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The Study of Flow Behavior and Performance of Polymer Injection in Homogenous Porous Media Using Etched Micromodel

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Abstract

The implementation of polymer injection on a field scale needs a preliminary laboratory test to analyze the performance and flow behavior of polymer injection in a porous media. Compared to core flooding method, micromodel provides the visualization of oil displacement mechanism and facilitating a more detailed process description. Understanding the effect of polymer concentration on the incremental of oil recovery factor and its displacement mechanism are essential to know the polymer injection performance with the intention of avoiding failures in the implementation of polymer injection at field scale. We used dry etching technique for the fabrication of acrylic micromodel with homogenous characteristic. In this work, pre-flush (waterflooding) is performed first before doing the polymer injection to determine the incremental oil recovery factor and analyze the effect of polymer concentration on oil recovery factor enhancement in homogenous porous media. They were positioned horizontally then saturated with synthetic brine and light crude oil as the initial condition before starting the injection scenario. The experiment was conducted at room temperature. The entire process of micromodel flooding test was monitored by camera and then for the further analysis was done using Digital Image Analysis (DIA). According to the polymer rheology and aqueous stability test, it can be proven that polymer is a non-newtonian fluid indicated by shear thinning behavior and it can be observed that FP3630S polymer is a good candidate for micromodel flooding test. The micromodel flooding result confirmed that the increasing of polymer concentration will result in higher incremental oil recovery factor. In addition, based on the final condition of the micromodel after the polymer injection process, there is improvement of sweep efficiency due to the front stability resulted by the decreasing of mobility ratio between displacing fluid (polymer solution) and the oil bank.

Keywords: Micromodel; Oil Recovery Factor; Polymer Injection

INTRODUCTION

Because the potential hydrocarbon resource left behind after secondary recovery method is still significant, the implementation of enhanced oil recovery (EOR) must remain a key way to recover more oil. The dynamics of flow through porous media had an important role in many petroleum engineering applications including enhanced oil recovery. Polymer solutions with different concentrations and rheological properties are increasingly and widely used in enhanced oil recovery application due to the use of polymer could give incremental oil recovery if waterflood was already considered not economically favorable. The most common problem encountered in waterflooding process is viscous fingering that could reduce the sweep efficiency of waterflooding. Adding suitable polymer solution to the injected water would make the oil flow more mobile than water mobility which would result in the reduction of viscous fingering effect due to the flood front stability, so that higher oil recovery could be obtained. Therefore, polymers are widely used to overcome viscous fingering problem that occurs in water flooding. However, in the implementation of polymer injection in a field project need preliminary laboratory study to know the performance of polymer injection in oil recovery by understanding the polymer flow behavior in porous media. Core flooding is a method that is commonly used in the experimental study, in which a core could represent the real reservoir condition. Nevertheless, to get the native core is not easy and needs high cost. In addition, core flooding method couldn't give visual mechanism of polymer flow behavior,

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while in this research work requires clear and detail visualization of the polymer injection mechanism in porous media, so transparent media is needed to make it easier in handling the observation. Therefore, to overcome this problem, micromodel is used as the porous medium that could closely represent the actual condition of the reservoir. Due to the transparency of micromodel, the entire process of oil displacement mechanism could be directly observed and monitored using camera then the result is analyzed by using Digital Image Analysis (DIA) to determine oil recovery. Understanding various factors that can influence the oil recovery obtained and its displacement mechanism is essential to comprehend the polymer injection performance in purpose to obtain the best result of polymer injection at field scale. Polymer concentration is very important parameter to be considered in designing polymer, where it could influence on the performance of polymer injection due to mobility ratio between displacing fluid (polymer solution) and displaced fluid (oil) is strongly affected by polymer rheology. Favorable mobility ratio must be achieved in order to get optimum result of polymer injection in a field scale. Therefore, in this research work a 2D micromodel fabricated with acrylic material is used as the porous medium to study the effect of polymer concentration on oil recovery.

LITERATURE REVIEW

Polymer Injection

Polymer injection enhances oil recovery factor through a combined mechanism of mobility control, viscoelastic nature of the polymers and disproportionate permeability reduction [1]. The main objective of polymer injection is to remedy the viscous fingering problems that occurs in the waterflood due to a high mobility ratio or due to heterogeneity which in a homogenous porous medium, mobility ratio is the main factor that can affect the success of polymer injection to improve oil recovery [2]. The displacing phase mobility (polymer) should be equal to or less than the lowest mobility of displaced phases (generally, oil phase mobility) multiplied by its normalized saturation [3]. The implementation of polymer injection in a field scale needs preliminary experimental study to know the performance of polymer injection in improving oil recovery at laboratory scale.

Micromodel

Micromodel is an artificial device used at pore scale to visualize the mechanism of oil displacement. Micromodel provides visualization of flow behavior of injected fluid with the purpose of observing and analyzing the fluid injection profile, which cannot be accomplished in the core flooding process [4]. The micromodel with two-dimensional design (2D Micromodel) is often used for the investigation of polymer injection at pore scale. Generally, there are two types micromodel according to the flow pattern characteristic, namely homogenous micromodel and heterogenous micromodel. A micromodel is typically made of a transparent material that enables visual observation, such as glass, quartz, or polymeric material. The requirement of small pores (<1 mm) is necessary for two-phase flow studies due to the capillary effects will be otherwise irrelevant [5].

