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Experimental Investigation of the Enhanced Oil Recovery Process Using a Polymeric Solution

Enhanced oil recovery methods are becoming an important source of oil production of wells that have already been explored and, by these methods, of increase of the total volume of oil extracted. An important example is the injection of polymeric solutions after the injected water has reached the breakthrough point. In the present work an experimental apparatus was built in order to test the ability of enhanced oil recovery of polymeric solutions, composed by Xanthan Gum (XG) dissolved in distilled water. This apparatus consists of an idealized porous media made with small spheres inserted in a cylindrical cell and then filled with oil with the same viscosity as the petroleum found in Campos Basin (Rio de Janeiro, Brazil). As displacing fluid, we tested polymeric solutions of different concentrations of Xanthan Gum and these non-Newtonian fluids were characterized using a rotational rheometer. The resulting characterization has shown that increasing the concentration, not only the level of viscosity, but also the elasticity of the fluid increases. The shear-thinning behavior of the solution can be well captured by a power-law model. For higher concentrations the shear-thinning feature of the Xanthan Gum solution is more pronounced. We conducted an experimental procedure to mimic enhanced oil recovery process by first injecting water until the breakthrough point. Increasing the polymer concentration, the extra amount of oil recovered also increase. Theoretical and heuristic analyses show that in the shear dominated regions, the Xanthan Gum polymeric solutions do not increase pore efficiency, but increase sweep efficiency, while the extensional character of the polymeric solution seems to indicate that in extensional dominated regions the polymeric solutions play an important role on the oil recovery efficiency from both perspectives: pore and sweep efficiencies.

Keywords: oil recovery, polymeric solution, porous media

Introduction

In the oil production activity, after a first technique to extract oil from a reservoir is used, the volume of oil that still remains inside this reservoir can be very significant, achieving values of 40% of the total original volume. In order to continue to produce oil there is a need for different techniques that can be applied in successive stages. A first stage occurs when a free path is built from the reservoir to the surface and then, there is a natural pressure gradient that pushes the oil to the producer wedge. After that, generally, it is necessary to inject another material that takes the place of the oil inside the porous space. In a secondary stage, a cheap fluid is injected. Most of the times this is done with water, since this fluid has a low degradation process, and is generally available, easy to be introduced, and therefore, the opportunity cost of a unit of water injection is favorable (Craig, 1980). This water is sometimes saline, since the sea constitutes a rich source. Generally when water is the injected fluid the fingering phenomenon that takes place avoids the possibility of high sweep efficiency. The sweep efficiency is low for several reasons: the mobility ratio is below one, the oil that is in contact with the porous surface has high adhesion forces, presence of natural fractures, etc. (Satter et al., 2008; Shedid, 2006). Because of that, the production of oil requires some method of enhanced oil recovery. This has been done in several countries with some success (e.g. China, see D-K. Han et al. (1999)), but still needs scientific investigation for a proper analysis and process control. An important review on the subject can be found in Babadagli (2003).

One of these methods is related to the use of surfactants (e.g. Ayirala and Rao (2004)) to induce the reduction in interfacial tension and alteration of wettability. Another possibility is to use thermal effects, mainly with heavy oils (e.g. Babadagli (2003)), generally to decrease the viscosity of the fluid and reduce the pump power to extract the oil. A third possibility is to inject a polymer,

where the Xanthan Gum is one of the most used polymeric solutions, as reported by D-K. Han et al. (1999). Its shear-thinning behavior and the fact that it has some elastic features improve its sweep efficiency. For some remarks on the friction losses of power-law fluids in expansions and contractions, the reader is referred to the works of Pinho et al. (2003) and Kfuri et al. (2011).

Analyses of processes involving non-Newtonian materials are becoming more and more important in the petroleum industry. There are mainly two reasons for this status change. One reason is that the evaluation of income flux in oil company needs more accurate calculations. Therefore, doing the calculations assuming that a complex fluid is Newtonian can lead to significant differences on the final result which can impact financial decisions in the Petroleum industry. Hence, in most of the cases a more realistic rheological description is necessary to accurately predict processes involving non-Newtonian materials. The second reason is related to the complexity of these materials. Since they can exhibit features that are not present in Newtonian fluids such as pseudoplasticity, viscoplasticity, elasticity, thixotropy, traditional processes where Newtonian fluids are used can be optimized by the intelligent use of these non-Newtonian features.

In particular, in the imbibition oil recovery process, a fluid is injected in the reservoir to produce oil. This is a rather complex problem and can be approached in different ways. In a rough manner, this problem can be divided into micro-scale and meso-scale approaches. In the first type, the one problem is solved for one pore and the results obtained are translated for the whole porous media. Some recent examples of fluid-fluid displacement, involving non-Newtonian liquids, when the capillary pressure is important, can be found in Sousa et al. (2007), Thompson et al. (2010), Freitas et al. (2011) and the references therein. An interesting algorithm for the upscaling problem can be found in Sochi (2009). One of the few investigations dealing with the relation between capillary flow in a tube and the flow through a porous media can be found in Soares et al. (2009).

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One of the pioneering works concerning the investigation of influence of concentration of polymeric solutions on the oil recovery in a porous media was conducted by Kabir et al. (1980). The porous media cell of the experiment was a consolidated one with permeability of 766 mD. Initially the cell was saturated with refined oil and the polymeric solution was injected at a constant flow rate of 8.9 ml/s. Their results showed a decrease in the mobility ratio accompanied by an increase of oil recovery from 58% to 64%. In a more recent work, Wang and Dong (2009) investigated the recovery of oils with viscosity values between 430 and 5500 cP, by means of injection of polymeric solutions with effective viscosities varying from 3.6 to 359.3 cP. The experiment was conducted using a porous cell of 7100 mD of permeability. Initially the porous media was saturated with water and after that with oil. The first injection was done using water at a constant flow rate (10 cm³/h) until a half of the porous volume. After that the polymeric solution was injected. They found an increase of oil recovery up to a certain point where a higher concentration did not bring oil recovery efficiency. Zhang et al. (2010) used a procedure of alternative injections: first water, second polymeric solution, and then water again. They used a polymeric solution with a viscosity of 29 cP to recover oil with a viscosity of 707 cP. The injection of the polymeric solution gave an addition of 13% of oil recovery.

