POLYMER DISPLACEMENT THROUGH SATURATED VISCOUS OIL POROUS MEDIA

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Abstract. *Rising of viscous oil reserves has imposed new challenges to petroleum industry. Efficiency and integration among drilling, completion, reservoir and production tasks, as well as environmental safety are pursued in order to improve exploitation process. Focusing only two important applications related with polymer invasion throughout porous formation we can mention "drill in" fluids and enhanced oil displacement. Goals of each application are different. However understanding of displacement phenomena has common aspects. Drilling fluids are formulated to minimize invasion into productive formations of petroleum and enhanced recovery fluids based on polymers are formulated to improve sweep displacement by reduction of mobility ratio. This article presents an extensive laboratory study focusing one-dimensional displacement of viscous oil (~300 cp) by polymeric solutions. Synthetic and natural polymer performances are compared under two levels of differential injection pressure, using oil saturated porous samples with different rock surface conditions. Measured results from twelve tests are compared and discussed. Monitoring of variables includes rock and fluids characteristics, volumes, injected and produced mass, temperature and pressure difference at four positions along displacement direction of the porous sample. Invasion profile was characterized by X-ray emissions and tomography scanning. Good repeatability was determined from similar independent samples submitted to the same imposed conditions. Superposition of data under different test condition allowed observing relative importance of several phenomena.*

Keywords*: Porous Media, Displacement Process, Polymer, Viscous oil.*

1. INTRODUCTION

The challenges imposed by current exploitation activities, which aims to combine heavy oil, deeper water targets, environmental limitations, safety and efficient operations, are extending research focus to non-Newtonian flow, no unit mobility ratio and rock surface interactions influences on displacement mechanisms.

Polymer flooding has been applied to improve volumetric sweep and anticipate oil production from reservoirs. When used in a high concentration as polymer-gel, the primary purpose is minimization of heterogeneity effects and water production control. Concerning drilling operations, polymer application is focused on formation damage prevention.

Drill-in fluids design must combine multiple functionalities and limitations. A good performance in terms of drilling efficiency, damage preventing, environmental legislation and modern online formation evaluation tools must be reached in an optimized way. The majority of drilling practices expenditures is due to equipments, however drilling fluids design and affecting mechanisms understanding has gain special attention. Define an appropriated formulation and the optimum concentration of each compound is a challenge.

This article is an attempt to understand displacement mechanisms of common interest of drilling and reservoir engineering. Reported tests are part of a large project, however in this paper more viscous oil was target related to those presented in Moreno et all., 2007. Test protocol and experimental apparatus were the same used before and are described here in a summarized way. Twelve results runs focus one-dimensional porous media saturated with ~300 mPa.s oil and submitted to injection of ~30 % of pore volume of PHPA (4,5 lb/bbl or 12,8 kg/m^3) or Xanthan solutions (3,0 lb/bbl or 8,56 kg/m^3). Comparative evaluations and discussions are conducted aiming pointing out the relative importance of affecting mechanisms. Final invasion saturation profiles are compared considering two type of polymer, two levels of differential injection pressure and three different rock surface conditions. Repeatability influences were also investigated.

2. BACKGROUND

Drilling mud can be defined as a multiphase liquid system containing solids in suspension; dissolved salts and dissolved, dispersed or emulsified organic compounds in water (Rodrigues et all., 2006). Some functions attached to these fluids are: a) cuttings carrying and stabilization; b) annulus cleaning; c) cuttings separation at the surface; d) cooling, cleaning and lubrication of drilling equipment; e) fluid formation inflow prevention; and, not less important, e) prevention of damage formation.

As reported by Mandal et all. (2006), for a given geology, well geometry and production method, the well unit productivity depends on the control over formation damage exercised during drilling operations. According to them, ideal drilling fluid must: a) exclude non-degradable fine solids (clay, barite, etc.); b) minimize drilled fine solids; c) minimize polymer invasion into pay zone; d) prevent clay swelling, e) reduce filtration loss; f) minimize whole mud invasion during trips and gel break circulations; g) prevent insoluble precipitation.

Focusing drilling fluids performance evaluation, Strickland (1994) selected the following characteristics: a) thermal stability; b) formation stability; c) protection of productive zone; d) lubricity and torque/drag reduction, e) drilling capability; f) environmental compatibility; g) stuck-pipe prevention; h) corrosion protection and, i) resistance to contamination.