Studies on Micromodels

One of the earliest micromodels was developed and used by Chatenever and Calhoun (1952) to examine the possibilities of visual approach in investigations of fluid behavior in porous media at microscale mechanisms [6]. Since then, micromodels have been used to study many processes and applications, especially in the studies of two-phase low. Chuoke et al. (1959) used a Hele–Shaw micromodel to study two-phase flow in a porous medium. Their work presented theoretical and experimental evidence for the existence of macroscopic instabilities in the displacement of a fluid by another immiscible fluid through a homogenous porous medium [7]. Mattax, C.C. and J.R. Kyte (1961) used etched glass micromodel to investigate the effect of wettability on fluid distribution and the impact of permeability on oil displacement mechanism. It was the first experimental study that used etching method in the micromodel manufacturing process, where hydrofluoric acid was used to make pore structure as the flow network [8]. Hematpour et al. (2011) conducted an experimental study to investigate the behavior of polymer flooding in low-viscosity oil and to study various aspects of micro-displacement. A glass-materials were used to construct one-quarter five-spot micromodel. The result showed that the use of hydrolyzed polyacrylamide (HPAM) gives the highest oil recovery [9]. Sedaghat et al. (2013) conducted an investigation of polymer flooding in fractured heavy oil five-spot systems to examine the role of salinity, wettability, connate water and fracture geometry in the recovery efficiency of the system [10]. Nilsson et al. (2013) studied the effect of fluid rheology on a microfluidic device. The micromodels were designed to reproduce a two-dimensional slice from a sandstone core [11]. Hosseini et al. (2019) used glass-type micromodel to investigate the effect of polymer type, polymer concentration, reservoir heterogeneity and injection flow rate on oil recovery factor. The experiment result showed that higher polymer concentration at lower injection rate could give better sweep efficiency. Also, the swept area was significantly affected by porous medium heterogeneity due to the flood front movement was affected by permeability difference [12]. **Figure 1** shows some micromodels with certain geometry model and different fabrication method made by previous researchers [8, 13-17].

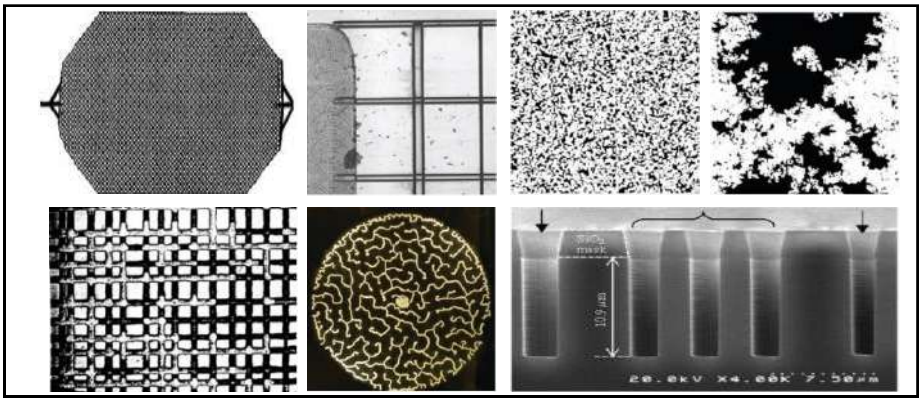

Figure 1. Micromodels Made by Previous Researchers [8, 13-17]

RESEARCH METHOD

The main objective of this research work was to investigate the effect of polymer concentration on the oil recovery factor and to understand the mechanism of polymer injection in displacing oil visually. The first step was micromodel manufacturing, the micromodel was designed with perfectly regular geometry model which the pore has a square shaped, thus the micromodel would have homogenous flow pattern. The material used to make a micromodel was polymethylmethacrylate (PMMA) or usually known as acrylic. The acrylic plate surface was etched by using plasma radiation, the etching process would follow the micromodel flow pattern design that had been made before by using CorelDRAW software. After the etching process was done, the plate with flow pattern was covered by another acrylic plate that didn't have flow pattern on the surface which was known as upper part or cover plate of micromodel. High temperature (175^{0}C) was used to fuse the two plates which is known as thermal bonding process, so that the gap between them would be the pore as the flow path for fluid in the micromodel. The homogenous micromodel was shown in **Figure 2** and for the micromodel properties was presented in **Table 1**.

The next step was polymer rheology test and then followed by polymer aqueous stability test. Polymer rheology test was performed to measure polymer viscosity under different shear rate and various concentration (500 ppm to 2000 ppm). Polymer product used in this experimental study was FP3630S which included as synthetic polymer (hydrolyzed polyacrylamide/HPAM). Polymer aqueous stability test was conducted to know the polymer solution stability within a certain period of time, in this study the test was conducted for seven days at different temperature (25^{0}C and 60^{0}C).

