SIMULATION OF VISCOELASTIC POLYMERIC SOLUTIONS INJETION PROCESS AT A RESERVOIR SCALE

Julia Frota Renha, juliarenha@gmail.com
Márcio da Silveira Carvalho, msc@puc-rio.br
Ranena Verónica Ponce Flores, poncerv@puc-rio.br
Pontifícia Universidade Católica do Rio de Janeiro

Abstract.
Aiming to increase the capacity of oil fields, conventional recovery methods are used. These methods consist in the injection of water or gas to maintain the reservoir pressure. The oil production typically takes place by displacing this oil in the porous media, where the displacing fluid (water) is injected to gradually occupy the space of the displaced fluid (oil).Since due to capillary effects and the heterogeneity of the porous media, a residual oil portion ends up trapped in the reservoir. These methods lead to low values of oil recovery factor, which occurs mainly by two factors: high viscosity of the reservoir's oil in relation to the viscosity of the injected fluid and high interfacial tension between the fluids. The addition of polymers to the water ensures an increase in the viscosity of the injected fluid, improving mobility ratio between water and oil in the porous media. Thus, standardizing forward swept and improving the swept efficiency due to improved oil displacement, which reduces the formation of preferential paths in the reservoir, usually called fingers. This paper analyzes the viscoelastic behavior of the polymer, by isolating the viscous and elastic effect in function of its extension and shear rates, implemented in a polymer injection simulation model in a reservoir scale. The effect of the rheological properties of the polymer solution show in the production results a more stable injection front and consequently an oil recovery rate improvement when evaluated as a purely shear behavior. However an improvement in the recovery rate and stability of the injection front for pure extensional behavior can only be observed when the capillary number is increased considerably.

Keywords: *Injection of polymer solutions, Viscoelastic behavior, Enhanced oil recovery, Simulation, Reservoir scale.*

1. INTRODUCTION

Oil exploration has been an important tool for generating much of the energy demanded by the population. But today, most of the oil and gas discoveries are concentrated in deep and ultra-deep layers 5 to 7 thousand meters of depth below sea level. Thus the discovery of new oil fields has become increasingly complex due to difficulties arising from the conditions of the environment, therefore making oil extraction increasingly expensive.

Some of the problems observed in the oil industry are related to the low oil recovery rates in mature fields. However, new research and studies are being developed for new extraction technologies for increasing the recovery factor in mature fields, which is crucial to meet the global energy demand, where oil represents the higher percentage of demand and must continue to meet by several decades (BEN, 2015).

The oil and gas industry has searched new technology to overcome the technical challenges and promote an increase in these recovery rates in producing wells, increasing the volume of oil produced. With that, enhanced oil recovery methods (EOR) are studied since they perform in cases where conventional processes are not efficient. Moreover, these methods are subsequent to a conventional method and are intended to displace the oil remaining in the reservoir.

One of the advanced recovery methods widely used is the injection of polymer solutions. The purpose of queries related to the injection of polymer solutions it to evaluate the polymer flow behavior in porous media so that it would be possible to better estimate the oil swept in the reservoirs. Oftentimes, reservoirs previously swept by water have an economically attractive percentage of remaining oil and its recovery is important to make production more profitable for this field.

Thereby many researches aim to study the non-Newtonian behavior of polymer solutions in which the viscosity of the polymer solution varies depending on the shear rate (shear thickening / thinning) and extension rate (extensional thickening / thinning) in the case of viscoelastic fluids (Seright et al., 2010).

2. POLYMER INJECTION

In the early 1960s, the injection of polymer was suggested as a method for enhanced oil recovery, with the primary functionality of increasing the viscosity of the displacing fluid, which in most cases is water (Sandiford, 1964). This pioneering work led by Sandiford was then followed by numerous studies, in order to recognize the benefits of using non-Newtonian fluids and particularly viscoelastic fluids as displacing fluids in oil recovery methods (Dominguez, 1977; Gleasure, 1990).

Ideally, the rheological behavior of the polymer solutions as a function of shear rate in porous media can be divided into three types: Newtonian, shear thinning and shear thickening.

During the injection of polymers in porous media the polymer molecules flow through a series of pores and throats, suffering elongation and contraction of the polymer chains. The effect of shear thickening (thickened by shear) occurs due to stretching of polymer chains as they pass through the pore throats, where the flow velocity is so high that the polymer molecules do not have enough time to relaxation, failing to elongate and contract in the time to suit the flow velocity.

A constitutive equation was first developed by Zhang et al. (2011) to represent the viscoelastic behavior of the HPAM polymer solutions in porous media. This equation indicates that the increment of the viscosity due to the elasticity is proportional to the relaxation time, the particle diameter, porosity, and is inversely proportional to the Darcy velocity and the square root of sinuosity. This equation shows that the calculated and experimental values are in agreement, which validates its applicability to quantify the shear thickening behavior in porous media.

A viscoelastic fluid is considered a non-Newtonian fluid, once it is able to present viscous fluid and elastic solid characteristics in the same material. The viscoelastic fluid has a memory which allows it to return partially to its original shape after a deformation. Due to the elastic behavior of certain polymer solutions, the speed distribution in the pores and pressure loss can be quite different from the distribution in case of a Newtonian fluids and it can lead to a reduced residual oil saturation in the areas swept by the aqueous phase.