One serious drawback of the analyses found in the literature is the lack of a full characterization of the rheology of the polymeric solution. Hence, the explanation of the increase in oil recovery is not provided or is given in terms of a constant apparent shear viscosity of the injected fluid.

The objective of the present work is to investigate how the different concentrations of Xanthan Gum on water influence the oil recovery efficiency of the two-stage procedure composed by: a) injection of water till the breakthrough point and b) injection of the polymeric solution considered. We also try to correlate the results obtained with the rheology of the injected fluid

The rest of the article is organized as follows. In section 2 the experimental procedure is described. This includes the experimental setup, with particular emphasis on the porous cell, the rheological characterization of the displaced and displacing fluids and the experimental methodology used to capture the results. The following section describes the results obtained and provides a discussion of the main aspects, given heuristic explanations based on the shear and extensional dominated regions. Finally, in the Final Remarks, the conclusions are given.

Nomenclature

- A = cross sectional area, m²
 g = gravity acceleration, m/s²
 G' = storage modulus, Pa
 G'' = loss modulus, Pa
 G^* = complex modulus, Pa
 k = specific permeability, mD
 K = consistency index, Pas⁻¹
 L = length of the media, m
 M = mobility, cP/mD
 n = exponent index, dimensionless
 p = effective pressure, Pa
 Q = flow rate, m³/s
 R_m = mean radius of curvature, m
 r_w = characteristic radius, m
 u_w = characteristic advancing velocity, m/s
 v = velocity vector, m/s

Greek Symbols

- ΔP = pressure drop, Pa

$\dot{\gamma}$ = shear rate, s⁻¹

H = shear viscosity, Pas

μ = dynamic viscosity, Pas

η_E = extensional viscosity, Pas

σ = interfacial tension, N/m

ψ_1 = first normal stress coefficient, Pas²

ψ_2 = second normal stress coefficient, Pas²

ρ = density, kg/m³

Subscripts

w = relative to water

k = relative to fluid

Experimental Procedure

Experimental setup

A sketch of the experiment used to simulate the enhanced recovery process is shown in Fig. 1. Below we make a brief description of each component of the experimental apparatus.

- (1) Air compressor
- (2) Manometer
- (3) Filter and air dehumidifier
- (4) Pressure regulator
- (5) Manometer
- (6) Sphere valves
- (7) Tank containing the injected fluid
- (8) Sphere valves
- (9) Nail valves
- (10) Manometer
- (11) Nail valves
- (12) Tank containing drained fluid
- (13) Porous cell
- (14) Nail valves
- (15) Tank containing the fluid taken from the porous cell
- (16) Nail valve
- (17) Vacuum recipient
- (18) Vacuum pressure transducer
- (19) Vacuum pump

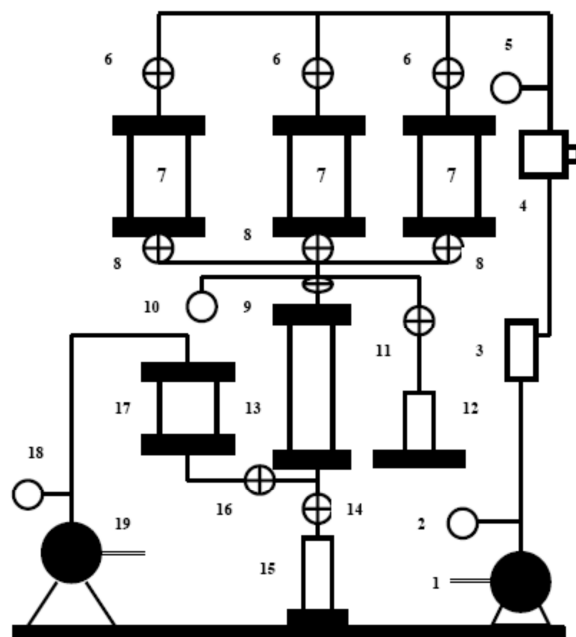


Figure 1. Scheme of the experimental apparatus.

The compressor (1) is responsible for pumping air to the tanks containing the injected fluid (7). Before owing to the tanks, this air passes through the dehumidifier (3) that dries the air in order to avoid contamination of water in the injected fluid. After that, the dried air passes through the pressure regulator (4) which is responsible for keeping constant the pressure of the air that feeds the tanks (7).

The sphere valves (6) allow selecting the number of reservoirs that are pressurized. On the other side, the sphere valves (8), placed at the end of the tanks, enable one to order the turn of each injected fluid. This mechanism allows one to make alternate injections, for example: water-polymeric solution-water, or three different polymeric solutions of increasing concentration.

The nail valve (9), placed at the entrance of the porous cell (13), allows the injected fluid to enter the cell. When the nail valves (9) and (14) are closed, one can remove the cell from the apparatus in order to clean it or to change the porous media inside. When the nail valve (14) is opened, the outcome fluid is collected in a graduated tank (15).

At the beginning of the injection process, is fundamental to fill up all lines, removing completely the air inside the injection circuit. To this end, one keeps valve (11) opened and valve (9) closed, and does the purge of the injection system, with the purged fluid being collected by tank (12).

After the end of the experiment, the sequence of closing valves, in order to avoid the return of the fluid, obeys the following order: valves (14), (9), (8), and (6).

Porous cell

The porous cell employed is a cylinder with length $L = 180$ mm and diameter $D = 44$ mm. Figure 2 shows the porous cell in its dismantled form. The description of these components is given below:

- A – Fixing nuts and washes
- B – Cover flanges
- C – Elastic sealing ring
- D – Flanges
- E – Fixing screws from cover flange
- F / J – Inlet / outlet connections
- G – Disc with a 1.0 mm diameter hole (outlet)
- H – Inlet fluid diffuser
- I – Acrylic cylinder where porous media is confined
- K – Steel rods to withstand the tensile stresses

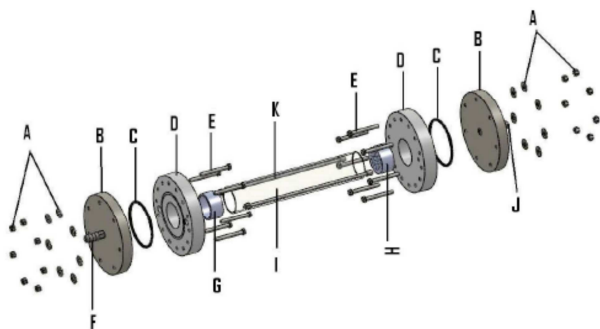


Figure 2. Porous media cell, exploded vision.