Fluids' designing has been studied by many researchers and petroleum companies (Kadaster et all., 1992; Hodge et all., 1997; El Essawy et all., 2005) and those typically composed of polymer and sized calcium carbonate or salt particulates, drill-in fluids,, have been suggested as an efficient and environmental safety solution (Beall et all., 1996).

During drilling process, positive differential pressure can cause fluid invasion into the hydrocarbon formation. If the invasion occurs when fluid pumping is stopped, invasion mechanisms is named static filtration and it is due to difference between the hydrostatic pressure in the well and the reservoir pressure. Damage thickness increases, and the invasion mechanism is dominated by cake permeability. Under dynamic pumping conditions, cake thickness depends of the equilibrium condition between particles deposition rate and erosion rate due to fluid flow through the wellbore and the mechanism is called dynamic or cross filtration (Martins et all., 2005).

Driven mechanisms associated with invasion process of polymeric solution into porous media can be classified as: a) hydrodynamic effects: molecular diffusion (longitudinal mixture due to concentration particles gradients), dispersion (transversal mixture) and convection movement (solvent movement); b) retention effects: size selection and surface adsorption; c) shear effects; d) elongational flow effects and e) degradation due to temperature, biological activity, mechanical stress, etc.. Relative magnitude of these phenomena depends of polymer type, fluids characteristics, porous media properties, fluids-surface interactions and flow conditions (Moreno et all., 2007).

Natural or synthetic polymers can be used on drill-in formulation; however each one keeps its advantages and limitations. PHPA polymers are characterized by high molecular weight and its properties (adsorption, shear and thermal stabilities) depend on the degree of hydrolysis; they are not resistant to shear stress and are vulnerable to degradation under high concentration of salts, high temperatures and high flow rate through low permeability porous media (Sorbie, 1991). Increase in electrolytes causes decrease in PHPA solution viscosity while adsorption increases (Liao and Siems, 1990). Also, PHPA solutions viscosity decreases with shear rate and increases with the extensional rate (Martins et all., 2005). Polyacrylamides have the ability to form good filter cakes, reducing the filtrate volume, however can not to be used when lubricity is a critical property (Rodrigues et all., 2006). Application of PHPA to improve hole stability have been also reported (Guerrero et all., 2006), (Mandal et all., 2006). Opposite to PHPA, viscosity of Xanthan gum is not influenced by salinity, and shear stress can be tolerated, however it is relative more expensive and, over 95°C, biodegradation can be significant. Its major application in drilling fluids is as a thickener or as a suspending agent (Lozano et all., 2006). Focusing on rock surface conditions, according to laboratory investigation conducted by Dong et all. (1996), polymer injection is not sensitive to reservoir wettability.

Polymer flooding through porous media deviates from Darcy´s formulation because: a) polymer viscosity is shear rate dependent; b) polymer molecules length is comparable to the pore throat length; c) molecular adsorption and mechanical entrapment modify porous media geometry. Traditional approach considering effective viscosity at correspondent shear rate has been used; however this procedure does not take into account elastic flow properties (Garrocuh and Gharbi, 2006; Yin et all., 2006). Although some approaches have been proposed aiming modeled viscoelastic behavior, a generalized understanding is not been completed reached.

2. MATERIALS AND METHODS

Displacement runs were performed using apparatus presented in the Photo 1. Experimental components allowed monitoring injected differential pressure, ambient temperature, produced volumes, produced/injected mass and differential pressure at four internal positions along displacement direction. Test cell are show in the Photo 2. Clean and dry samples of Botucatu sandstone were 100% saturated with Lubrax® oil and submitted to polymer solution displacement. Twelve tests were run combining two levels of differential pressure (~100 psi and 200 psi; 14,7 psi = 1 atm); two polymeric solutions (PHPA 4,5 lb/bbl – NaI 153000 ppm and XC 3,0 lb/bbl – NaI 153000 ppm) and three porous surface conditions (natural; with previous polymer adsorbed; hydrophobic). Some tests were run twice using independent samples in order to verify repeatability. Core properties and test characteristics are presented in the Table 1. Oil viscosity and polymers rheology are shown in the Figs. 1 and 2, respectively. Detailed information about experimental set-up and test protocol can be found in Moreno et all. (2006[a], 2006[b], 2007). Wettability change treatment is described in Moreno et all. (2005).

