximum compactness. The load was adjusted and estimated by the difference in water level read in 2 manometer tubes. For each load, the flow velocity at 20 °C was calculated. The ratio between the flow velocity and the applied load is the soil permeability in cm/s. Table 1 presents the results of the soil characterization used for the tests.

Table 1 – Porous media properties.

Sand density (g/cm ³) 2.68
Sand mean diameter (mm) 0.65
Maximum void index 0.865
Minimum void index 0.592
Maximum compactness porosity 0.372
Soil permeability (cm/s) 0.028

To obtain the desired results for the Newtonian scenario, two immiscible liquids were selected: a solution of castor oil and soybean oil (base oil) and a solution of water, polyethylene glycol (PEG) and ethyl alcohol grade 92.8 (water base). The solutions were characterized at 23 °C. The use of solutions has the advantage of adjusting the properties thereof, according to the amount of each substance used. In this way, it was possible to fine-tune both the viscosity (μ) and the specific mass (ρ) of the fluids, making it possible to obtain the desired viscosity ratio ($N\mu$) and density ratio ($N\rho$). Tables 2 to 4, illustrate, respectively, the composition and the properties of water-based Newtonian fluids and the composition and the properties of the oil base fluids.

Table 2 - Properties of water base solutions.

Solution	% Water	% Ethanol	% PEG	ρ (kg/m ³)	μ (mPa.s)
Solution A	35	65	0	907,1	2,53
Solution B	13	61,5	25,5	939	24,9
Solution C	25	60	15	931,2	12,5
Solution D	16	43	41	990,6	81,3
Solution E	35	22,7	42,3	1036,6	111
Solution F	30	58	12	933,1	9,8

Table 3 - Properties of the oil base solutions.

Solution	% Soybean Oil	% Castor bean oil	ρ (kg/m ³)	μ (mPa.s)
Solution G	100	0	916,8	55
Solution H	80	20	922,9	81
Solution I	70	30	929,2	103,1
Solution J	100	0	959,7	791,3

The parameters resulting from the combination of the two immiscible Newtonian fluids used for the tests, i.e., viscosity ratio ($N\mu$), density ratio ($N\rho$), interfacial tension (σ_i) and Bond number (Bo). The Bond number is defined as the ratio between gravitational and capillary forces and since in this study its value is much smaller than 1, it means that the gravitational forces are negligible when compared to the capillary forces.

From the viscosity ratios obtained, each pair of fluids was taken to the experimental bench in order to obtain the lost mass (m_e) fraction. The experiments were performed in such a way that Reynolds' number (Re) was much smaller than one and the number of capillarity (Ca) had no influence on the efficiency of recovery, making it possible to isolate the effect of viscosity ratio variation in the lost mass fraction.

Table 4 - Combination between two Newtonian solutions.

Injected Solution	Produced Solution	$N\mu$	$N\rho$	σ_i (mN/m)	Bo
Solution A	Solution I	40,1	1,02	3,89	0,0156
Solution A	Solution G	21,82	1,01	5,5	0,0007
Solution F	Solution H	8,2	0,992	3,86	-0,0082
Solution C	Solution G	4,4	0,976	6,43	-0,0147
Solution B	Solution G	2,2	0,972	5,6	-0,0185
Solution D	Solution H	0,93	0,93	4,6	-0,0610
Solution E	Solution G	0,5	0,88	4,72	-0,105

The experimental apparatus consist of a controlled speed hydraulic actuator, with a 40 mm piston diameter. Attached to the top of the press was the displacing fluid storage tank, making it possible to saturate the hydraulic actuator by gravity. The maximum stroke of the press is 100 mm and the maximum displacement fluid volume that can be injected into the porous medium, considering the piston diameter, is 125.7 cm³. A low pressure hose connected the tank to the actuator. The connection between the hydraulic actuator and the porous medium was made by a high pressure hose. The length of the porous medium of the experiments was set to 70 mm. At the outlet of the metal tube, a low pressure hose allowed the recovered fluid to be collected in a beaker. Still in the metal tube, a relief valve was installed to allow the replacement of the air present inside this tube by the displacing fluid. Figure 1 shows the schematic of the bench.

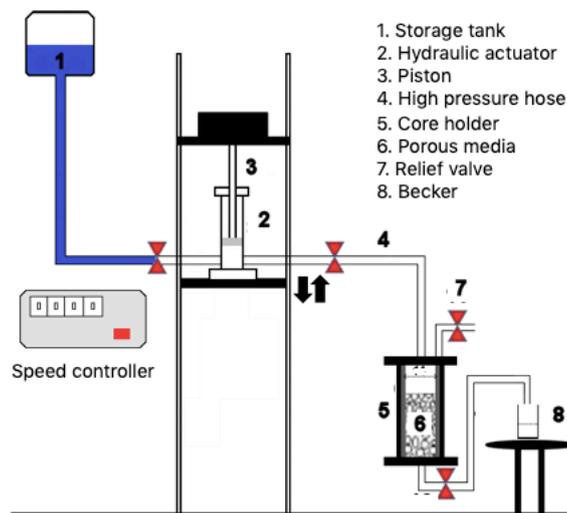


Figure 1 - Schematic of the experimental bench.

During the execution of the tests, the displaced fluid (oil base), with viscosity of 52.3 mPa.s, was kept fixed and different displacement fluids were used. By varying the percentages of ethanol and PEG in the solutions, different viscosity values were obtained for each displacing fluid used, keeping the density ratio close to 1 to exclude the influence of gravity in the experiments.

