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PORE-SCALE ANALYSIS OF OIL DISPLACEMENT BY POLYMER SOLUTION

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Abstract. *Water flooding is the most commonly used oil recovery method in the industry. However, the high mobility ratio limits the amount of oil displaced by the water phase. An effective alternative to minimize this limitation is the application of technologies that act as mobility control agents. Polymer solution is used in many cases as a way to increase the water phase viscosity and consequently reduce the mobility ratio.*

Experimental evidences have shown that the elastic behavior of some polymer solution may contribute to a better pore level oil displacement, reducing the residual oil saturation. This pore level behavior is not clearly understood.

Here, a glass microfluidic chip is used as a two-dimensional model porous space. This device has the principal features of a porous media and provides means for pore level flow visualization. The evolution of the water phase as it displaces oil is recorded. Three different water phases were used: pure water, a high molecular weight PEO solution and a glycerol-water mixture with the same viscosity of the polymer solution. Flow visualization provides specific information about the presence of the trapped oil phase and the movement of the oil/water interface in the network. Results show that the polymer solution can modify the liquid distribution in the porous media, improving the displacement efficiency at pore scale and consequently the final oil recovery factor.

Keywords: *polymer, enhanced oil recovery, viscoelasticity, porous media, micromodel*

1. INTRODUCTION

The global energy demand is increasing substantially over the years, so it is necessary to develop techniques that seek a better use of hydrocarbon resources.

In order to produce oil, the reservoir needs a certain energy, known as primary energy, which depends on various reservoir conditions (such as volume, porosity, permeability, pressure and temperature) and fluids properties (viscosity, density and content of impurities).

According to Montalvo (2008), over time, primary energy loss occurs, which directly involves reducing the pressure and consequently the production rate, making it economically unfeasible. In order to minimize the effects of energy loss, different processes are employed to recovery additional oil.

Water flooding is the most commonly used secondary recovery method, because of low-cost and water availability. The application of water injection is responsible for more than half of oil production in the world, but this process has a limited reservoir sweep efficiency, leaving a considerable quantity of oil in the reservoir. This is due to unfavorable mobility ratio between oil and water, caused by the low viscosity of water compared with the oil, which results in the appearance of viscous fingers and inefficient sweep of the reservoir (Fig. 1).

Polymer solution is used in many cases as a way to increase the water phase viscosity and consequently reduce the mobility ratio. In the literature, many studies have been developed to understand polymer injection and its behavior in the reservoir. Sandiford (1964) started doing studies in the laboratory with hydrolyzed polyacrylamide to verify its efficiency to increase the viscosity of water and then performed field tests of water and polymer solution flooding to improve oil recovery.

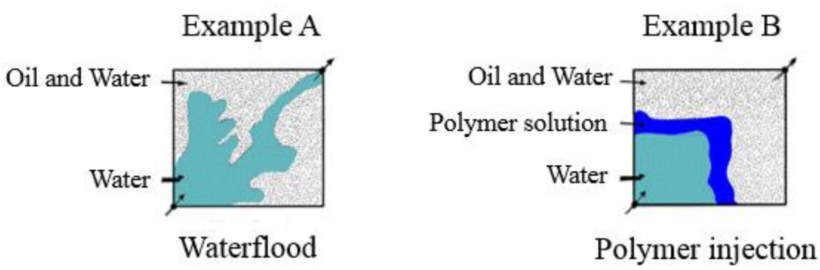

Figure 1. Polymer solution increase the viscosity of water and avoid the formation of viscous fingers

Smith (1970) an Acharya (1986) had recognized viscoelastic effects of polymeric solutions flowing through the porous media. Ranjbar et al (1992) performed experiments in natural and artificial cores and found a critical injection rate beyond which the elastic properties manifests itself.

A rheological curve of polyacrylamide was obtained by Weiying (1994) that realized that the viscoelastic effects of polymer was exhibited only when passing through the porous media and therefore dependent on shear rate. Demin et al (2000) did studies that correlated the increase on oil recovery in microscopic scale to elasticity of polymeric solutions.