It is filled with sand grains of diameters within a range of 0.3 mm to 0.6 mm. The granulometry measurements obey the Brazilian Association of Technical Rules and the respective distribution is depicted in Fig. 3.

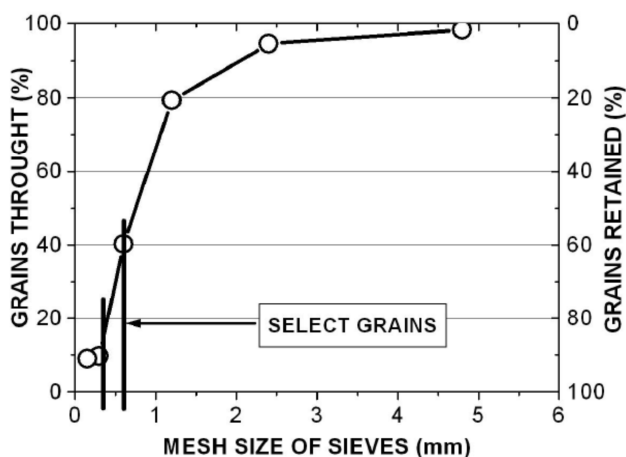


Figure 3. Granulometry results.

Permeability and porosity

In order to determine the permeability of the porous media, oil SAE 90 was injected at different pressure levels. By doing this we could calculate the relation between the pressure gradient and the mean velocity. In Fig. 4 we can find that the relation between these variables is very close to a linear behavior, since a linear hypothesis gives an excellent curve fitting. This result allows the use of the approximation of the Darcy's law, and, therefore, we can use it to determine the permeability through the well known expression given by

$$k = - \frac{Q}{p + \rho g L} \frac{\mu L}{A} \tag{1}$$

where k is the specific permeability of the porous media, Q is the flow rate, ρ is the density of the fluid, g is the gravity acceleration, μ is the dynamic viscosity, L is the length of the media and A is the cross sectional area.

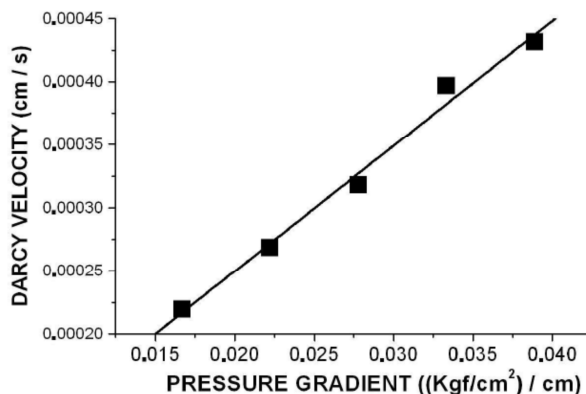


Figure 4. Measured linear interpolation of the gradient hydraulic as function of the specific discharge.

The effective porosity, ϕ , was obtained through the difference in weight between the porous cell after and before this media was saturated with oil SAE 90. The results were $k = 4636.82$ mD and $\phi = 43\%$.

Rheological characterization

A rotational rheometer AR-G2 (TA instruments) with conical (40 mm and 2°) and concentric cylinder was used to characterize the fluid rheology. Figure 5 shows a comparison between the viscosities of a sample of petroleum taken from Campos Basin¹ and commercial oil used in the automobile industry, SAE 90, as a function of the shear rate. We can see that their viscosities are very similar, which justifies the use of SAE 90 in our experiments. The advantage of using this oil is related to easier cleaning procedures and to avoid corrosion.

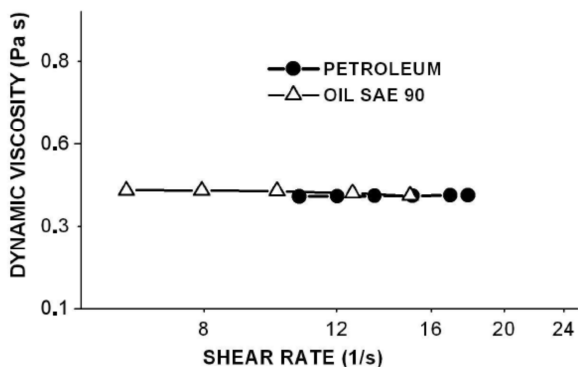


Figure 5. Viscosity as function of the shear rate. A comparison between petroleum taken from Campos Bay in Brazil and oil SAE 90.

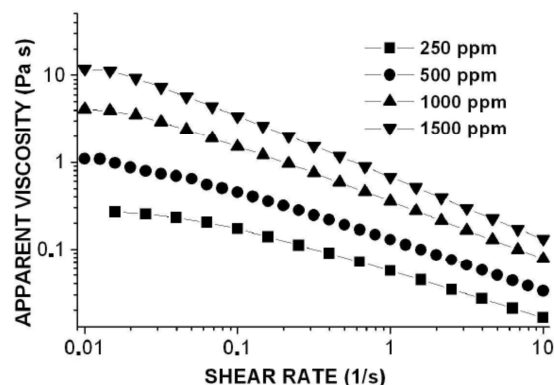


Figure 6. Viscosity as a function of the shear rate for different concentrations of the Xanthan Gum.