Table 1. Samples properties and test characteristics

Test	Sample	Poros. [fr]	Permeability		Differ. Pressure [psi]	Produced Pore Vol. [%]	Residual Saturation [fr]	Injection Time [min]	Test Temper. [oC]	Treatment	Polymer	Np [cc]	Wp [cc]
			Gas [mD]	Oil [mD]									
13	R01LX-200	0,232	539	327	200	29,9	0,728	51,0	27	No	Xanthan	14,8	1,8
14	R02LX-200	0,231	565	314	200	32,0	0,704	44,0	27	No	Xanthan	15,6	1,2
15	R03LX-100	0,235	619	393	100	29,9	0,695	245,0	28	*No*	Xanthan	16,6	
16	R22LXt-196	0,241	315	220	196	30,6	0,697	80,0	28	XC Adsorption	Xanthan	16,9	0,1
17	R23LXt-196	0,241	544	330	196	30,6	0,700	39,0	26	XC Adsorption	Xanthan	16,9	0,1
18	R04LXq-200	0,232	680	464	200	30,9	0,710	33,0	27	Hydrophobic	Xanthan	15,4	1,0
19	R24LP-204	0,249	720	412	204	30,4	0,753	23,0	26	No	PHPA-2	13,6	3,4
20	R25LP-204	0,246	655	318	204	29,9	0,762	42,0	26	No	PHPA-2	13,4	3,2
21	R07LP-100	0,241	749	344	100	31,3	0,738	42,0	27	*No*	PHPA-2	14,6	2,6
22	R27LPt-200	0,238	329	228	200	32,9	0,679	43,0	27	PHPA Adsorption	PHPA-2	17,5	0,1
23	R28LPt-200	0,233	312	215	200	33,1	0,676	57,0	28	PHPA Adsorption	PHPA-2	17,3	0,1
24	R26LPq-203	0,239	684	421	203	31,5	0,760	23,0	29	Hydrophobic	PHPA-2	13,0	4,0