In the review work from Wei et al (2014) it is shown that polymer flooding is economically and technically successful in EOR (enhanced oil recovery) projects. Also when flooding with viscous polymer solution, the mobility ratio between the displacing fluid and the displaced fluid becomes more favorable comparing to water flooding.

According to Wei et al (2014), the product of the macroscopic displacement efficiency and the microscopic displacement efficiency defines the overall oil displacement efficiency during oil recovery processes. Macroscopic displacement efficiency is a measure of the effectiveness of the displacing fluid in contacting the oil zone volumetrically; and the microscopic displacement efficiency is related to the effectiveness of the displacing fluid in mobilizing oil trapped at the pore scale by capillary forces.

Many works have explained the macroscopic effects of polymer addition to water to increase the oil recovery, but the pore level behavior (microscopic displacement efficiency) is not clearly understood, and this is the main objective of this study.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 Experimental setup

The experimental setup used in this work is shown in Figs. 2 and 3.

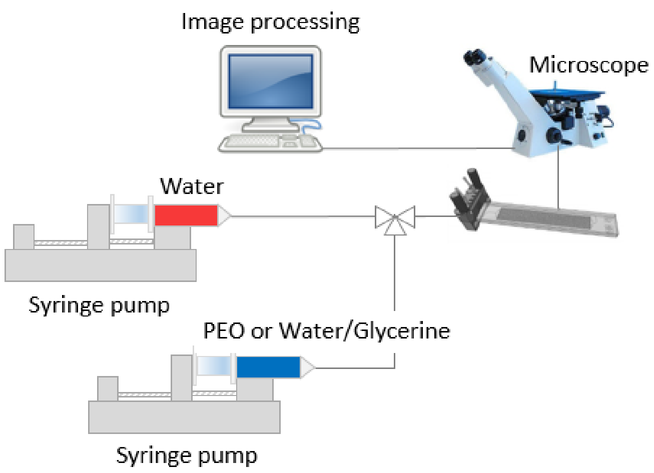

Figure 2. Experimental setup

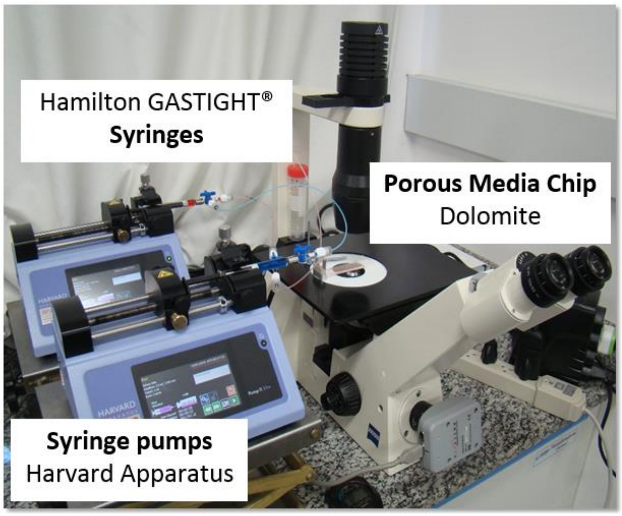

Figure 3. Syringe pumps and microscope

It consists of the following components:

1. Glass porous media chip, formed as an array of interconnected pores and throats.
2. Fluid injection system, consisting of two injection syringe pumps.
3. Visualization system of flow through porous media, consisting of a microscope and a camera.
4. Image processing, a computer with a MATLAB program to process the images.

2.1.1 Porous media chip

The two-dimensional porous media chip used in this work (Dolomite Microfluidics) is shown in Fig.4. It is a regular network of channels. The channels have a nearly circular cross section (channel depth = 100 micrometers and channel width = 110 micrometers) as shown in Fig. 5. The channels have different throats (63, 85 and 100 μm) that are randomly distributed throughout the device, as also shown in Fig.5.