Studies have shown that increasing the recovery factor at a microscopic scale is related to the elastic properties of the polymer. The selection of polymers with elastic properties required for an injection project is important because the difference in increased recovery may vary at 6% of OOIP (original oil insitu) (Wei, 2013).

A similar trend was obtained by Urbissinova et al. (2010), which also assessed the polymer elasticity contribution in advanced recovery methods. Likewise, they found that polymer solution which had greater elasticity also had greater resistance to flow in porous media. What caused a better scanning efficiency and increased oil recovery rate at a macro scale. This mechanism can also improve the microscopic displacement efficiency to move residual oil immobile due to capillary forces and rock properties (Wang et al., 2000).

Wang et al. (2000) studied extensively this issue by evaluating the efficiency of polymer injection to displace the residual oil after water injection at different flow conditions. Firstly it was considered residual oil located in dead cavities, then residual oil on the rock, then residual oil in pore throats trapped by capillary forces and finally residual oil flow in a micro scale composed of heterogeneous portions of the porous media. In all cases, Wang et al. (2000) perceived that the residual oil was considerably reduced after the polymer injection.

Otherwise, Zhou et al. (2010) observed the increase in displacement efficiency of polymer injection and argued that the essence of this phenomenon was related to the increased mobility ratio between oil and water, caused by polymer injection, and consequently bypassed the flow of the injected fluid, which leads to a redistribution of oil saturation. The combination of the effects of water path and the viscoelasticity of the polymer mobilizes and displaces the residual oil.

Once selected, the polymer is added, under very specific conditions, to the injection water in order to increase the viscosity of the aqueous phase in the reservoir, decreasing its mobility. Consequently, the mobility ratio water / oil and effective water permeability decreases standardizing forward feed and improving sweeping efficiency.

3. SIMULATION MODEL

The polymer displacement efficiency was studied considering separately the shear and extensional effects. To describe the flow of polymer solutions in porous media, the mass conservation equations and Darcy's law were used. The purely extensional viscosity and shear models were idealized and studied separately for evaluating the contribution of each effect in the displacement efficiency of polymer solutions.

The derivation of the flow equation in porous media, known as pressure and saturation equations, were performed by applying the continuity equation and Darcy's Law, which are supplemented for the non-isothermal cases through the use of state equations. Whereas the polymer as a component connected to the aqueous phase polymer transport equation is given by (Aarnes, Gimse, Lie, 2007):

$$\emptyset \frac{\partial}{\partial t}\left(C_p S_w\right) + \nabla \cdot \left(C_p f_w v_t\right) = C_{p0}\left(\frac{q_w}{\rho_w}\right) + C_p f_w q \tag{1}$$

The pressure, saturation and transporting polymer equations are typically solved in commercial simulators for polymer injection process. Since the goal of this paper is to get the analysis of each effect separately, viscous and viscoelastic models used are described below.

To describe the viscosity model considering only the effect of local shear rate Christopher and Middleman (1995) models were used, which has estimated shear rate during single phase flow in porous media as:

$$\dot{\gamma} = \frac{3n+1}{4n} \cdot \frac{12v}{150k\phi^{1/2}} \tag{2}$$

Where v is the water velocity from Darcy's velocity considering the fractional flow f_w, k is the absolute permeability, ϕ is the porosity and n is the power ratio which is a rheological property dependent on the concentration of the fluid.

To set the viscosity as a function of the local shear rate, the power model given by the following equation was used:

$$\mu_{pw} = H \cdot \dot{\gamma}^{n-1} \tag{3}$$

Whereas the polymer is a component in the water phase, the viscosity of the injected fluid can be determined by Eq. (4), by considering the viscosity of the water phase (pure and with polymer) by the concentration of each component:

$$\mu_w(\dot{Cp}) = \mu_w(1 - Cp) + Cp \cdot \mu_{pw} \tag{4}$$

Considering viscoelastic solutions, an increment on the pressure drop in flow through porous media can be described as an effect purely associated with the extensional viscosity, for single phase flow, which is an extension rate function ($\dot{\varepsilon}$) defined as (Vorwerk and Bunn, 1993):

$$\dot{\varepsilon} = \frac{\sqrt{2}}{\alpha} \frac{v}{k^{\frac{1}{2}}} \frac{\phi^{1/2}}{(1 - \phi)} \tag{5}$$

Where, $\alpha = 180^{1/2}$, k is the absolute permeability, ϕ is the porosity and v is the velocity of the water according to Darcy velocity. For purely extensional viscosity model, the Carreau-Yasuda model was modified to:

$$\mu_{pw} = \mu_{e\infty} + (\mu_{e0} - \mu_{e\infty}) \left[1 + \left(\dot{\varepsilon}\lambda_{cy}\right)^2\right]^{\frac{n_{cy}-1}{2}} \tag{6}$$

Where μ_{e0} is the apparent viscosity when the shear rate tends towards zero, $\mu_{e\infty}$ the apparent viscosity when the shear rate tends to infinity, λ_{cy} is a characteristic time of the fluid, which is equal to the inverse of the extension rate value, $\dot{\varepsilon}$ and n_{cy} is the power-law exponent. Where all rheological parameters are typically used in Carreau-Yosuda model which defines dependence of the extensional viscosity with the shear rate.