The fluid used in the enhanced oil recovery experiment was prepared with a solution of the polymer Xanthan Gum in distilled water. The Xanthan Gum was provided by PROQUIMIOS S.A. The experiments were conducted with four polymeric solutions of XG in distilled water with concentrations of 250, 500, 1000, and 1500 ppm (parts per million). These solutions were mixed for 4 hours by a 500 rpm mixer and taken to rest for more 24 hours. The rheological characterization was provided by steady and oscillatory tests. An important material function to be determined is the shear viscosity, η , as a function of the shear rate, $\dot{\gamma}$. This is depicted in Fig. 6. This figure shows the viscosity shear-thinning behavior of the polymeric solutions tested. We can see that the behavior in the log-log graphic presented, and, therefore, a traditional power-law model of the form $\eta = K \dot{\gamma}^{n-1}$, where K is the consistency index and n is the power-law exponent, can fit very well the data. A simple linear regression leads to Table 1 for different solutions.

¹ Campos Basin is one of the biggest sources of petroleum in Brazil. Its main activities are controlled by PETROBRAS.

Table 1. Consistency and exponent indexes for the fitting of the power-law model to solutions of Xanthan Gum in water.

Xanthan gum (ppm)	Consistency index – K (Pa s ^{n})	Power-law exponent – n
250	0.05335	0.5437
500	0.12415	0.4780
1000	0.34191	0.3918
1500	0.66790	0.3203

It can be seen that for higher concentrations of the polymeric solutions the fluid becomes more shear-thinning, with power-law assuming lower values.

In the case of the oscillatory tests, a previous test was conducted in order to determine the linear viscoelastic range, see Fig. 7. In the case the frequency of oscillation is fixed while the stress amplitude varies linearly with time. The linear viscoelastic range is bounded by a critical value of the stress amplitude below which the complex modulus does not change with respect to this quantity. In this case, this value is $S_a \approx 0.35$ Pa. Once the critical value is known, we perform oscillatory test in the linear tests, in the linear viscoelastic limit, for a wide range of frequency values to get curves correspondent to the storage modulus (G') and the loss modulus (G''), see Fig. 8 and Fig. 9, respectively. As it can be seen by the complex modulus (G^*) curves, shown in Fig. 10, the elasticity of the solution increases also with the increase of the concentration of Xanthan gum in the solution. This can be verified by noticing that, as the polymer concentration increases, the magnitude of the Complex Modulus becomes more and more similar to the magnitude of the storage modulus.

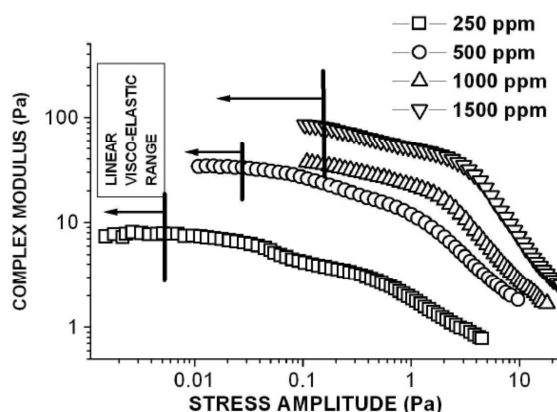


Figure 7. Determination of the limit between linear and non-linear viscoelastic ranges.

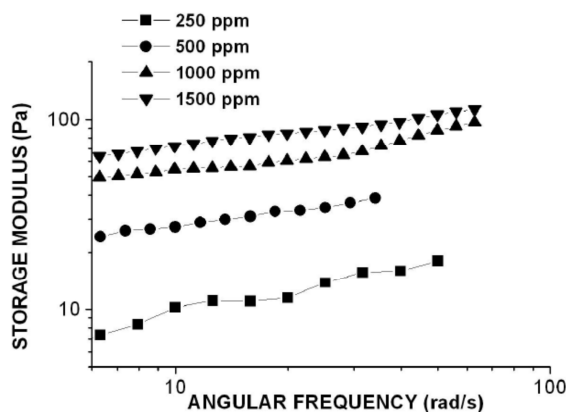


Figure 8. Dynamic test for the polymeric solutions of Xanthan Gum in distilled water. Storage modulus.

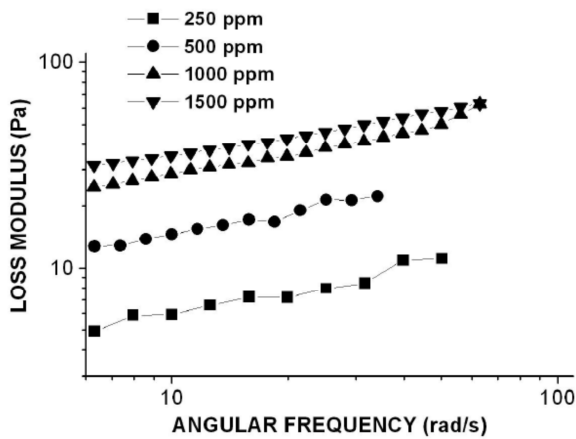


Figure 9. Dynamic test for the polymeric solutions of Xanthan Gum in distilled water. Loss modulus.

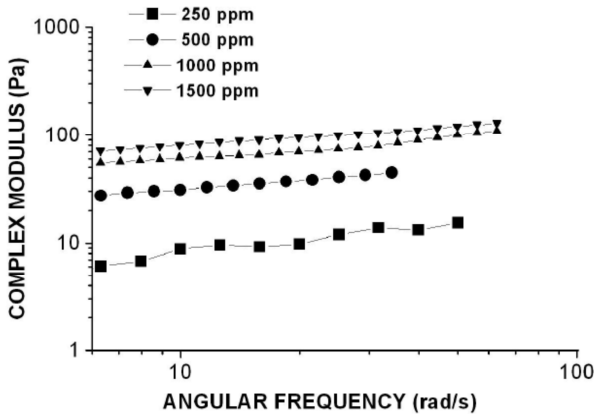


Figure 10. Dynamic test for the polymeric solution of Xanthan Gum in distilled water. Complex modulus.

Experimental methodology

The experiments are conducted at a temperature of 26°C, a relative humidity of 79% and atmospheric pressure of 760 mmHg.