Table 1. Homogenous Micromodel Properties

Homogenous Micromodel	
Length (mm)	50
Width (mm)	50
Etching Depth (mm)	0.58
Pore Size (mm)	0.23
Grain Size (mm)	1.1
Bulk Volume (ml)	1.45
Grain Volume (ml)	0.794
Pore Volume (ml)	0.656
Porosity (%)	45.24
Absolute Permeability (D)	31.34

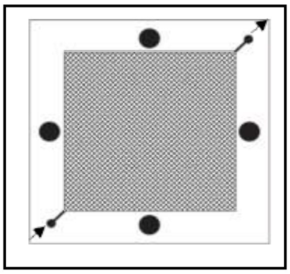

Figure 2. Homogenous Micromodel

The last step was micromodel flooding test which was the main test in this experimental study. The micromodel flooding test consist of micromodel setup, water saturation, oil saturation, waterflooding and polymer injection. In this experimental study, synthetic brine with a salinity of 10000 ppm NaCl was used as the wetting phase and light oil (43.278 ^{O}API) with a viscosity of 2.15 cp (at 25^{O}C) was used as the non-wetting phase in the micromodel. The experimental setup was shown in **Figure 3.** In this micromodel flooding test, there were three scenarios namely: Scenario 1: Waterflooding + 1000 ppm polymer injection, Scenario 2: Waterflooding + 1500 ppm polymer injection, and Scenario 3: Waterflooding + 2000 ppm polymer injection. Every polymer injection scenario was conducted in homogenous micromodel. The step of micromodel flooding test was shown by **Figure 4** and for detailed polymer injection scenarios were presented in **Table 2.** Camera was used to monitor and capture images during the micromodel flooding test, and then the result would be analyzed by using Digital Image Analysis (DIA). The synthetic brine and polymer solution with different concentration should be colored first before the micromodel flooding test, so that the saturation of each fluid could be obtained by color image processing software, then the oil recovery factor could be determined.

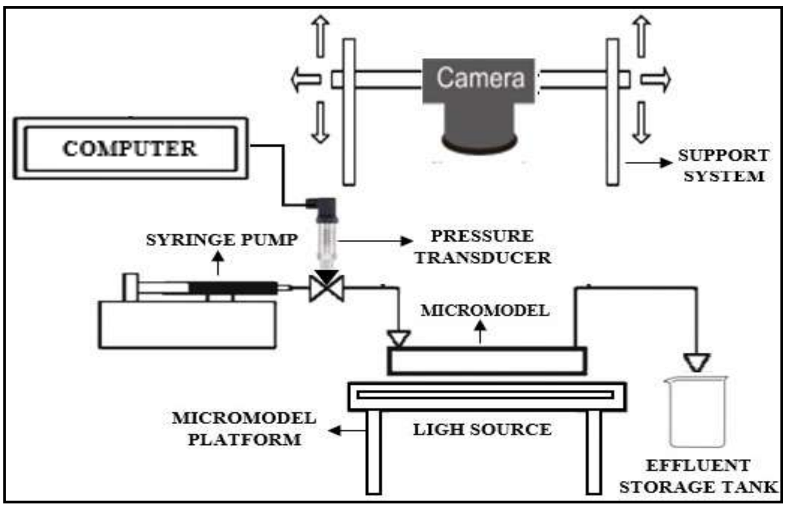

Figure 3. Micromodel Flooding Step

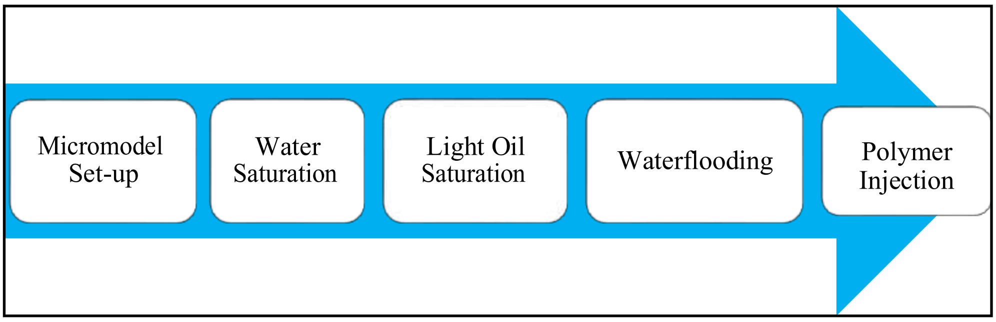

Figure 4. Step of Micromodel Flooding Test

Table 2. Micromodel Flooding Scenario

Scenario	Flooding Scenario	Injection Rate	Zone
Homogenous Micromodel			
Scenario 1	Waterflooding + Polymer Injection (1000 ppm)	0.05 cc/min	Homogenous Permeability Zone
Scenario 2	Waterflooding + Polymer Injection (1500 ppm)		
Scenario 3	Waterflooding + Polymer Injection (2000 ppm)		

RESULT AND DISCUSSION

Polymer Rheology

The measurement of FP3630S polymer viscosity for various concentrations was shown by Figure 4 and Table 3. As it can be seen in Figure 5, the polymer solution with concentration 1000 ppm, 1500 ppm, and 2000 ppm will have viscosity of 11.52 cp, 24.34 cp and 43 cp respectively. According to the graph of polymer viscosity vs concentration in Figure 5, it can be observed that the increasing of polymer concentration will give higher viscosity. This result was used as benchmark for polymer concentrations injected in a micromodel.