Finally, in the same manner as in pure shear rate viscosity model, the viscosity of the injected fluid considering pure extensional viscosity model can also be determined by Eq. (4).

The differential equations system is discretized using the finite volume method through the approximation of the derivatives in the pressure equation by TPFA method (Two-point flux approximation). The code solves the coupled system of equations solving in implicit form the pressure equation and explicit form the saturation equation (IMPES method, implicit pressure - explicit saturation).

The uncoupled solution of pressure and saturation equations is performed in an iterative manner for each time step. Firstly, with initial distribution saturation values, the phase mobility is calculated to solve the pressure equation. Once the global pressure is obtained, the total velocity field is computed. In the case of polymer injection, the viscosities are calculated as a function of the velocity field according to the viscous and viscoelastic models. Then maintaining the overall speed, v_t, constant, the saturation and polymer transport equations are solved iteratively in an explicitly form, dividing the time step (global $\Delta\tau$) into smaller fractions (local Δt) to satisfy the CFL stability condition (Aarnes, Gimse, Lie, 2007).

Then, with new values for saturation and polymer concentration the pressure equation is solved again, repeating the same process for each time step until the end of the injection process.

4. RESULTS AND DISCUSSIONS

4.1. Reservoir Model

The reservoir described in the second model of the 10th comparative project of the SPE (Society of Petroleum Engineers - SPE 10 - www.spe.org) was used. The full geological model has dimensions of 365.76 x 670.56 x 51.82 m³, described on a regular Cartesian grid containing 60 x 220 x 80 cells.

In this paper only the first layer of the geological model was used, considering the dimensions of 365.76 x 670.56 x 0.6096 m³, containing 60 x 220 x 1 cells. The original value for the permeability field was used for this layer, while the porosity field was changed considering a minimum porosity of $\varphi = 0.01$. The arrangement of the wells was modified to a 1/4 5-spot, which considers the injector and producer wells in opposite corners of the mesh.

The wells were monitored through injection and production flow rates equal to $Q_{ip} = 9.2 \cdot 10^{-4} \text{ m}^3/\text{s}$. The water and oil viscosities were defined respectively as $\mu_w = 0.001 \text{ Pa.s}$ and $\mu_o = 0.01 \text{ Pa.s}$, although when considering the extensional behavior, the oil viscosity considered to be twice the viscosity of water. The connate water saturation was defined as $S_{wc} = 0.2$ and residual oil saturation as $S_{orw} = 0.4$. Finally the relative permeability of water and oil in the residual saturations were respectively $k_{rw} = 0.6$ e $k_{ro} = 1.0$.

4.2. Results obtained considering the variation of viscosity with shear rate

The simulation carried out aimed to demonstrate the main impacts of the injection of polymer solutions considering the variation of viscosity with the shear rate in the porous media in comparison with the injection of water. In Fig. 1 it can observed the typical behavior of viscosity as a function of shear rate according to the power model used.
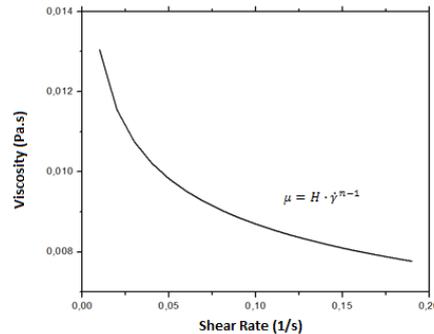

$$\mu = H \cdot \dot{\gamma}^{n-1}$$

Figure 1 – Representative viscosity behavior of the shear rate according to the power law model.

For non-Newtonian model study, the rheological parameter and the power index used were respectively: H = 0.0058 e n = 0.824, considering that the residual saturation did not change within polymer injection.

Therefore, for analysis of viscosity variation with shear rate were evaluated two types of injection: continuous injection and water injection alternating polymer-water (APA). Since the alternate injection was based on the variation amount of pore volumes injected. Whereas when the total amount of pore volumes (PV) injected VP was 5 both for continuous injection and for alternating.

A variety of cases were studied to evaluate the behavior of the injection of polymer solutions in porous media. Where the effects of the type of injection were evaluated and when considering an alternate injection, the start time of polymer injection was evaluated, as well as the flow variation and the comparison between non-Newtonian and Newtonian fluid. These cases are listed in Tab. 1.

Table 1 – Studied cases for the viscosity varying according to the shear rate.

Cases	Injections	PV Injected	Injection flow	Rated effect
Basis	Water	5	Q_{ip}	-
1	Water-Polymer-Water	0.1-1-3.9	Q_{ip}	Type of injection and injection start time
2	Water-Polymer-Water	1-1-3	Q_{ip}	
3	Polymer	5	Q_{ip}	
4	Water-Polymer-Water	1-1-3	0.1 Q_{ip}	Flow variation
5	Water-Polymer-Water	1-1-3	10 Q_{ip}	
6	Water-Polymer-Water	1-1-3	Q_{ip}	Newtonian fluid

Therefore, case consists of 0.1 PV of injected water, followed by 1 PV of polymer and 3.9 pore volumes of water to complete the injection. Then case 2, considered alternating injection of 1 PV of water, followed by 1PV of polymer and 3 PV of water. And case 3 is a continuous injection of polymer.