The porous cell is filled with sand grains selected in accordance with ABNT (NBR NM 248/2003) norm with a size distribution as depicted in Fig. 3. Before its use, the grains are washed and dried in an oven at 100°C. At each turn when a volume of 40 cm³ is filled, the sand is compacted and the cell is weighted. When the cell is completely filled with the sand grains, this porous media is saturated with oil SAE 90. Oil is introduced in the porous cell by means of a vacuum pump with a pressure of -100 mmHg. The process of saturation is conducted in a carefully and slowly manner, taking six hours to be completed, after which the cell is again weighted. From the difference between this value and the weight of the empty cell, the porosity is determined.

After the porous cell is saturated with oil, we start the imbibition oil recovery process using water as the injected fluid. A constant level pressure of 0.5 Kg/cm² is imposed.

The mixture of oil and water taken from the porous cell is kept at rest for twenty four hours and then the fluids are separated, using a density separator, and each volume is measured.

When the produced fluid is almost composed solely by water, we start an enhanced oil recovery process using, as displacing fluid, a XG polymeric solution. We tested four solutions, namely 250, 500, 1000, and 1500 ppm, one at a time. The pressure level of this enhanced process is kept at the same level as the water injection

process, i.e. 0.5 Kg/cm². The subsequent steps follow the same procedure described in the secondary stage where water was the injected fluid.

The polymeric solution preparation for the injection followed the same procedure of the samples that were characterized by the rheometer, i.e. the solution was made of Xanthan Gum in distilled water, with concentrations 250, 500, 1000, and 1500 ppm and mixed for four hours with a mixer at 500 rpm. After that, the solutions are kept at rest for twenty four hours.

Results and Discussion

Results

Due to the inherent complexity of the random dispersion of pores and solid material, the path the injected liquid chooses to follow when displacing the fluid inside the porous media varies even for the same procedure. Figure 11 shows this fact for water as injected fluid. These curves were obtained with the same methodology. We can find also a range limited by the two vertical lines where breakthrough takes place. The term breakthrough is used here in the sense that a great amount of injected fluid is being produced.

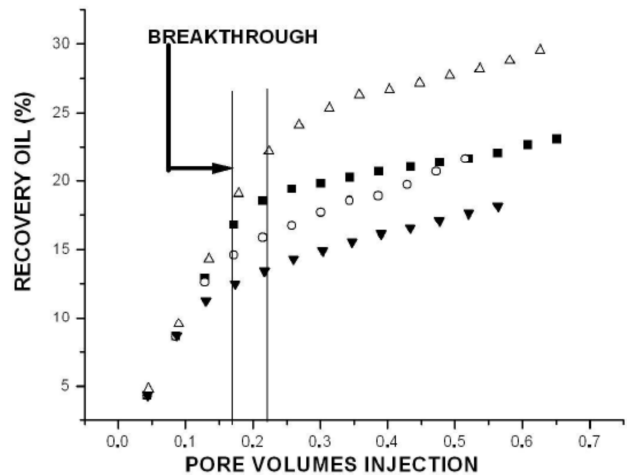


Figure 11. Different realizations of water injections with the same procedure. Vertical lines correspond to a range of breakthrough.

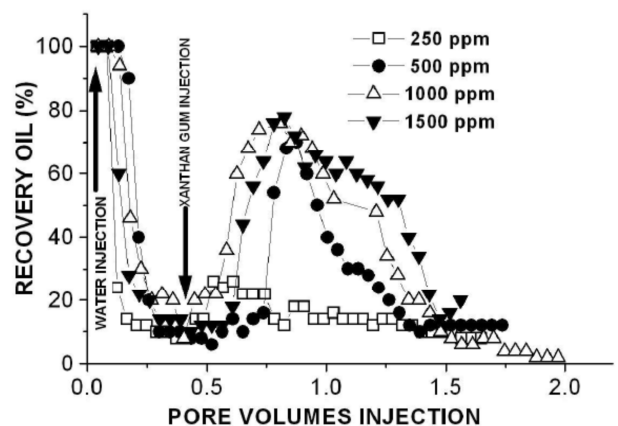


Figure 12. Oil recovery for different concentrations of Xanthan Gum, after injection as a function of the pore volumes injected.

Figure 12 presents the volume of oil produced with two injection stages. The first one, a water injection, takes place at the

beginning of the process. The second one, the polymeric injection, is performed when the oil production has achieved a very low value.

When water is being injected, initially only oil is produced. At approximately 8% in volume of occupancy of the displacing fluid, the oil being recovered drops drastically, reaching minimum values when $\approx 40\%$ in volume of the porous cell is occupied. At this point, the volume of oil produced is $\approx 10\%$, what means that $\approx 90\%$ of water is being produced. As pointed above, the differences between the curves, until this point, indicate the stochastic nature of the problem, showing different percentages of oil recovery with the same procedure and injected fluid. These different results are due to the fact that different paths are chosen by the displacing fluid at a time, even when the procedure is carefully repeated, Turksoy and Bagci (2000).

This is the optimum point to inject the polymeric solution of Xanthan Gum, when almost all the produced fluid is composed of water. As shown in Fig. 12, there is a substantial increase in the produced oil, except from the 250 ppm solution. It should be noted that when the volume of injected fluid is $\approx 80\%$ of the porous cell volume, the quantity of oil recovered is maximum, achieving 70 to 80% of the volume produced. After this point, the percentage of oil produced starts to decrease and achieves its minimum around 150% of porous volume injected with a percentage of oil recovery varying between 8% and 20%.

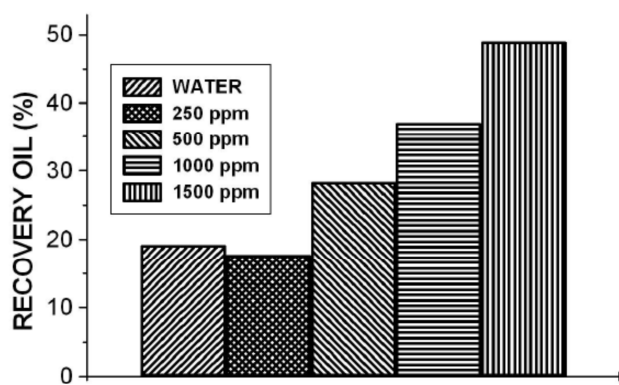


Figure 13. Percentage of oil recovery. The values obtained for the polymeric solutions are after the injection of water.