To validate the experimental bench, tests considering $N\mu = 18.2$ were also performed and the results obtained were compared with those observed by Taylor (1961). The authors have found that the viscosity ratio of 18.2 was sufficiently high to represent the displacement of the liquid by a gas and the decrease in the viscosity ratio, for a same capillarity value, increases the oil recovery efficiency. Thus, for the entire viscosity ratio range studied, the lost mass fraction increased with increasing Ca until an asymptotic value was reached, a phenomenon that occurs when the interfacial forces are negligible when compared to the viscous forces.

3. RESULTS

Figure 2 shows the results obtained for the lost mass fraction as a function of capillarity number for different viscosity ratios.

Based on the results presented in Figure 2, for every range of viscosity ratio studied, it was observed that Ca was high enough so that the lost mass fraction was independent of this parameter. The order of magnitude of the capillarity number leading to a recovery efficiency ranged from 10^{-4} to 10^{-2} .

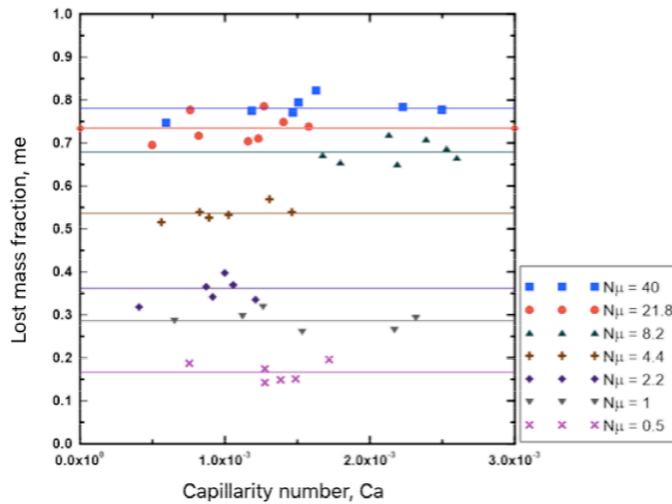


Figure 2 – Influence of capillarity number on lost mass fraction.

Still concerning Figure 2, it was observed that the lost mass fraction increases as the viscosity ratio increases. By reducing the viscosity ratio, that is, when the dynamic viscosity of the displacing fluid approaches the dynamic viscosity of the displaced fluid, the shear force imparted by the displaced fluid is increased, contributing to the increase in the amount of liquid carried out by the displacing fluid, leading to a decrease of m_e .

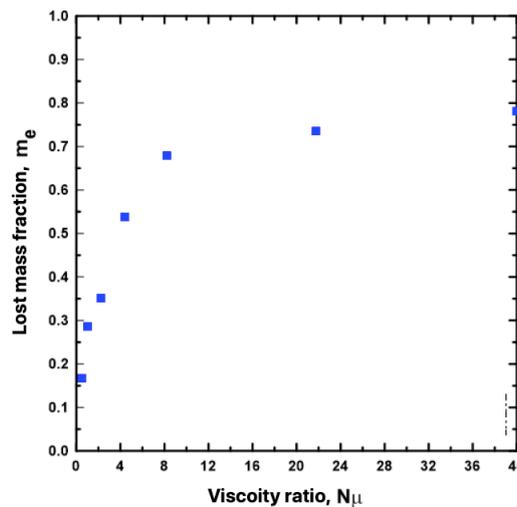


Figure 3 – Influence of viscosity ratio on lost mass fraction.

The results shown in Figure 3 show that the lost mass fraction increases as the viscosity ratio increases. By reducing the viscosity ratio, that is, when the dynamic viscosity of the displacer fluid approaches the dynamic viscosity of the displaced fluid, the shear force acting on the displaced is larger, contributing to the increase in the amount of liquid flowing out of the porous medium, leading to a decrease in the lost mass fraction. These results are in accordance with those obtained by Soares et al. (2015). Besides that, the reduction of the viscosity ratio contributes to increase the number of pores that are swept by the injected fluid, increasing the recovery factor. This is consequence of the increased shear force that exceeds the capillary force in the smaller pores, allowing the flow of displaced fluid contained in the smaller pores.

Additionally, it was possible to relate the flow patterns obtained by Lenormand et al. (1988) and Zhang et al. (2011) during the occurrence of the displacement of a Newtonian fluid in a porous medium by injecting another Newtonian fluid immiscible with the lost mass fraction obtained in the experiments. In the scenarios with high viscosity ratios,

which showed low recovery efficiency (high values for the lost mass fraction), the flow pattern that occurred was the viscous fingering, characterized by the appearance of preferential paths. This flow pattern occurs due to the low amount of pores swept by the displacer fluid, whose shear force imposed on the displaced fluid does not exceed the capillary force in the majority of the pores. On the other hand, in the low viscosity ratio scenarios, the porous medium is swept more evenly, amplifying the amount of fluid displaced recovered. The capillary fingering flow pattern was not observed in the experiments, because this occurs in scenarios where the number of capillarity exerts influence on the lost mass fraction.

4. CONCLUSIONS

With regard to the viscosity ratio, it was found that decreasing it results in a decrease in the lost mass fraction. This increase in mass recovered is due to shear imposed by the fluid injected into the displaced fluid to be able to drag more liquid out of the porous medium. In addition, there is an increase in the number of pores that are swept up by the displacing fluid, further contributing to the reduction of the lost mass fraction. These results corroborate the results of other researches available in the literature and can contribute to the improvement of the performance of tertiary oil recovery methods.

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