Photo 1. Experimental Apparatus

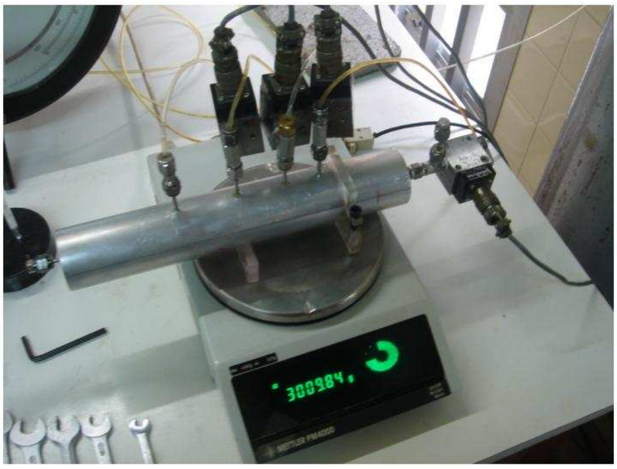


Photo 2. Test Cell

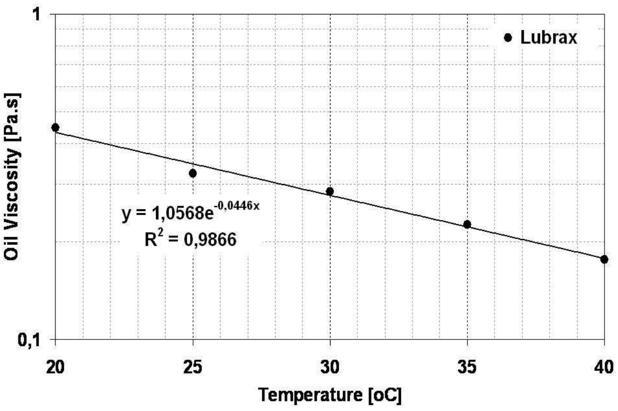


Figure 1. Oil Viscosity vs. Temperature

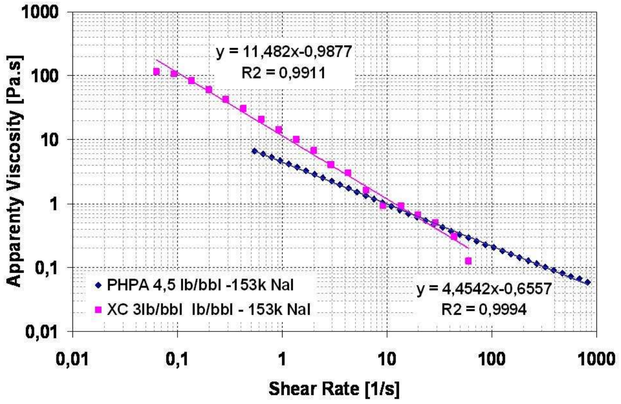


Figure 2. Polymer Apparent Viscosity vs. Shear Rate

2. TEST RESULTS AND COMPARATIVE ANALISYS

In this section are presented a comparative flow performance of two polymeric solution types: one based on Xanthan Gum and another based on PHPA. Polymeric solution was injected in two levels of differential pressure (~200 psi and ~100 psi) into oil saturated porous media and the invasion process was evaluating at three rock surface conditions (not treated, submitted to previous polymer adsorption and hydrophobic rock surface). Some runs were conducted using independent samples with similar permo-porosity characteristics.

Repetition of Xanthan injection at 200 psi through natural rock samples are presented in Figure 3, while PHPA invasion at the same conditions can be seen in the Figure 4. In these cases, repeatability of results was impressive, considering all affecting factors associated with laboratory practices.

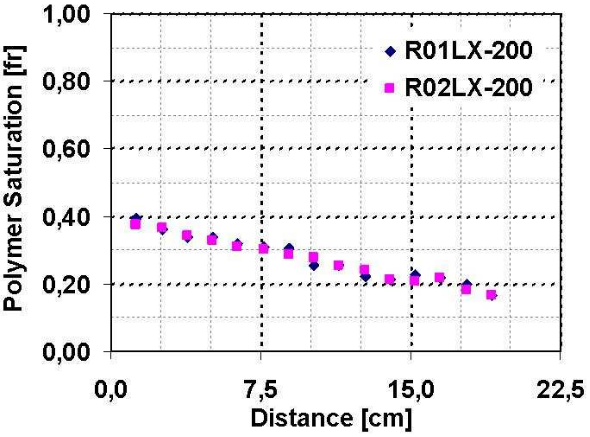


Figure 3. Repeatability of Xanthan Flow into Not Treated Samples

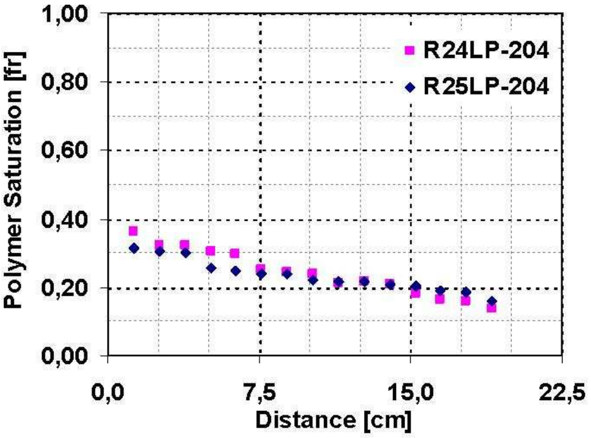


Figure 4. Repeatability of PHPA Flow into Not Treated Samples

In the Figure 5 and the Figure 6, one can see repetitions of polymeric solution injection through samples previously submitted to polymer adsorption process. Figure 5 shows results for Xanthan invasion, while Figure 6 shows saturations profiles related to PHPA injection tests. All runs were performed under ~200 psi of differential pressure. Although the same trend can be seen on respective repetitions, more sensitive results than that observed for natural rock runs were registered. Samples submitted to PHPA adsorption processes presented more homogeneous reduction on permeability (R_k=1,91 for R27LPt and R_k=2,00 for R28LPt), while for the samples R22LXt and R23LXt, ratio between original permeability and permeability after the treatment were R_k=2,27 and R_k=1,21, respectively. Peaks on profile saturations seem being related to this reduction factor, since a relative smoother profile was obtained in the sample R23LXt.