Table 3. Measured Polymer Solution Viscosity at Room Temperature (25°C)

Polymer Solution Concentration (ppm)	Polymer Solution Viscosity (cp)
500	5.37
750	8.05
1000	11.52
1250	16.48
1500	24.34
2000	43.00

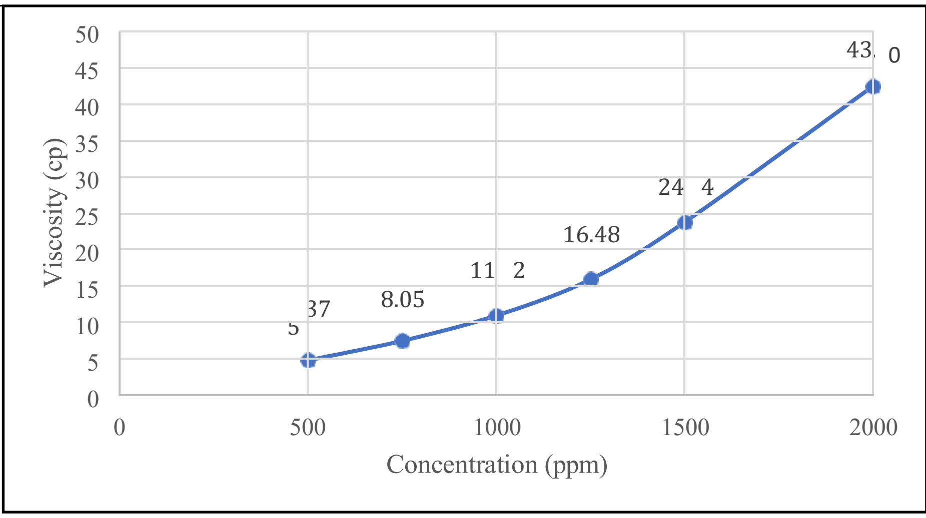

Figure 5. Polymer Solution Viscosity vs Concentration

The measurement of FP3630S polymer viscosity vs shear rate for polymer solution with concentration of 1000 ppm, 1500 ppm, and 2000 ppm were shown by **Figure 6**, **Figure 7** and **Figure 8** respectively. Based on all of these graphs, it can be observed that the viscosity of polymer solution decreases under shear strain. This means that the polymer viscosity decreases with the increasing of shear rate, this behavior is known as shear thinning or pseudoplastic fluid behavior. According to this result, it proves that polymer is non-newtonian fluid.

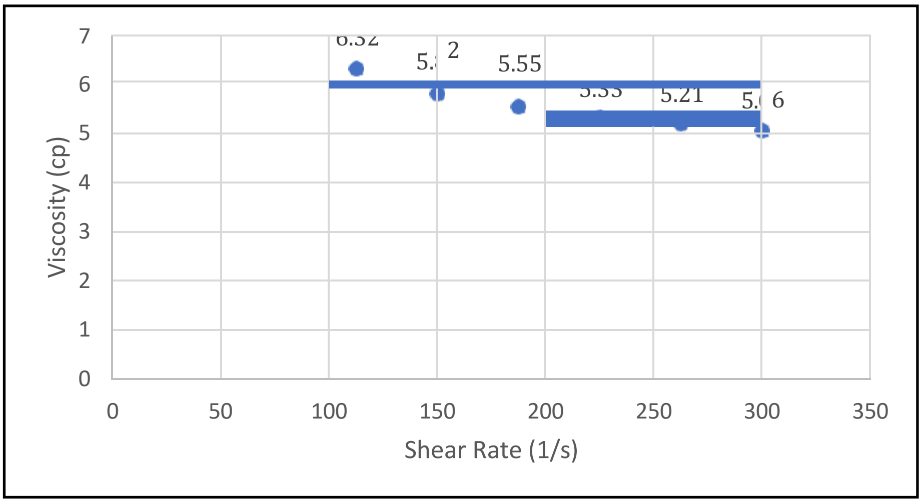

Figure 6. Polymer Solution Viscosity vs Shear Rate (1000 ppm)

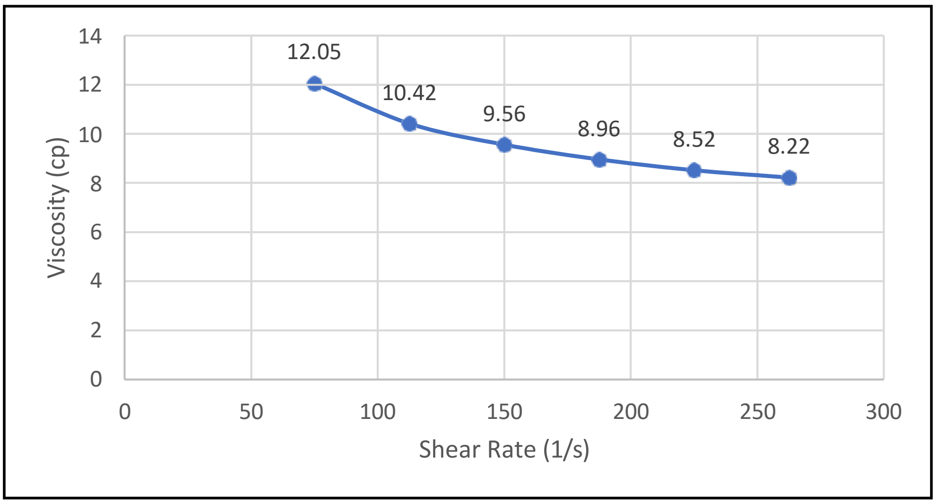

Figure 7. Polymer Solution Viscosity vs Shear Rate (1500 ppm)