Figure 4. 2D Porous Media Chip

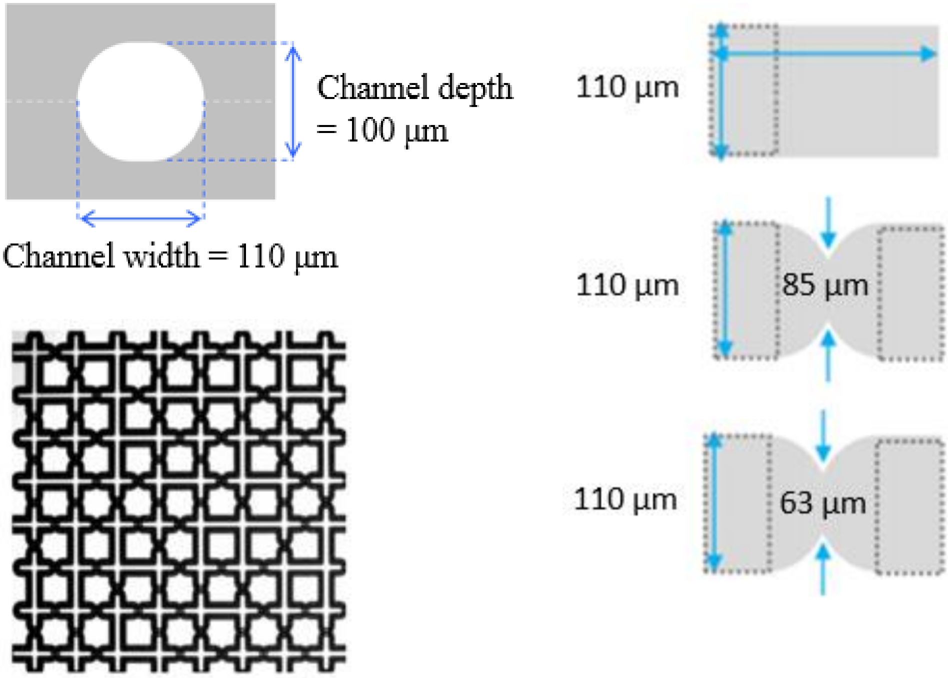

Figure 5. Configuration of the chip and the sizes of the constrictions

Colmenares Vargas (2014) calculated the pore volume in this microchip experimentally weighing the dry chip and then weighing the chip again saturated with water, and the porosity, using the ratio between the pore volume and the total volume of the micromodel. The amount found was 30 microliters for the pore volume, which leads to a porosity of 50%.

The permeability can be estimated using Carman's (1937) relation. Taking the tortuosity to be a function of porosity (Dias et al, 2006), the estimated permeability was 86 D.

2.1.2 Fluid injection system

The fluid injection system consists of two pumps (Harvard Apparatus Pump 11 Elite) used for injecting different fluids in the chip. All experiments were performed using glass syringes Hamilton Gastight, its termination in Teflon with Luer Lock coupling provided ease connection with the accessories used for the assembly of the injection setup.

Three-way SOLIDOR valves were used to establish the connection between the syringe and the microchip and also to control the flow, hoses with 1/32" internal diameter and special connectors for microfluidics complete the system.

2.1.3 Visualization system of flow through porous media

The experimental setup also includes an inverted microscope (Axiovert 40Mat, Zeiss) for the visualization of the oil displacement in the chip. The illumination was made using a light source from the top and the objective len used has a magnification of 2,5X.

A PixeLINK camera (PL-A662) was used to capture high-resolution videos and images of fluid transport within the network.

2.1.4 Image processing

The images were then imported to a MATLAB code that reports the percentage of each fluid in the image. Compare the percent of oil before and after polymer injection allow us to determine the amount of oil mobilized during the process.

2.2 Materials

In this study, we used a mineral oil (Drakeol 7, properties shown in Tab.1), deionized water, a dilute solution of polyethylene oxide (M_w=8,000,000 g/mol, supplied by Sigma-Aldrich) and a water-glycerine mixture. For properly distinguishing the different phases during the experiments, blue and red dyes were mixed with the fluids.