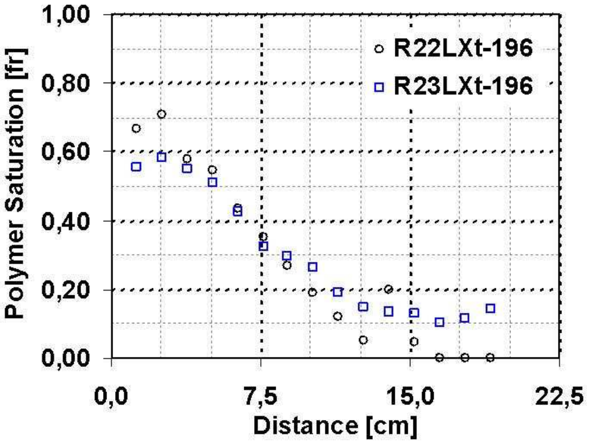


Figure 5. Repeatability of Xanthan Flow into Treated Samples

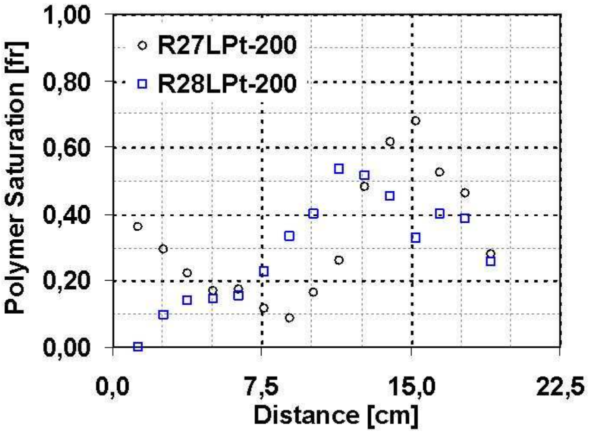


Figure 6. Repeatability of PHPA Flow into Treated Samples

Complementary insights about previous adsorption effects can be drawn comparing final saturation distributions presented in the Figure 7 and in the Figure 8. Peaks of retention are registered for both polymeric solutions when porous media were previously exposed to the polymer (R22LXt and R27LPt). Invasion process through natural porous media can be characterized by low sweep efficiency and deep invasion, since water breakthrough occurred before 33% of displaced pore volume (see Table 1). It was also evident that in these cases PHPA invades faster than Xanthan solution, since time injection is lower and produced water is higher in the first case. The same conclusion can be taken from treated samples results: more oil was contacted during much less time in the case of PHPA injection than when injecting Xanthan. Concerning of polymer saturation distribution, while Xanthan is retained next to the injection face, PHPA presented higher entrapment close to the production face (see R22LXt and R27LPt saturation distributions in the Figure 9 and in the Figure 10). As it showed in the Figure 11 and in the Figure 12, invasion polymeric solution was not affected by wettability change of the rock surface. Permeability factor associated to these samples were almost a unit (R_k=0,92 for R04LXq and R_k=0,94 for R26LPq).

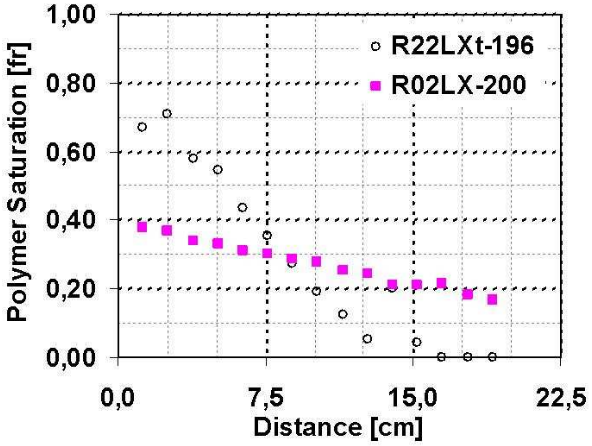


Figure 7. Xanthan Flow into Not Treated Samples vs Samples with Previous Xanthan Adsorption.

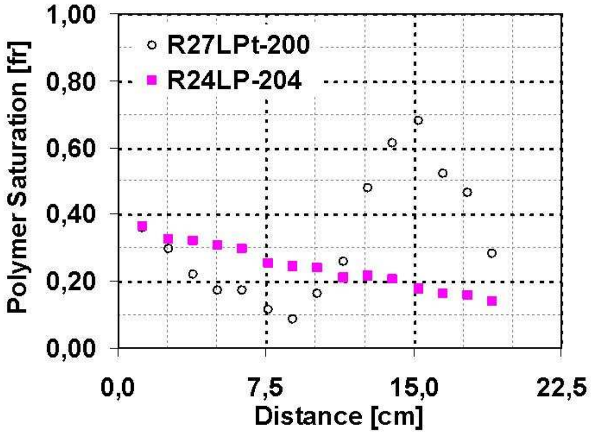


Figure 8. PHPA Flow into Not Treated Samples vs Samples with Previous PHPA Adsorption.