To evaluate the efficiency of the injection of polymer solutions all cases were compared with continuous injection of water, regarded as a base case, for the same operating conditions.

Figure 2 shows the recovery factor (FR) and the polymer concentration in the injector (Cpinjector) versus PV injected for cases 1, 2 and 3 under study, comparing the same with continuous injection of water . In the same figure the water cut (WCUT) and the pressure of the injector (IBP) are represented as a function of the PV injected for the same cases described.

Analyzing the above cases, it can be seen that the use of polymeric solutions is effective to increase the oil recovery rate, since in all cases a higher production of oil due to the polymer injection was achieved when comparing with the injection of water which resulted in 46% recovery.

Comparing the cases of alternate injection and continuous injection of polymer it can be seen that the cases had no significant difference in the final value of the oil recovery factor, which resulted in around 47%. However, it is important to note an existing injection advance of polymer (case 1) accelerating the recovery of oil, since its production curve undergoes a more abrupt rise immediately after the onset of polymer injection.

Moreover, it is noted that the injection pressure increases when the polymer solution is being injected, but then returns to the range of pressure equivalent to the injection of water. Emphasizing that this pressure remains high and

constant in the case of continuous injection of polymer. In the graph it can be observed that the greatest reduction of water cut occurs during the process of alternate injection of polymer within the case with larger pore volume of polymer injected (case 2) and not during the continuous injection of polymer which can only delay a little the inrush of water.
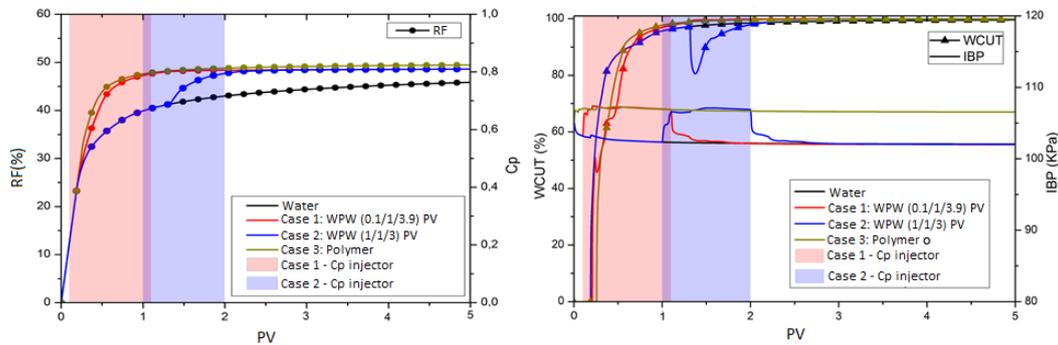

Figure 2 - Recovery Factor, water cut and injection pressure due to PV injected to the continuous injection of water (basis case), alternate injection WPW (case 1 and 2) and continuous injection of polymer (case 3) - Effect of the type of injection and the beginning of polymer injection.

The production results were also analyzed as a function of the maps for the water saturation difference (ΔS_w) between each polymer injection case (alternating or continuous) and the injection of continuous water ($\Delta S_w = S_{w_{APA/Polímero}} - S_{W_{água}}$). Fig. 4 shows the maps for water saturation difference between cases 1, 2 and 3 and continuous injection of water (base case) respectively.

It may be noted that for case 2, the polymer injection has not been initialized when first analyzing, PV equal to 0.4. With this, the water saturation is the same for case 2 and for the base case, where the water saturation difference is around zero. However, cases 1 and 3 have already started the injection of polymer, therefore the water saturation is higher near the injection well because a higher amount of oil has already been swept by the polymer solution. It is worth mentioning the existence of an area of increased oil saturation in both cases represented by a larger difference in water saturation.

Analyzing the saturations in 4 pore volumes, there is a positive water saturation difference across the reservoir for the three cases where it has higher water saturation throughout the reservoir for all three cases compared to continuous injection of water. Proving the volumetric efficiency of the injection of polymer solutions, since they lead to a more stable front and consequently a higher recovery factor.