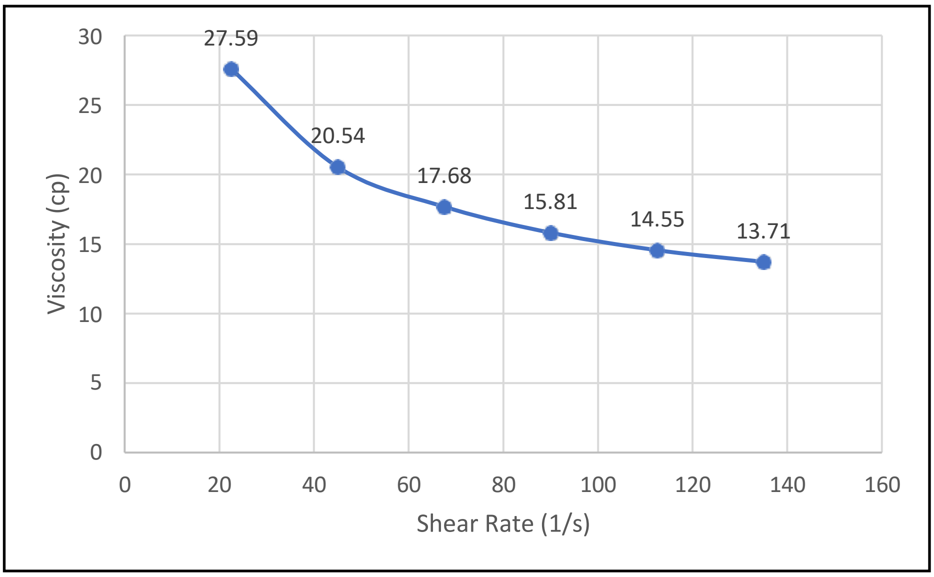

Figure 8. Polymer Solution Viscosity vs Shear Rate (2000 ppm)

Polymer Aqueous Stability

The result of aqueous stability test for seven days (one week) under temperature of 25°C and 60°C were shown in **Figure 9** and **Figure 10** respectively. According to **Figure 9** and **Figure 10**, it can be seen that FP3630S polymer has good stability at 25°C and 60°C which was indicated by no solid sediment was formed and the polymer solution still in a homogenous condition. This is a method for selecting a good candidate of polymer type that will be used for micromodel flooding test.

Figure 9. The Result of Polymer Aqueous Stability Test for Seventh-day at 25°C

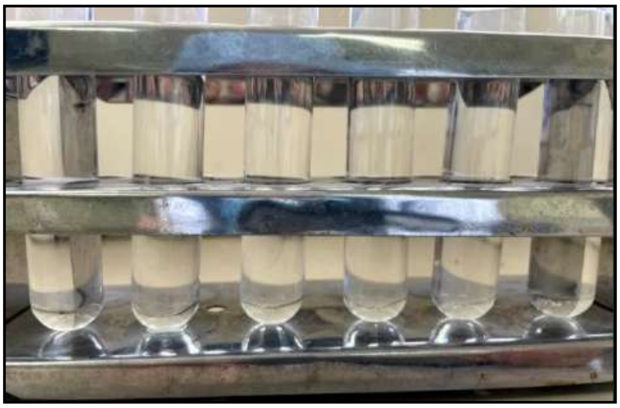

Figure 10. The Result of Polymer Aqueous Stability Test for Seventh-day at 60°C

Micromodel Flooding

In this micromodel flooding test, waterflooding was performed before each scenario as the preliminary flooding so that incremental recovery factor resulted by each polymer injection scenario could be compared to study the effect of polymer concentration on incremental oil recovery. The visualization of oil displacement mechanism in the homogenous micromodel for scenario 1, scenario 2 and scenario 3 were illustrated in **Figure 11**, **Figure 12** and **Figure 13**, respectively.