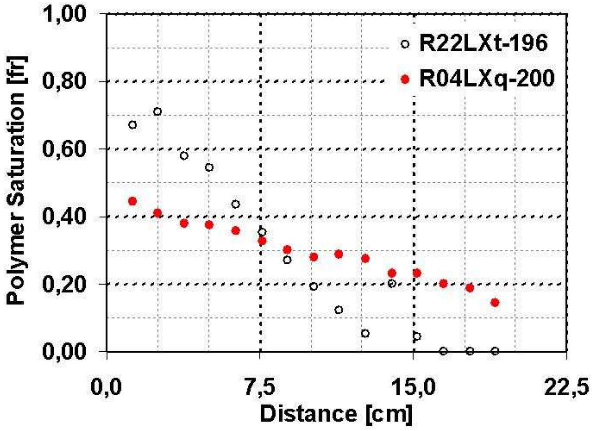


Figure 9. Xanthan Flow into Hydrophobic Samples vs Samples with Previous Xanthan Adsorption.

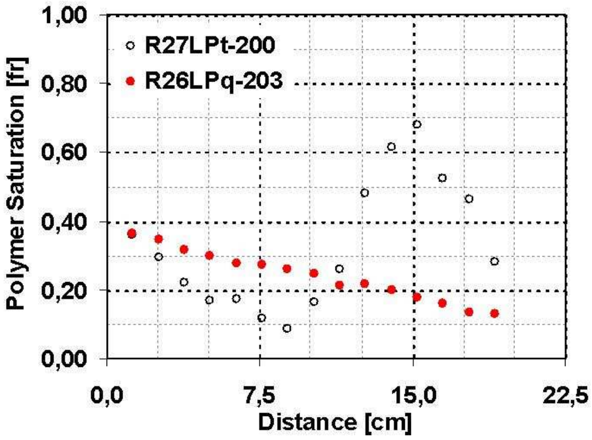


Figure 10. PHPA Flow into Hydrophobic Samples vs Samples with Previous PHPA Adsorption.

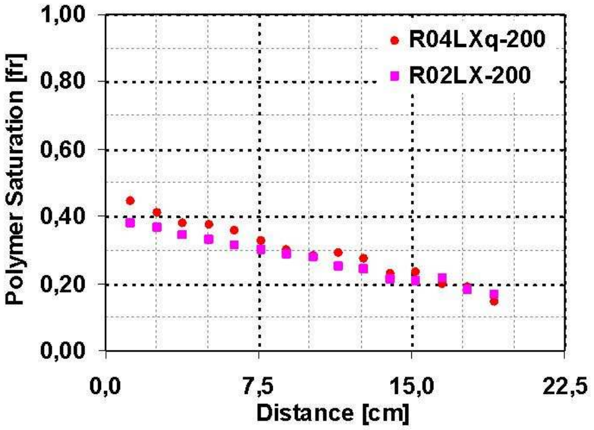


Figure 11. Xanthan Flow into Hydrophobic Samples vs Not Treated Samples

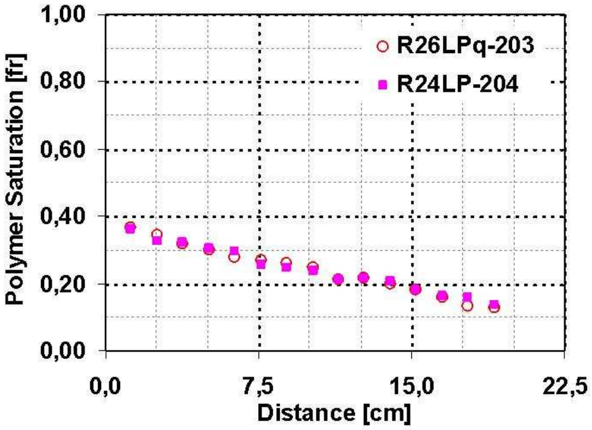
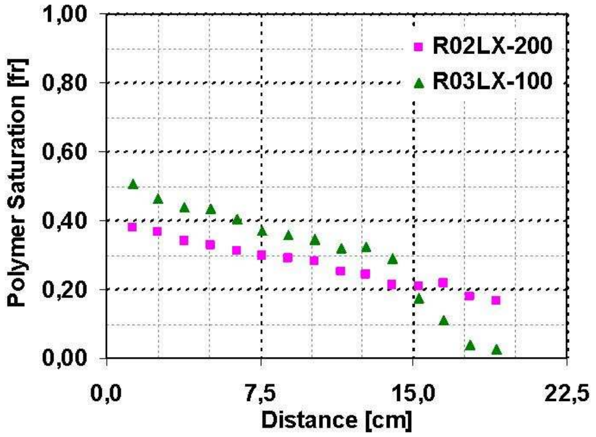