Comparing the results with the production saturation difference maps, is possible to observe the arrival of a front of oil in the production well for all cases on PV = 1.6. Note however that case 2 has an anticipation of this arrival, as it can be observed before 1.5 PV. Consequently with the arrival of this oil, these pore volumes have a decrease in water cut. It is also possible to note that there is an existing advancing front of saturation for cases 1, 2 and 3 which are very similar, justifying the similar behavior in the recovery factor, Fig. 2, suggesting that the alternating injection WPW (1/1/3) is as effective as a continuous injection of polymer without the risk of having high injection pressures.
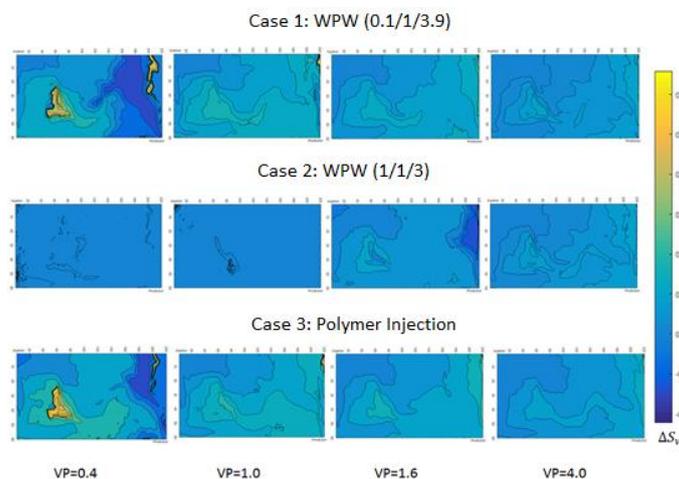

Figure 3 – Maps of water saturation difference during alternate injection WPW (case 1 and 2) and continuous injection of polymer (case 3) - Effect of the type of injection and the beginning of polymer injection.

The same graphics generated previously were produced for different injections flow for alternate injection of polymer and compared again with continuous water injection. Where for case 4 the flow injection was reduced ten times and in case 5 the flow rate was increased ten times. Emphasizing that in both cases the polymer injection started after the injection of 1 PV of water.

It is observed in Fig. 5 an increase regarding the recovery factor for both cases, but case 4 reaches a higher recovery factor (48%) than case 5 (47%). Which can be explained by analyzing the behavior of the polymer viscosity with the shear rate, where higher flow rates lead to higher shear rates and therefore lower polymer solution viscosities and greater mobility ratio oil / water.

With respect to the water cut, the curves are very similar, only being noticed a more marked drop when the polymer injection starts for both cases (4 and 5), caused by an increment of oil production. The pressure of the injector well becomes noticeably higher in case 5, due to the high rate of flow injection.

Looking at the maps of saturation difference, Fig. 5, it possible to see that for 1.6 PV injected, the advance fronts are very similar and unstable in both cases, although the flows are different. During the process of injection the saturation maps are quite similar, so no case is shown to be more effective than the other.

Results suggest a small increase in displacement efficiency due to the improvement of the volumetric efficiency, through the reduction of polymer injection rate, an effect that is a direct consequence of the increase of the polymer solution viscosity and therefore also an improvement in the reduction of water mobility. However, the major effect provided by the reduction of injection flow is provided by the lower injection pressure, as shown in Fig. 4.
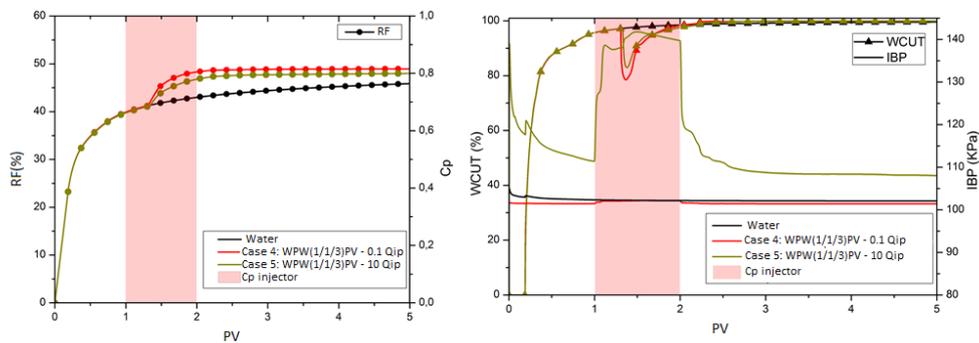

Figure 4 - Recovery Factor, water cut and injection pressure due to PV injected for the continuous injection of water (basis case) and alternate injection WPW (case 4 and 5) – Injection flow effect.
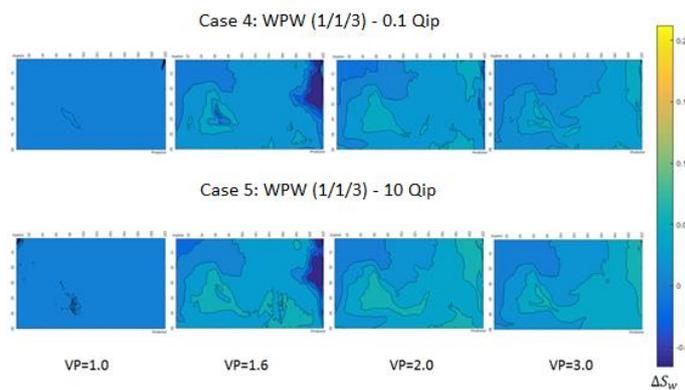

Figure 5- Maps of water saturation difference during alternate injection WPW (case 4 and 5) - Injection flow effect.

Then cases comparing the behavior of a Newtonian and non-Newtonian fluid were evaluated. Case 6 took into account the injection of a constant viscosity polymer ($\mu_p = 0.0545$), behaving as a Newtonian fluid with higher viscosity than water and it was compared with case 2, corresponding to the injection of polymer as a non-Newtonian fluid behavior. The viscosity of the polymer in case 6 is defined as the higher viscosity obtained in case 2 considering all cells of the reservoir. It was considered alternate injection of polymer for both cases after 1 PV of water injected.