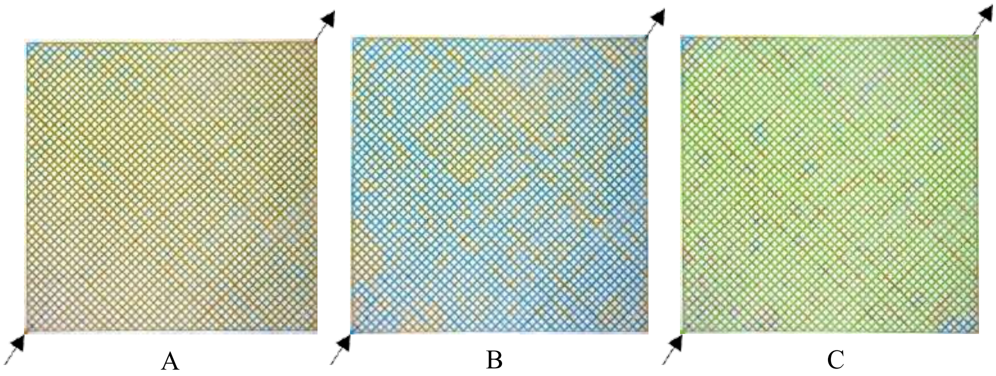

Figure 11. Visualization of Micromodel Flooding Test for Scenario 1
(A = Initial Condition, B = Waterflooding, C = 1000 ppm Polymer

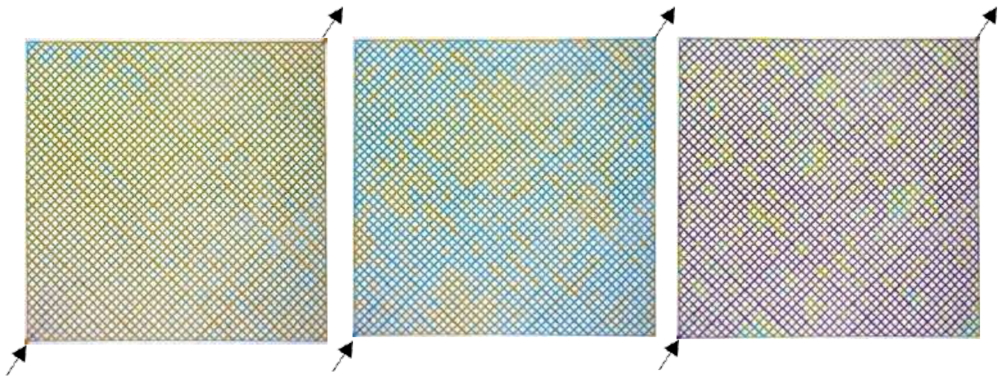

Figure 12. Visualization of Micromodel Flooding Test for Scenario 2
(A = Initial Condition, B = Waterflooding, C = 1500 ppm Polymer
Injection)

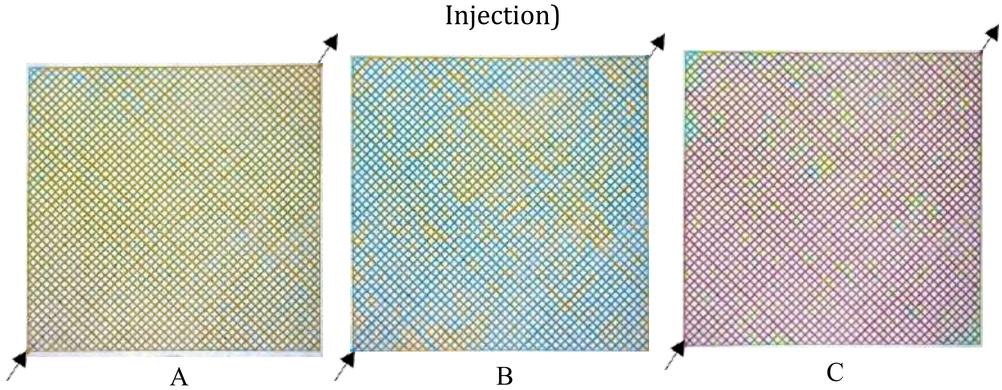

Figure 13. Visualization of Micromodel Flooding Test for Scenario 3
(A = Initial Condition, B = Waterflooding, C = 2000 ppm Polymer

According to the visualization of micromodel flooding result, after waterflooding process was performed it can be observed that there are still a lot of bypassed oil in the micromodel due to the unfavorable mobility ratio in the waterflood which resulting in viscous fingering problem that caused water breakthrough. But after the injection of polymer solution to the micromodel, it can be seen in the figures that the injected polymer solution could displace most of the remaining oil in the micromodel due to the mobility ratio could be remedied by the addition of polymer resulting in more piston-like oil displacement.

Figure 14 shows recovery value of waterflooding and polymer injection for each scenario at different pore volume injection. Based on **Figure 14**, it can be seen that after injection of 1 pore volume (PV) of synthetic brine there is no significant incremental oil recovery which indicates that the water breakthrough was already happened. Thus, the polymer solution with different concentration (1000 ppm, 1500 ppm and 2000 ppm) for each scenario was injected until 2.13 PV in which 3.28 PV in total for the injection of synthetic brine and polymer solution.

The graph of incremental recovery factor vs pore volume injected was shown by **Figure 15** and **Figure 16**. **Table 4** also displays the comparison of recovery factor generated by each scenario. Based on these results, it can be observed that the increasing of polymer concentration will give higher incremental oil recovery, therefore the injection of polymer solution with concentration of 2000 ppm has the highest incremental oil recovery compared to scenario 1 and scenario 2. In scenario 3, the injection of 2000 ppm polymer could enhance oil recovery factor by 15.61%OOIP and 48.42%ROIP. Obviously, scenario 1 (1000 ppm) will have the lowest incremental oil recovery factor among the other scenario. The difference of incremental recovery factor between scenario 3 and scenario 1 are 3.23%OOIP and 8.12%ROIP. The higher polymer concentration will give more favorable mobility ratio and has better flood front stability that can minimize the effect of viscous fingering therefore the oil displacement will be more piston-like which resulting in higher oil recovery.