Figure 12. PHPA Flow into Hydrophobic Samples vs Not Treated Samples

Differential injection pressure level effects are presented in the Figure 13 for Xanthan invasion and in the Figure 14 for PHPA invasion. At the lower level of differential pressure, no water was produced and the diffusive character of advance front could be registered, time injection was much longer than that relative to higher differential pressure and more oil was contacted and displaced by polymeric solution next to injection face (see Figure 13). At similar test conditions, PHPA invasion was faster than Xanthan invasion and negligible differences were registered for saturation profile when displacing oil by PHPA at lower pressure (see Figure 14).



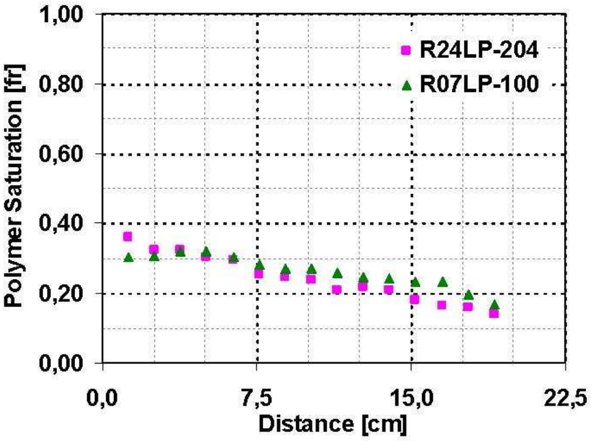
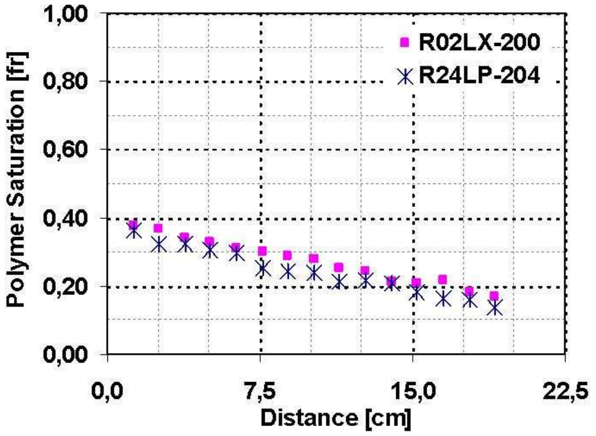


Figure 13. Influence of Injection Differential Pressure on Xanthan Inflow: ~200 psi vs. ~100 psi

Figure 14. Influence of Injection Differential Pressure on PHPA Inflow: ~200 psi vs. ~100 psi

Analyzing type of polymer influence, under differential pressure about 200 psi, it is observed that no differences on saturation profile were pointed out (Figure 15), however, to displace the same pore volume (about 30%), more PHPA solution were injected and consequently produced, during less time of displacement (see Table 1). Comparing results from low level of differential pressure runs, one can verify different saturation profiles for Xanthan invasion and PHPA invasion. In the case of Xanthan, displacement was slow and water was not produced, diffusive retention was registered for saturation profile behind advance front and over it, and also, higher amount of oil were contacted behind advance front relative to that mobilized by PHPA solution. In the case of PHPA injection, some end effects were registered next to the entrance and exit points. They are, respectively, characterized by soft rising and soft decreasing on polymer saturation data (Figure 16).



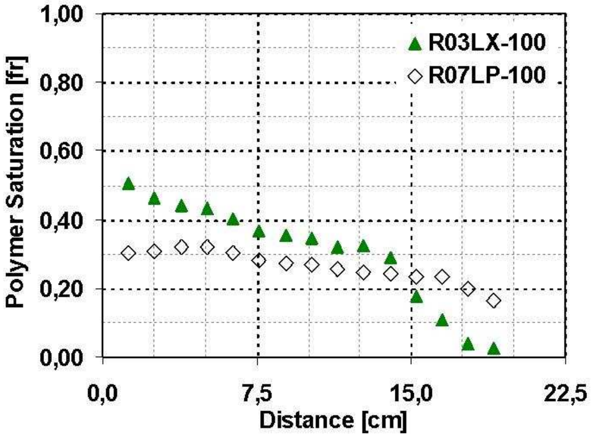


Figure 15. Comparative Invasion Performance of Xanthan vs. PHPA – Not treated Sample at ~200 psi.