Figure 6 shows a slight acceleration of production and a slightly higher recovery factor for the polymer solutions injection, case 6, where the polymer viscosity is considered to be constant. The lower recovery factor provided by case 2 caused by the viscosity values variation within each cell reaching a very broad scope, ranging from very low viscosities to even higher viscosities, unlike in case 6 where it was taken into consideration a constant viscosity equal to the maximum value found in case 2.

It is also noticed a very high injection pressure when considering the polymer as a Newtonian fluid, as the fluid injected became more viscous and the water cut curves are very similar, again suffering a sudden drop when the polymer injection starts, due to an increment in oil production.

The fact that the viscosity of the polymer declines with shear rate causes the injection pressure to be lower, without compromising the production of oil.

Likewise in the production graphics, the maps of the saturation difference, Fig. 7 also show that when the polymer is considered as a Newtonian fluid it offers a better sweep efficiency. At time equal to 2.6 pore volumes, case 6 has a higher saturation difference when comparing to case 2, so its water saturation is higher and the oil saturation is lower. Leading to a better efficiency swept by having less residual oil.
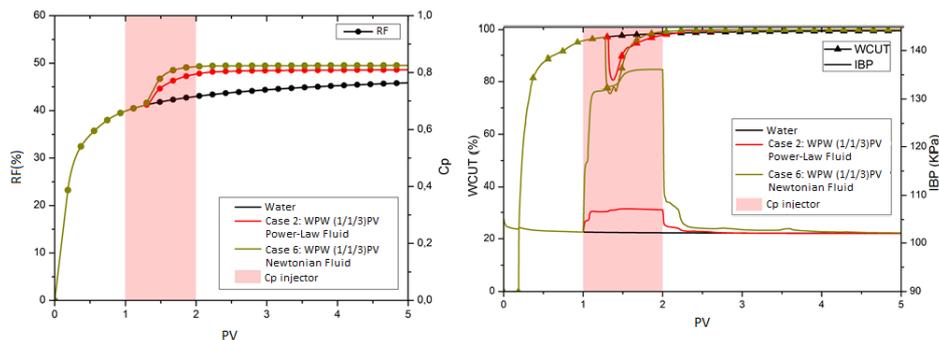

Figure 6 - Recovery Factor, water cut and injection pressure due to PV injected for the continuous injection of water (basis case) and alternate injection WPW (case 2 and 6) - Effect of the viscosity varying according to the viscous model.
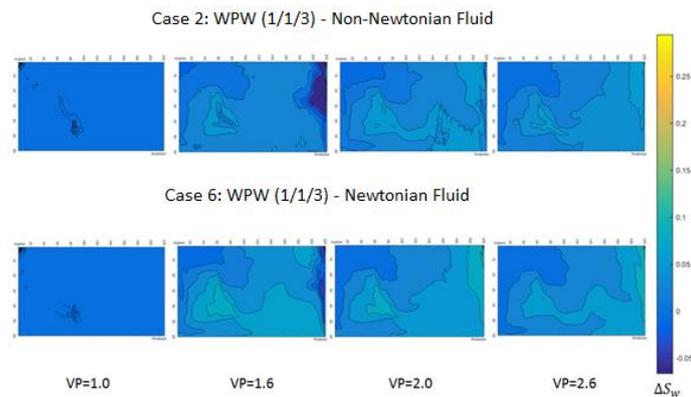

Figure 7 - Maps of water saturation difference during alternate injection WPW (case 2 and 6) - Effect of the viscosity varying according to the viscous model.

4.3. Results obtained considering the variation of viscosity with the extesional rate

The elastic polymer solutions effects may be manifested as an increment in the extensional viscosity of the fluid in the extension rate. Thus, the flow of a viscoelastic fluid through a porous media can represent an increase in the pressure drop when compared to the flow of a Newtonian fluid having the same viscosity. This can be modeled by making the viscosity change with the extension rate.

The parameters used for the model were: rheological parameter Carreau-Yassuda $n_{cy} = 0.8$, viscoelastic constant $\alpha = 180^{1/2}$, relaxation time of the molecule $\lambda = 5.0$ and initial and endless viscosities respectively $\mu_0 = 0.001$ and $\mu_\infty = 0.01$. In Fig. 8, it is represented the typical behavior of the viscosity variation as a function of the extensional rate for viscoelastic polymer solutions.

As in the previous section, the continuous water injection was compared with the alternate injection of water and polymer and the continuous polymer injection, but using the viscoelastic model for calculating the viscosity of the polymer. The effects of the injection flow rate variation and the type of injection were analyzed. These cases are listed in Tab. 2.
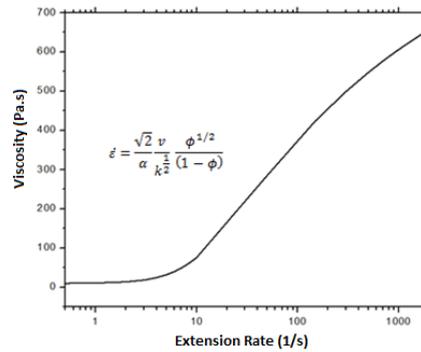
Figure 8 - Representative viscosity behavior as a function of the extension rate according to the Carreau-Yassuda model.