The percentage of oil recovery for different concentrations is depicted in Fig. 13. The values shown in the figure are: an average value for the percentage of oil recovery using solely water and the percentage of oil recovery using each of the solutions of Xanthan Gum after water was used. The partial values are: 19:26% for the average percentage of water, 17:80% for the partial percentage of 250 ppm of XG in water, 28:41% for the 500 ppm solution, 37:16% for 1000 ppm solution, and 49:00% for the 1500 ppm solution. The comparison between the first and last column in the graph shows clearly the enhancing capability of the addition of the polymers on a water solvent. From pure water to a 1500 ppm solution there is an increase of more than 100%. It is also clear that a very-diluted polymeric solution, such as 250 ppm of XG does not lead to an enhancement in oil recovery. The total amount of oil produced, including a first stage of water as a fluid injector is depicted in Fig. 14, where the evolution of the oil production is shown as the injection proceeds. Reproducibility of the results obtained in this graph, as well as an estimate of the dispersion is verified by data contained in Fig. 15, where two different set of tests are necessary to ensure the reliability of the procedure. Figure 14 shows an important feature of the process: the three active polymeric solutions have a region, between 0.6 and 1.0 pore volumes injection, where the curves are more or less coincident.

After a certain point, the less concentrated solution detaches from this curve. A bit further, the second solution detaches from the more concentrated. This fact shows that the increase on the capability of displacing a larger amount of oil by a more concentrated solution happens along the process and does not start at the beginning of it. The final values of oil recovery are shown in Table 2.

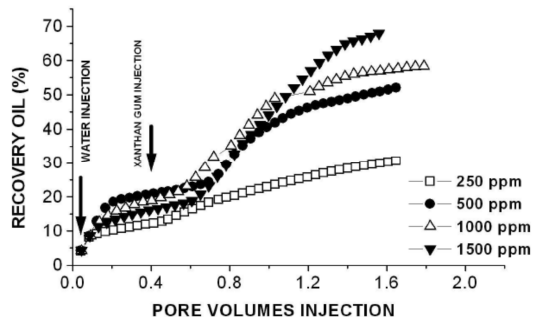


Figure 14. Cumulative oil recovery including the stage of water injection.

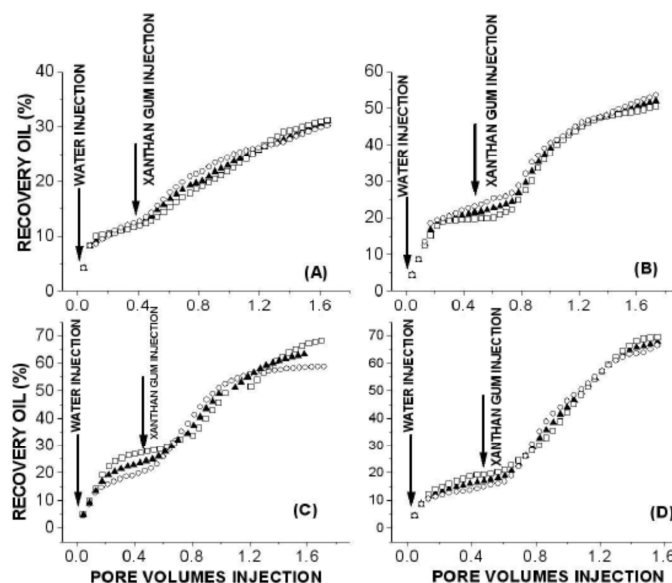


Figure 15. Cumulative oil recovery including the stage of water injection. Two different tests: hollow squares and circles and their average value: black triangles. A) 250 ppm; B) 500 ppm; C) 1000 ppm; D) 1500 ppm.

Table 2. Final value of percentage of oil recovery for each concentration of Xanthan Gum on water.

Xanthan gum (ppm)	Oil recovery (%)
250	30.65
500	52.08
1000	58.79
1500	67.90

Reproducibility and an estimation of the standard deviation of mobility tests are illustrated in Fig. 16 where the mobility of the oil SAE 90 was calculated for a number of realizations. We can see that the mobility of the water is one order of magnitude higher than the mobility of oil.

Figure 17 shows the mobility of the different couplings fluid-porous-media. In the context where the Darcy law holds, the mobility is defined as:

$$M = \frac{Q/A}{\Delta P/L} \tag{2}$$

where $P = p + \rho gh$ is the modified pressure, simply given by $M = k/\mu$. In this case permeability, a feature of the porous media, and viscosity, a feature of the fluid, are decoupled. When the fluid is non-Newtonian, the features of the porous media and the fluid are combined in a more complex way, and so, the mobility is the reciprocal of the resistance of the coupling fluid-porous-media. Figure 17 shows that the mobility decreases as the solution becomes more concentrated.

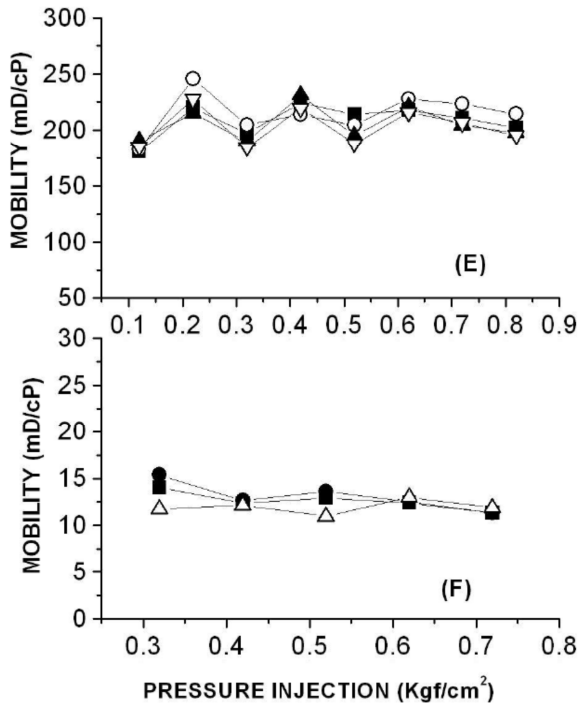


Figure 16. Mobility of the Newtonian fluids involved in the experiment: E) water; F) oil SAE 90.