Table 4. Oil Recovery Factor of Each Scenario

Concentration (ppm)	Waterflood RF (%)	Polymer Injection RF (%)	Incremental RF (%OOIP)	Incremental RF (%ROIP)
1000	69.29	81.67	12.38	40.31
1500	65.80	80.47	14.66	42.88
2000	67.76	83.37	15.61	48.42

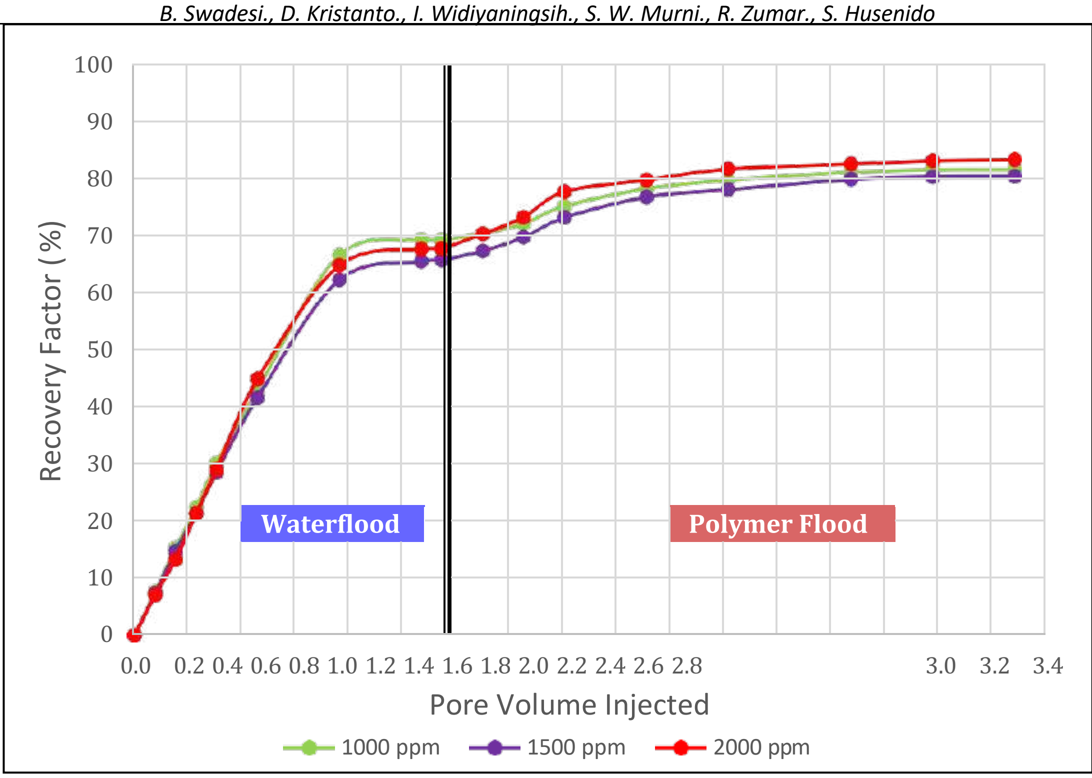

Figure 14. Recovery Factor% vs Pore Volume Injected of Each Scenario (injection rate = 0.05 cc/min)