Figure 16. Comparative Invasion Performance of Xanthan vs. PHPA - Not treated Sample at ~100 psi.

Figure 17 shows polymer injection through hydrophobic samples at 200 psi. At these conditions, no differences relative to affecting displacement mechanisms can be observed. The only exception is higher mobilization of oil attached by Xanthan than by PHPA. Sweep behavior probably are due to flow velocity, since Xanthan invasion were slowly than PHPA one (see injection time in Table 1). Polymer flow through rocks, which were previous submitted to polymer injection, shows quite different saturation profiles relative to those presented for hydrophobic samples Figure 18). End effects seem to be important to displacement. Slower movement of Xanthan than PHPA through porous sample was observed again and so was oil mobilization next to the entrance for Xanthan while to the PHPA, higher oil sweep are concentrated to exit side of the sample. Besides that, comparison between R23LXt-196 and R28LPt-200 showed a little different final saturation profile relative to those presented in Figure 18, which indicate more sensitive influence of tested conditions.

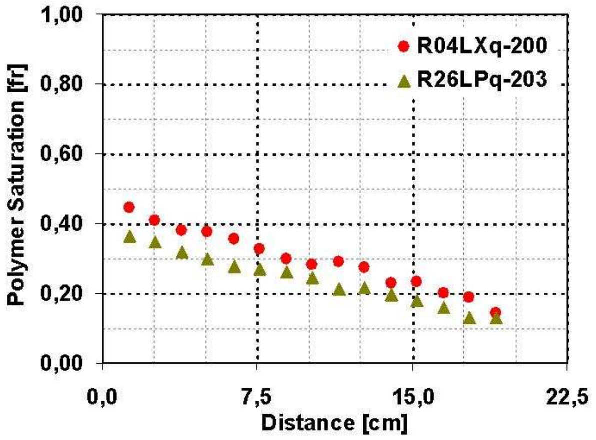


Figure 17. Comparative Invasion Performance of Xanthan vs. PHPA - Hydrophobic Sample at ~200 psi.

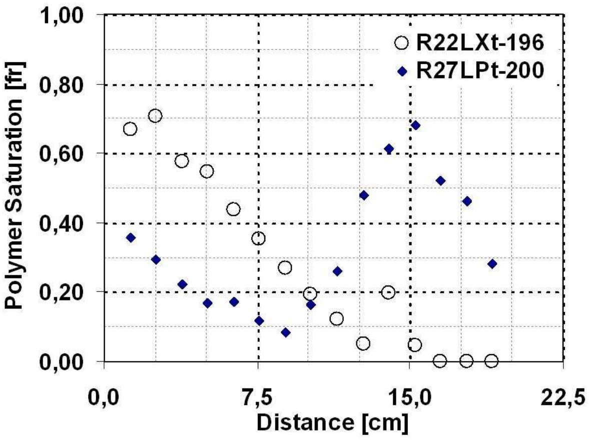


Figure 18. Comparative Performance of Xanthan vs. PHPA - Sample with Previous Adsorption at ~200 psi.

4. CONCLUSIONS

After discussion and comparative analysis of registered data presented in this paper, some conclusions can be highlighted as follows:

- Repeatability of results from independent runs performed using similar permo-porosity natural rocks under same displacement conditions was impressive.
- In the cases of previous rock surface exposition to the polymeric solution, tests performed under same operational conditions on similar samples showed quite similar final saturation profiles. However, registered data was not superposed as observed in the runs performed on natural rocks.
- Peaks of retention were registered for both polymeric solutions when porous media were previously exposed to the polymeric solution.
- Invasion process through natural porous media can be characterized by low sweep efficiency and deep invasion
- PHPA solution invades faster than Xanthan one.
- Concerning of polymer saturation distribution, while Xanthan gum is retained next to the injection face, PHPA presented higher entrapment close to the production.
- Invasion of both polymeric solutions was not affected by wettability changing of the rock surface.
- Under tested conditions, different injection pressure level shows influence over Xanthan saturation profile displacement, but not over final saturation registered for PHPA injection.
- At higher differential injection pressure runs, no influence of polymer type was observed on final saturation profile.
- Lower differential injection pressure has influenced differently Xanthan gum and PHPA invasion.
- End effects seem to be important to displacement: in the case of Xanthan, oil mobilization is more pronounced close to the entrance, while to PHPA injection, higher oil sweep are concentrated to exit side of the sample.

3. ACKNOWLEDGEMENTS

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