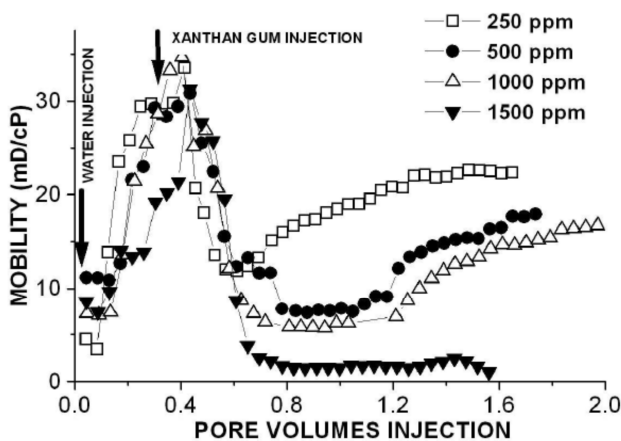


Figure 17. Partial mobility of the inject polymeric solution.

Discussion

The results depicted in Figs. 12 and 13 show a clear enhance of the capacity of Xanthan Gum to displace the oil that was present in the porous media. The rheological measurements conducted in the

present work and the results largely reported in the literature show that Xanthan Gum exhibits shear-thinning elastic features and, therefore, these features are probably related to the enhanced oil recovery process. It is worth mentioning that increasing the concentration of the polymer used, the displacement efficiency of the polymeric solution is also increased.

There are mainly two reasons for the increase of the displacement efficiency of higher concentrations of the Xanthan Gum solution: the first one is an increase of the sweep efficiency, i.e. the ability of the fluid to invade pores which are still occupied by oil; the second, is the ability of the fluid to leave a thinner layer of oil near the solid, in the considered pore. Since this is a complex flow, it is hard to separate the different effects of elasticity, normal stress difference in shear and extensional viscosity. However, we will analyze the tendency of the different manifestations of the polymeric solution from the two classical perspectives, namely viscometric and extensional flows.

General displacement analysis

A scheme showing the injected fluid advancing inside the pore cell is shown in Fig. 18. The local displacement inside a pore is depicted in Fig. 19.

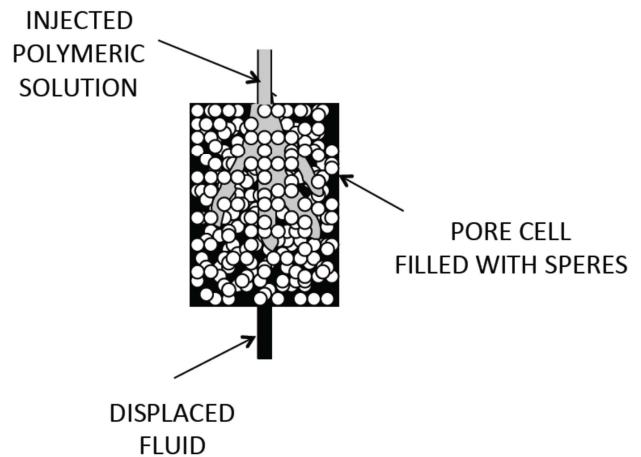


Figure 18. Scheme of the porous cell.

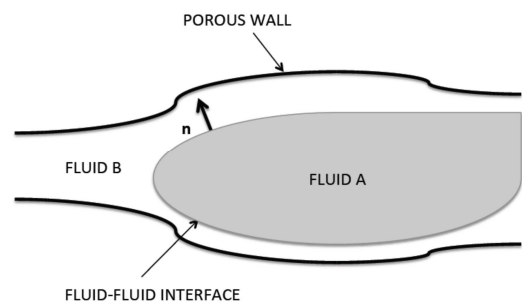


Figure 19. Scheme of the local displacement inside the pore.

The continuity and momentum balance equations for each phase, assuming steady state, are given by

$$\nabla \cdot \mathbf{V}_k = 0 \tag{3}$$

$$\rho_k (\mathbf{V}_k \cdot \nabla \mathbf{V}_k) = \nabla \cdot \mathbf{T}_k + \rho_k \mathbf{g} \tag{4}$$

where the subscript $k = A; B$ define the respective fluid, \mathbf{V}_k is the velocity field in each fluid, ρ_k is the density of each fluid, \mathbf{T}_k is the total stress and \mathbf{g} is the gravity acceleration. We will call Fluid A the displacing fluid, in our case the polymeric solution, and Fluid B the Newtonian displaced solution.

Assuming that the two fluids are immiscible, the continuity and balance of forces at the interfaces are given by

$$\mathbf{V}_A = \mathbf{V}_B \quad (5)$$

$$\mathbf{n} \cdot (\mathbf{T}_A - \mathbf{T}_B) = \frac{\sigma}{R_m} \mathbf{n} \quad (6)$$

where σ is the interfacial tension between the liquids, R_m is the mean radius of curvature, and \mathbf{n} is the unit vector normal to the interface (see Fig. 19).

Equation (6) states that there is a normal stress jump at the interface proportional to $\frac{\sigma}{R_m}$ and that the tangential-to-the-interface stresses are continuous through the interface.

For the present analysis, we can consider that inertial and body forces are negligible. We will also consider that the interface tension between the fluids does not change significantly when compared to other changes.