Table 1. Drakeol 7 properties

Drakeol 7	Temperature (ºC)				
	20	25	30	40	50
Viscosity (mm2/s)	26,22	21,05	17,24	12,02	8,780
Specific gravity (g/mL)	0,8467	0,8446	0,8413	0,8338	0,8277
Surface tension (mN/m)	27,8	28,3	28,6	28,4	28,6

The polymer solution was a PEO (polyethylene oxide) solution at 0,2% by weight, that has a shear thinning behavior at this concentration. At lower concentrations, it is well known that PEO behaves like a Boger fluid, i.e. the viscosity does not vary with shear rate.

Rheology tests were performed in Physica MCR 501 rheometer (Anton Paar) using cross hatch geometry. The viscosity function is shown in Fig. 6.

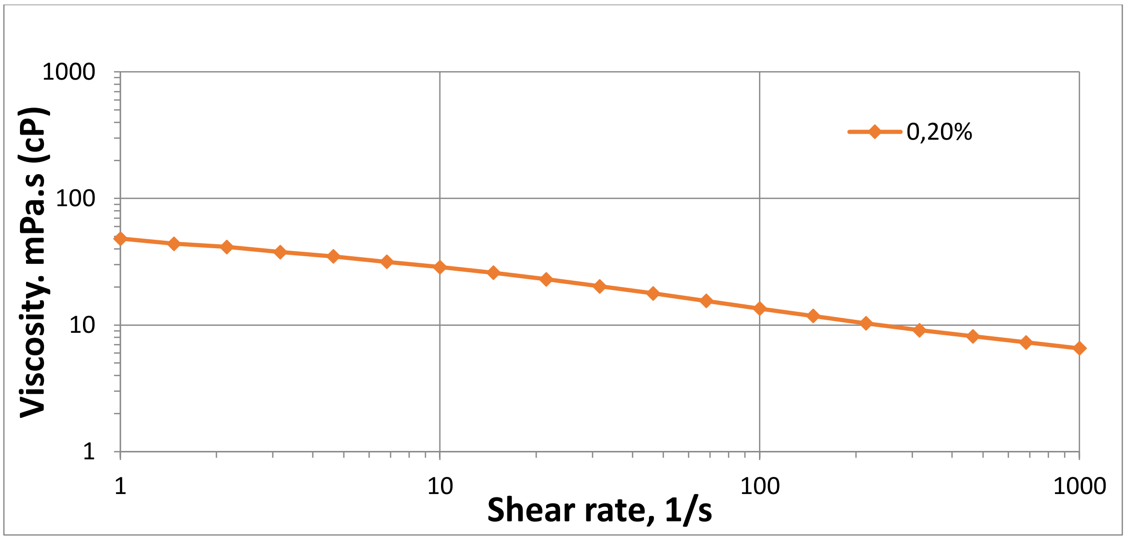

Figure 6. PEO viscosity curve showing a shear thinning behavior

In order to estimate an average value of the polymer solution viscosity as it flows through the micro channels, it is important to estimate a characteristic shear rate of the flow. The average shear rate in porous media may be estimated by the expression (Eq. 1) presented by Christopher and Middleman (1965):

$$\dot{\gamma} = \frac{12u}{(150K\varepsilon)^{1/2}}\left(\frac{3n+1}{4n}\right) \quad (1)$$

Using n = 0.778, u = 3.6 m/s, the shear rate ($\dot{\gamma}$) is estimated to be equal to 0.58 s^{-1}. The characteristic viscosity is estimated by using a power-law equation to describe the measured viscosity function.

$$\mu = K_c . \dot{\gamma}^{(n-1)} \quad (2)$$

μ = viscosity.
K_c = flow consistency index.

The viscosity found was 54,6 cP.

2.3 Procedure

Using the syringe pump, oil is introduced in the chip at a constant injection rate of 5mL/h and continued until the chip is completely filled with oil.