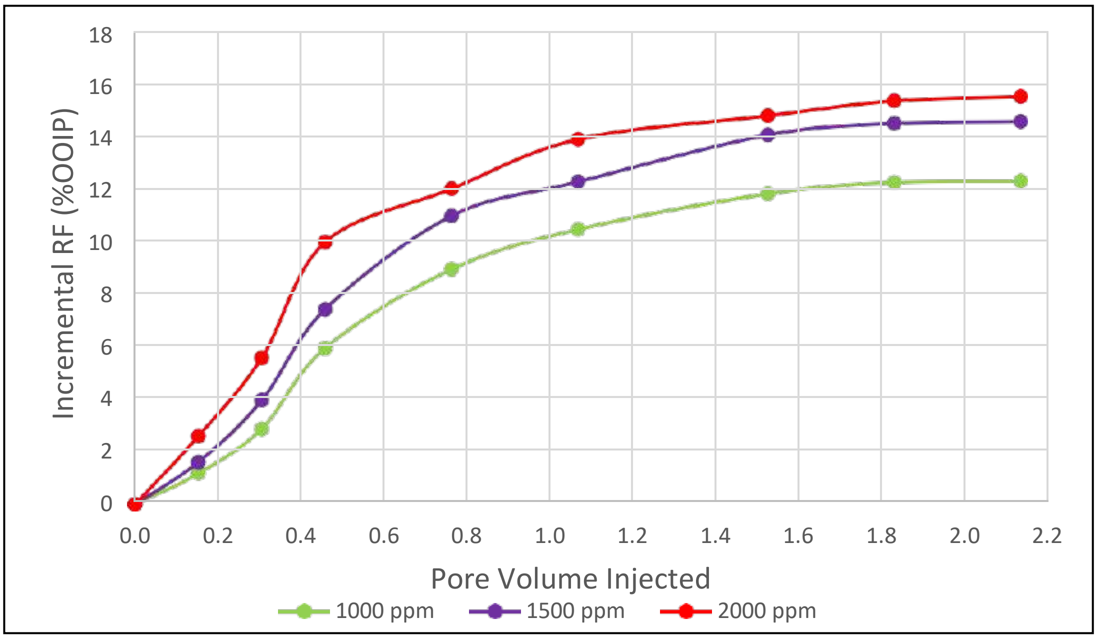

Figure 15. Incremental Recovery Factor (OOIP%) vs Pore Volume Injected of Each Scenario (injection rate = 0.05 cc/min)

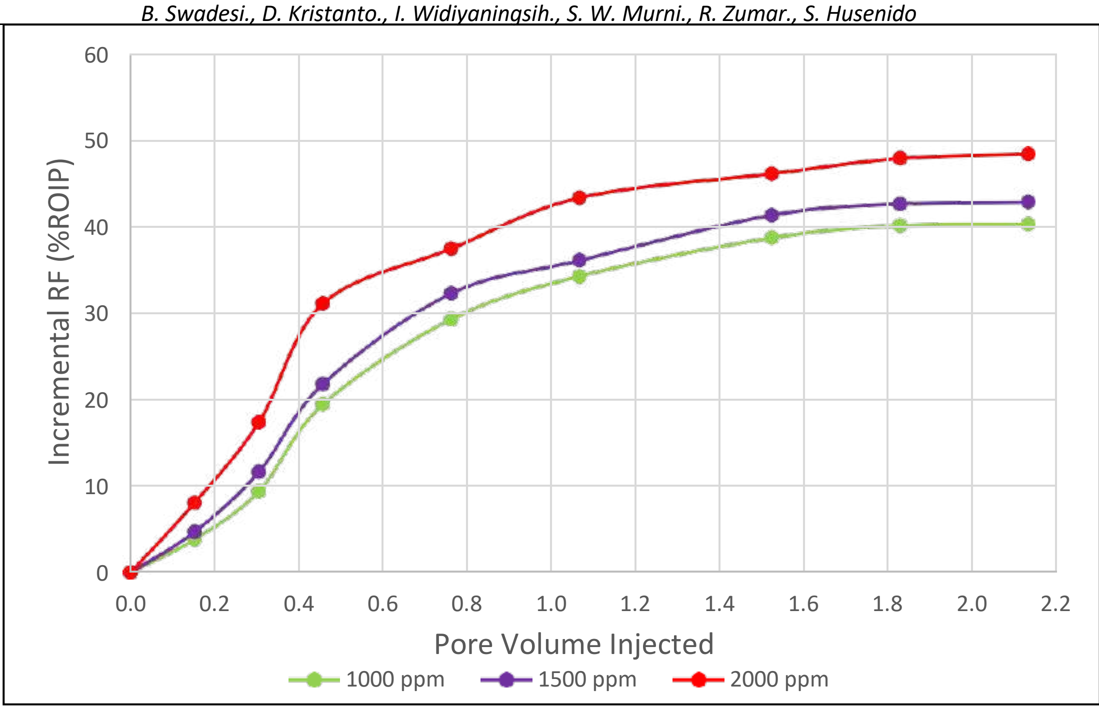

Figure 16. Incremental Recovery Factor (ROIP%) vs Pore Volume Injected of Each Scenario (injection rate = 0.05 cc/min)

CONCLUSION

Micromodel can be used as an alternative porous medium to represent the fluid flow behavior in a reservoir. Due to the transparency of a micromodel, the visualization of oil displacement mechanism can be obtained and analyzed by digital image analysis to determine the fluid saturation in a micromodel, therefore the recovery factor can be calculated based on fluid saturation data. The homogenous micromodel used in this study has a porosity of 45.24% with a pore volume of 0.656 cc and for the absolute permeability is 31.34 Darcy. Based on the polymer rheology test, it can be proven that polymer is non-newtonian fluid which is indicated by shear thinning or pseudoplastic behavior of FP3630S polymer. According to the aqueous stability test, it can be observed that FP3630S polymer solution has a good aqueous stability at 25°C and 60°C indicated by no solid sediment formed and the polymer solution is still in a homogenous condition. The results of micromodel flooding test show that the performance of polymer injection in enhancing oil recovery is affected by polymer concentration where an increase in polymer concentration will result in higher oil recovery due to the mobility ratio achieved will be more favorable and has better flood front stability that can minimize the effect of viscous fingering. Moreover, polymer injection can improve oil recovery significantly due to the polymer characteristic that can divert the fluid flow from zones that have been swept by the injected water to the unswept zone containing more oil. Therefore, various factors that can affect the performance of polymer injection such as polymer concentration must be taken into account before any polymer injection projects to obtain optimum result. This experimental study is conducted to show the application of micromodel for the understanding of enhanced oil recovery techniques (polymer injection) at pore scale visually and quantitatively.

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