Shear dominated regions

When interface between the two fluids is more aligned to their bulk velocity, the flow can be approximated to a shear flow. In this case, the stress in fluid A, the polymeric solution, can be given in matrix form by

$$[\mathbf{T}_A] = \begin{bmatrix} -p_A + \frac{\dot{\gamma}_A^2}{3}(2\psi_1 + \psi_2) & \eta_A \dot{\gamma}_A & 0 \\ \eta_A \dot{\gamma}_A & -p_A - \frac{\dot{\gamma}_A^2}{3}(\psi_1 - \psi_2) & 0 \\ 0 & 0 & -p_A - \frac{\dot{\gamma}_A^2}{3}(\psi_1 + 2\psi_2) \end{bmatrix} \quad (7)$$

where p_A is the mechanical pressure, ψ_1 and ψ_2 are the first and second normal stress coefficients of the solution of xanthan gum in shear, and η_A is its shear-thinning viscosity. The matrix form of \mathbf{T} is such that direction 1 is the direction of the flow, direction 2 is the shear direction (variation of velocity) and direction 3 is the neutral direction. Stress in the oil is simply by

$$[\mathbf{T}_B] = \begin{bmatrix} -p_A & \mu_B \dot{\gamma}_B & 0 \\ \mu_B \dot{\gamma}_B & -p_B & 0 \\ 0 & 0 & -p_B \end{bmatrix} \quad (8)$$

Hence, the general Eq. (6) can be decomposed into the following two equations:

$$p_A - p_B + \frac{\dot{\gamma}_A^2}{3}(\psi_1 - \psi_2) = \frac{\sigma}{R_m} \quad (9)$$

which represents the normal stress jump at the interface and

$$\mu_B \dot{\gamma}_B - \eta_A \dot{\gamma} = 0 \quad (10)$$

which represents the shear rate jump at the interface. As shown by our measurements, an increase on concentration of polymer in the polymeric solution increases viscosity and normal stress differences due to elasticity. Thompson and Soares (2012) have recently analyzed the role of increasing the power-law viscosity of the displacing fluid. They found, based on a dimensionless analysis of Eq. (10) that increasing this viscosity induces an increase on the fingering effect inside the pore and therefore, decreases displacement efficiency at each pore. From Eq. (9) we also see that concerning the elastic effects captured by normal stress differences, since it is known that the first normal stress difference is one order of magnitude higher than the second one and the second normal stress difference in viscoelastic fluids is, most of the times, negative, the normal stress difference effects act to decrease the displacement efficiency at each pore. Therefore, it seems that polymeric shear effects inside the pore are not able to explain the increase on displacement efficiency found by the experiments.

The other possible explanation that can come from a shear analysis concerns the sweep efficiency. Here we offer a heuristic explanation to show that the more shear-thinning behavior favors the displacing fluid to seek for pores which are still filled with oil and, therefore, are strongly correlated to the enhancing oil recovery efficiency. Let us suppose that the preferred path chosen by water has a characteristic radius (where water flows) of r_w . Then, the characteristic advancing velocity is given by $u_w = \frac{Q}{\pi r_w^2}$, where Q is

the flow rate. The representative shear rate, $\dot{\gamma} = \frac{u_w}{r_w}$, can be obtained:

$$\frac{u_w}{r_w} = \frac{Q}{\pi r_w^3}.$$

Now, with the injection of the polymeric solution, when it starts flowing through r_w , the viscosity, η , behaves like

$$\eta = K \left(\frac{Q}{\pi} \right)^{n-1} r_w^{3(1-n)}.$$

Hence, when n decreases the viscosity through the chosen path increases and then the injected fluid tends to spread to different paths. By this phenomenon, the characteristic radius r_w increases and therefore, the mobility of polymeric solutions with higher concentrations increases still more.

Extension dominated regions

Porous media are known to produce flows with a strong extensional character. This happens due to variation of the cross section area the fluid experiments. If we consider the special case of uniaxial extension, the stress tensor in the polymeric solution and the oil are now given by

$$[\mathbf{T}_A] = \begin{bmatrix} -p_A + \frac{2}{3}\eta_E \dot{\epsilon} & 0 & 0 \\ 0 & -p_A - \frac{1}{3}\eta_E \dot{\epsilon} & 0 \\ 0 & 0 & -p_A - \frac{1}{3}\eta_E \dot{\epsilon} \end{bmatrix} \quad (11)$$

where $\eta_E(\dot{\epsilon})$, the extensional viscosity of the polymeric solution, is a non-decreasing function of the extensional rate, $\dot{\epsilon}$, and

$$[\mathbf{T}_B] = \begin{bmatrix} -p_B + 2\mu_B \dot{\epsilon} & 0 & 0 \\ 0 & -p_B - \mu_B \dot{\epsilon} & 0 \\ 0 & 0 & -p_B - \mu_B \dot{\epsilon} \end{bmatrix} \quad (12)$$

Hence, equilibrium at the interface is now given by

$$p_A - p_B + 2\dot{\epsilon}\left(\mu_B - \frac{\eta_E}{3}\right) = \frac{\sigma}{R_m} \quad (13)$$

Here we can see explicitly that the enhancement of the extensional uniaxial viscosity acts to increase the displacement efficiency inside the pore. Moreover, when the xanthan gum solution finds a throat whose pore is still filled by this fluid, the resistance associated to the penetration of this pore is higher, making the polymeric solution to avoid this pore and to find another one filled by oil. This process increases the sweep efficiency.

Final Remarks

An experimental apparatus to test enhanced oil recovery efficiency was constructed. The injected fluids were polymeric solutions with different concentrations, from 250 to 1500 ppm of xanthan gum (a widely used polymer in the petroleum industry), in water. The procedure adopted here was to inject the polymer solution after a first stage of water injection, so as to reproduce more real conditions. The fluid characterization has shown that the solutions exhibit shear-thinning behavior. As the concentration is increased, not only the viscosity of the solution, but also its elasticity increases, for the range of deformation rate tested.

The experiments have shown that increasing the concentration of the polymeric solution tested increased the efficiency of the oil recovery process. Another important result is that the higher concentration of polymeric solutions increases their recovery efficiency after a certain amount of pore volume injection, suggesting that the polymeric solutions should be injected at stages, increasing the concentration from one stage to the next one.

Our analysis was based on splitting the effects of the rheological functions into two parts: a shear and an extensional contribution. The equations are easier to analyze from the perspective of the pore efficiency. The analysis of the sweep efficiency is more heuristic.

The shear rheological effects, viscosity and normal stress differences, seem to indicate that the increase on the oil recovery efficiency is not related to the efficiency inside the pore, but to the sweep efficiency. The extensional flow analysis indicates that from

both perspectives the extensional viscosity enhance oil recovery efficiency. Not only inside the pore, but also from the sweep efficiency perspective, an increase of the extensional viscosity is favorable to the oil recovery process.

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