Table 2 – Studied cases for the viscosity varying according to the shear rate.

Cases	Injections	PV Injected	Injection flow	Rated effect
7	Water-Polymer-Water	1-1-3	Q_{ip}	Type of injection and injection variation
8	Polymer	5	Q_{ip}	
9	Water-Polymer-Water	1-1-3	10,000 Q_{ip}	
10	Polymer	5	10,000 Q_{ip}	

Fig. 9 represents the recovery factor for the cases 7 and 8 compared to the continuous injection of water. It can be noticed that the curves overlap for all cases. The same occurs for the water cut curves and injection pressure. Therefore, no efficacy in the injection of polymer solutions with viscoelastic behavior can be seen.

The same conclusion can be taken when evaluating the maps of the saturation difference, Fig. 10, it is shown that the value of water saturation difference between the cases of polymer injection and the case of water injection is around zero during the whole map. This means that the water saturation throughout the reservoir for the two cases and for the basis case is the same. So there wasn't an improvement in the sweeping efficiency of the reservoir by analyzing the viscoelastic behavior of the polymer.
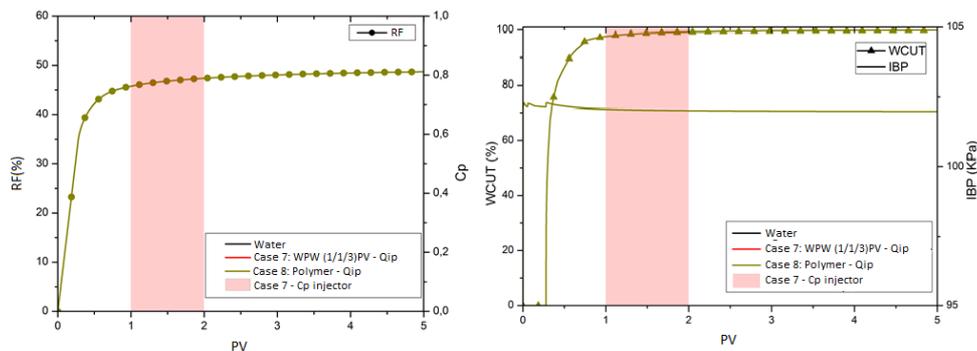

Figure 9 - Recovery Factor, water cut and injection pressure due to PV injected for the continuous injection of water (basis case), alternate injection WPW (case 7) and continuous injection of polymer (case 8) - Viscoelastic model using the initial flow Qip.

Next, to explore the viscoelastic behavior of the polymer injection, an increment of ten thousand times was considered to the injection flow , cases 9 and 10, to achieve extensional rate values that lead to higher viscosities. It is important to emphasize that for a realistic case the geomechanical behavior of rock should be considered to avoid fractures propagation due to high injection flow rates. Furthermore, the speed typically used in reservoir flow injections is in the range between 1 to 3 feet / day. Therefore the flow used in this model exceeds these values, thus it was only used for a parametric analysis to evaluate if it was possible to estimate the viscosity behavior according to its extension rate for polymer injections.

Figure 11 represents the recovery factor for cases 9 and 10. It can be observed a higher oil recovery regarding the polymer solution injection when compared with continuous water injection. It is also possible to observe an acceleration of production during the continuous injection of polymer (case 10). Although the final FR is equal for both cases (50%), this increased oil production is associated with improved displacement efficiency of the oil due to the increment in the extensional viscosity provided by elastic deformation of the polymer on the porous media.
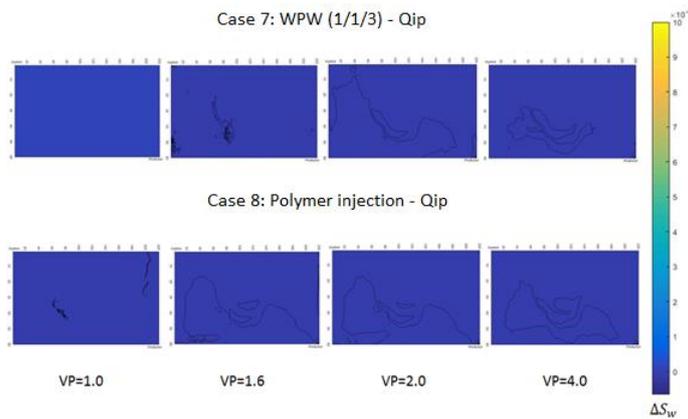
Figure 10– Maps of water saturation difference during alternate injection WPW (case 7) and continuous injection of polymer (case 8) - Viscoelastic model using the initial flow Qip.