In the next step, water containing the red dye (in the picture water is pink because of the concentration and the microscope configurations) is injected at a rate of 0.013 mL/h in the microfluidics device. In this process, water displace the oil inside the chip. The choice of the flow rate is based on the current experimental constraints. In actual reservoir water flooding case, a typical injection rate of 0,013 mL/h translates to an average pore velocity of 1 ft per day in typical oil fields.

Water injection continued until steady state was reached. Steady state was defined as the flow condition at which the oil phase stopped being produced. Typically, two pore volumes of water were injected until this condition.

Then, viscoelastic polymer solution with blue dye (green in the picture) was injected. The volume of trapped oil after water and polymer solution injection was compared to evaluate if the polymer changes the residual oil saturation at different locations of the porous microchip.

In order to determine the amount of oil recovered, images were taken when the device was fully flooded with oil. The original images were then compared against images of the chip after the driving fluid had been pumped through the microfluidic device.

3. RESULTS AND DISCUSSION

The most common driving fluid used for oil recovery is water. Thus, for this study, water is used to compare the polymer displacement of oil. The flowrate of the injected fluids were 0.013 mL/h and four different areas of the chip were examined: the entrance, the exit and two areas in the middle with the same distance from de entrance/exit. For each area 4 pictures were taken. The pictures presented in Fig. 7 show different steps of the flooding procedure in the entrance of the microchip.

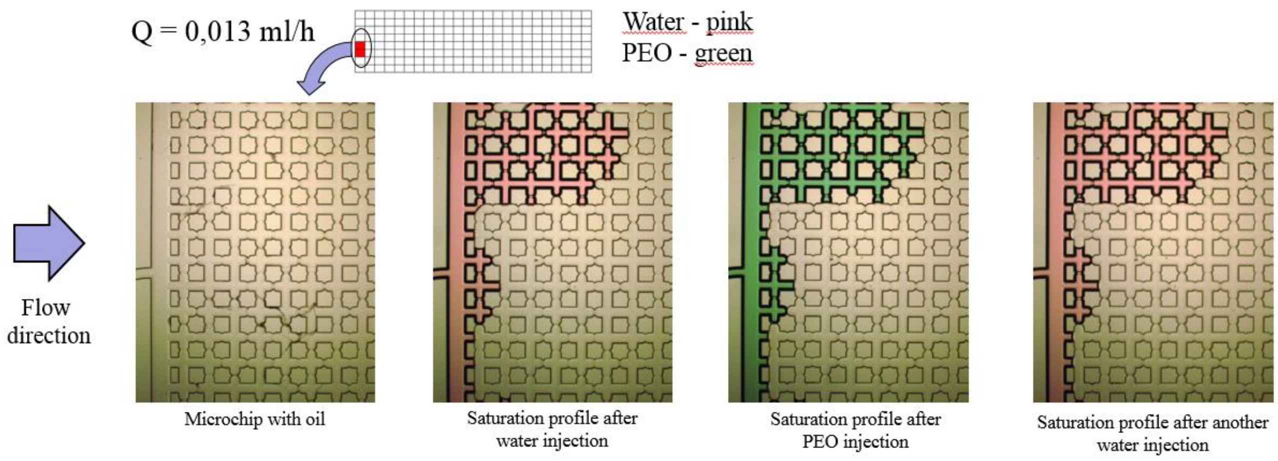

Figure 7. Saturation profile at the entrance

The saturation at the exit of the chip is shown in Fig. 8. The red squares shows the oil mobilized after PEO injection and the yellow squares after the second water injection.