It is also observed that injection pressure becomes higher when the polymer solution begins to be injected. The water cut curves are very similar, suffering a slight decrease in the alternate case, case 9 during the polymer injection period. The maps of saturation difference, Fig. 12 shows a front feed slightly more stable in the event of a continuous injection of polymer, but the maps of both cases are very similar, thus none of the cases represents a better efficiency relative to each other.
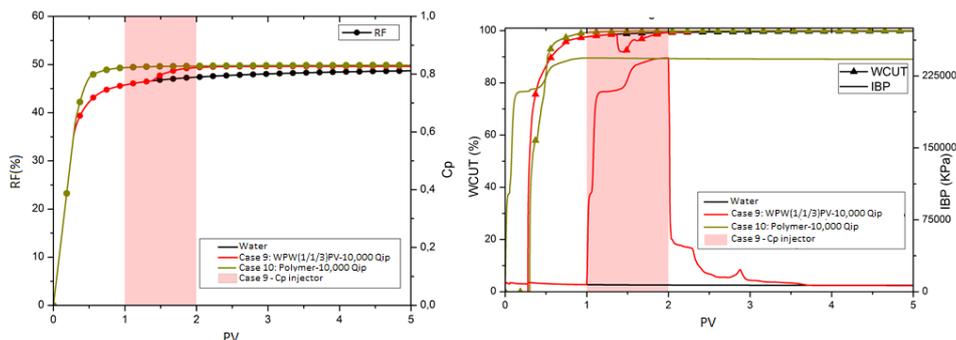

Figure 11 - Recovery Factor, water cut and injection pressure due to PV injected for the continuous injection of water (basis case), alternate injection WPW (case 9) and continuous injection of polymer (case 10) – Effect of the injection flow according to the viscoelastic model.
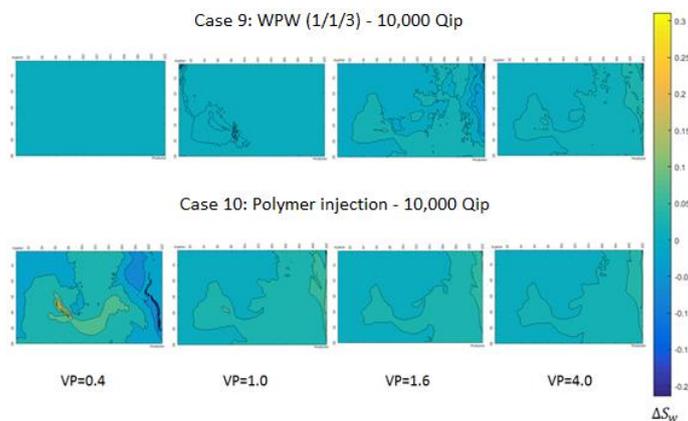

Figure 12– Maps of water saturation difference during alternate injection WPW (case 9) and continuous injection of polymer (case 10) - Effect of the injection flow according to the viscoelastic model.

5. FINAL CONCLUSIONS AND SUGGESTIONS

In this paper the shear and elastic effects of polymeric solution flow in porous media in a reservoir scale were evaluated separately. Therefore, idealized models of viscosity were used to describe the viscosity varying according to the shear rate under a power law model and the viscosity varying according to the extensional rate through Carreau-Yassuda model.

Viscous model results show that the alternate injection of polymer can be as efficient as the continuous injection of polymer regarding the stabilization of the front injection, avoiding high injection pressures without significantly affecting the recovery factor. When evaluating the start time of polymer injection considering the alternate injection cases, it was observed that the early injection considerably accelerates oil production. Although a significant difference has not been observed in the final value of the recovery factor among the cases of polymer injection, the difference with respect to water injection was higher, 48% FR for the injection of polymer and 45% for water injection. The effect of the flow reduces the recovery factor due to polymer thinning with increasing shear rate, making the mobility ratio water / oil unfavorable. When evaluated using the polymer modeling with the power law model and a Newtonian fluid of high viscosity, the results show for the alternate injection of polymer a more stable displacement of the front injection regarding the Newtonian case, which can be translated into a slight increase recovery factor, as well as an acceleration of production. However, high injection pressures were observed in all Newtonian cases.

With respect to purely extensional behavior of the polymer described by the use of the viscoelastic model, the evaluation of the type of injection showed that for lower injections rates, both continuous and alternating polymer injection, it was not possible to observe any related enhancement to the recovery factor, since the viscosity over the reservoir remained almost constant and very close to the value of the viscosity of water.

To allow the evaluation of the viscoelastic behavior of the polymer injection, it was necessary to increase the injection flow rate in ten thousand times for both continuous and alternating polymer injection, this considerable increment of the injection flow increased the extensional viscosity of the polymer along the reservoir, which due to the flow resistance generates the elongation of the polymer chains. This effect is observed in macroscopic scale through the reduction of the mobility ratio water / oil and through the increase in the displacement efficiency.

Importantly, in all modeled cases of polymer injection a substantial increment in the injection pressure was observed, which can be avoided without impairing the recovery factor through the reduction of the flow rate of injection and by choosing a type of polymer with higher relaxation times.

Future studies are recommended to enhance the viscosity models used, considering properties of the rock characteristics of the multiphase flow, as well as evaluating the effect of the elastic polymer in the microscopic swept efficiency by reducing the residual oil saturation and changes in the relative permeability curves. As the work presented here studied idealized viscosity models in order to separately study the viscous and the viscoelastic effects of polymers during the flow in porous media, any experimental validation was not possible, but it is recommend the use of experimental data for the analysis of results with realistic data.

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