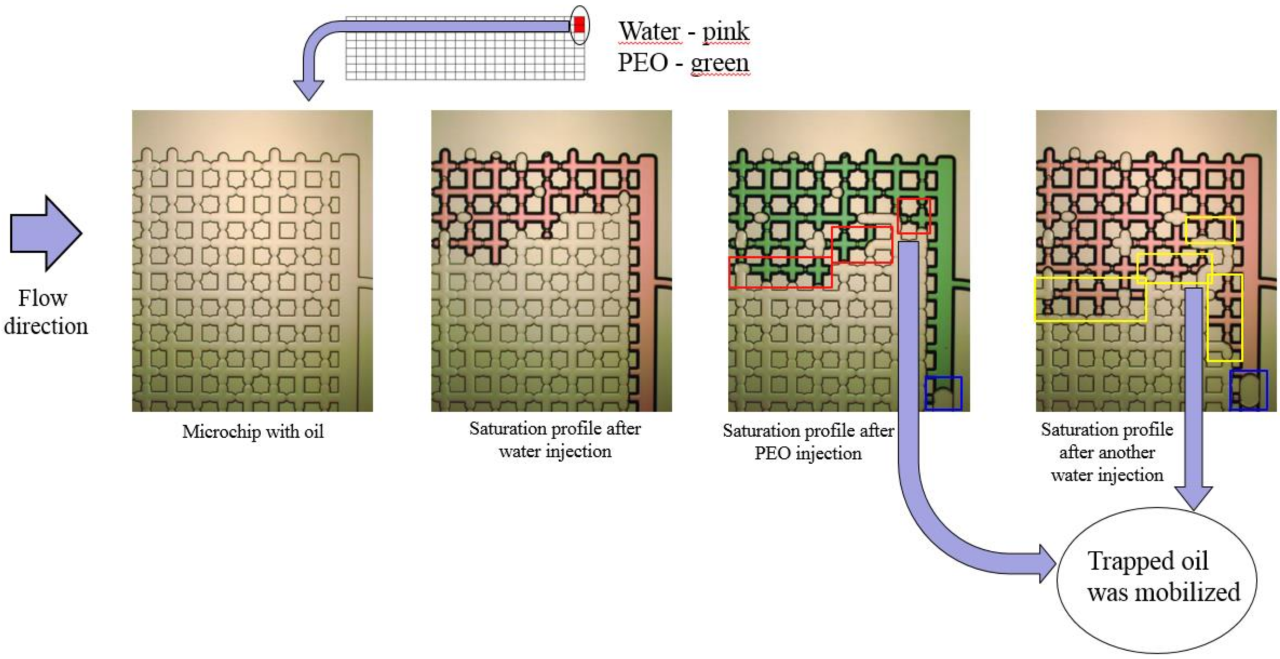

Figure 8. Saturation profile at the exit

4. ONGOING WORK

We are presently conducting new experiments to explore the effect of flow rate (deformation rate of the polymer solution) in the oil displacement process. An image processing tool, developed in MATLAB is being used to evaluate the local saturation of each phase during the experiments, as sketched in Fig.9.

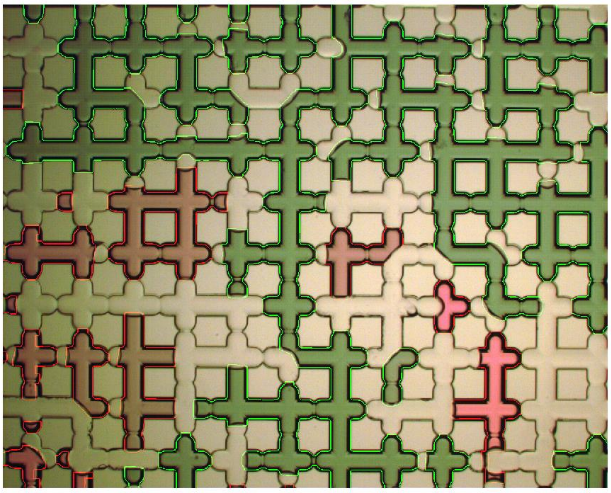

Figure 9. The areas delimited that will be calculated by MATLAB

5. CONCLUSION

Enhanced oil recovery is an increasingly important field, and this work presents the efforts of developing microfluidics experiments to understand how polymer solution displaces oil a porous media and how they can modify the liquid distribution improving the displacement efficiency. Variations of fluids and flow rates will be examined for their ability to increase the recovery.

Future work with more complex, lower permeability microfluidics device will be performed and also with a device that allow measurements of the pressure drop.

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7. RESPONSIBLE NOTICE