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Experimental Study of Polymer Injection on Oil Recovery Factor Enhancement Using Homogenous and Heterogenous Micromodel Porous Media

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Abstract

Polymer injection is one method of chemical enhanced oil recovery, which increase oil recovery by improving mobility when viscous fingering occurred in waterflooding operation. The result of polymer injection is better sweep efficiency, which is presented by more even distribution of the injected fluid. However, in common laboratory evaluation for polymer injection testing, it was no visual observation that presents directly for the fluid distribution. This experimental study was carried out to visually observe the polymer injection mechanism to displace oil by micromodel as porous media. The micromodel used in this study is transparent acrylic material which was etched by laser engraving technology to create grains that resemble reservoir rocks. The micromodel was saturated by brine water and light oil respectively as initial reservoir fluids. Then, the water was injected as waterflooding operation to displace oil in a micromodel. Hydrolyzed Polyacrylamide (HPAM) polymer with various concentrations were injected into the micromodel as the last scenario. Through this experiment, the movement and distribution of fluids in chemical enhanced oil recovery especially polymer injection was able to be recorded for further analysis. Observation for each scenario was done by Digital Image Analysis (DIA). The micromodel flooding results showed that the higher concentration of polymer would give higher oil recovery. The front stability and good distribution of polymer will result in better sweep efficiency, then higher oil recovery will be achieved. This experiment gives result visually how polymer enhance oil recovery. This experiment is expected to be leading innovation for Enhanced Oil Recovery (EOR) laboratory studies in Indonesia.

INTRODUCTION

The laboratory test is an important step in assessing the performance of polymer injection. In making a plan pertaining to the implementation of a polymer injection project, an experimental study must first be conducted to test the performance of polymer injection on a laboratory scale, in order that we can obtain the most optimum polymer that is compatible with the reservoir condition, and then continued to the pilot test project. When this step proves to be economical, it can be applied on a larger scale in the field (Hosseini & Foroozesh, 2019).

A method that mostly used in the laboratory test to determine the optimum development option for an oil reservoir and evaluate the effect of injecting fluids is core flooding. This is specially designed to enhance oil recovery such as polymer, in which a core plug can represent the actual condition of the reservoir. However, having native core plug is not easy and requires high cost. Furthermore, core flooding is unable to visualize the flow behavior of the injected polymer in order to observe its displacing mechanism, while this

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experimental study of polymer injection requires clear and detailed visualization of the polymer injection performance through porous media, it is necessitating the use of transparent media to do the flow behavior observation (Hosseini & Foroozesh, 2019).

Micromodel is an artificial porous medium that can reflect the real condition of a reservoir to study the active recovery mechanisms during polymer injection and the effective parameters in oil recovery (Danesh et al., 1987). The whole process of the oil displacement mechanism can be closely monitored and captured by a camera due to the transparency of the micromodel (Hosseini & Foroozesh, 2019). As a result, it can be used to evaluate oil recovery by analyzing the process of polymer injection at the pore size using Digital Image Analysis (DIA) (Kenzhekhanov, 2016).

In this research work, 2D micromodel is used as the porous medium to study the fluid flow behavior and the effect of polymer concentration on incremental oil recovery factor. The homogeneous micromodel was made with polymethylmethacrylate (PMMA) material or also known as acrylic. In this study, high polymer concentration was used due to the injection of high concentration HPAM can further improve the recovery factor and reduce water cut significantly (Yang et al., 2006).

Literature Review

Polymer

Polymers are macromolecules made up of small repeated units called monomers that are structured like a chain (Jenkins, 2004). In general, synthetic polymers such as HPAM and biopolymers such as xanthan gum are commonly used type of polymer in the EOR process. HPAM is the most commonly used polymer in EOR applications (Manrique et al., 2007). As a polymer is added to water (brine), the solution's viscosity will increase. As a result, polymer injection will modify fractional flow and mobility ratio, and also causing fluid diversion. Therefore, polymer can assist in the reduction of viscous fingering effect and the improvement of water injection profile, resulting in better sweep efficiency (Buchgraber, 2008; Barati, 2011; Sorbie, 1991; Needham & Doe, 1987; Chang, 1978). Each type of polymer has advantages and drawbacks due to its distinctive characteristics. Synthetic polymers have many benefits, including a low cost, sufficient viscosity when used with fresh water, and suitable adsorption on the rock surface (low adsorption). This type of polymer, on the other hand, is sensitive to flow rate and shear degradation. In high-salinity water, it also has a poor efficiency. Meanwhile, the type of biopolymer shows higher resistance to high salinity water and shear degradation, but it is sensitive to bacterial degradation at low reservoir temperatures (Sheng, 2013; Sheng et al., 2015; Buchgraber, 2008; Barati, 2011)).

The polymer injection has been effective in most cases. An additional average recovery has been reported about 7%. The majority of formations injected with polymer have been sandstone rocks (Clampitt & Reid, 1975; Lozanski & Martin, 1970; Shaw & Stright, 1977; Rowalt, 1973).

Micromodel

The oil displacement process at the pore scale is visualized using a micromodel, which is an artificial device. Micromodel visualizes the flow behavior of injected fluid in order to study and analyze the fluid injection profile, which is impossible to do with the core flooding method (Bou-Mikael, 2012). The injected fluid in this case is polymer. The micromodel with a two-dimensional design (2D Micromodel) that has homogeneous or heterogenous characteristic is a common option for the study of polymer injection.

Many researchers had made micromodels using different technique and material. Recently, photo-etching techniques on glass, silicon, or polymer materials are commonly used to manufacture micromodels. The material used to manufacture a micromodel is determined by the study's objectives, with each material having its own advantages and disadvantages (Javadpour & Fisher, 2008). Micromodels have been a vital tool in the EOR applications because they could provide visualization of fluid flow behavior at pore scale that may be captured for qualitative observation, quantitative analysis, and simulation studies (Aadland et al., 2020). The distribution of phases in micromodels can be observed using (confocal) microscopes, digital cameras, or their combination. Micromodels have been employed to analyze two-phase displacement processes, fluid–fluid interfacial area and phase saturation measurements, relative permeability measurements, and enhanced oil recovery studies (Karadimitriou & Hassanizadeh, 2012). Chatenever & Calhoun, (1952) conducted one of the first micromodels study to investigate micro scale mechanisms of fluid flow in porous media. Since then, micromodels have been used to investigate a wide range of two-phase flow processes and applications. Sugar, Torrealba, et al., (2020) utilized a polydimethylsiloxane (PDMS) micromodel to investigate the mechanism of polymer retention (adsorption, mechanical entrapment, and hydrodynamic retention) in porous media. Soft-lithography method was used to fabricate the micromodel (Sugar, Torrealba, et al., 2020). In different research work, Sugar, Serag, et al., (2020) also conducted an experiment by using a micromodel as the porous media to evaluate the formation damage induced by polymer flood, in which the micromodel was made with polymethyl methacrylate

(PMMA) or acrylic material by using dry-etching method to construct the flow pattern (Sugar, Serag, et al., 2020).

The challenge in using a micromodel derives from the manufacturing process, because it is difficult to create a micromodel with the characteristics that can represent the actual reservoir conditions accurately. Many micromodels with various pore patterns have been made, and each has its own set of advantages and drawbacks. Figure 1 shows several types of micromodels created by researchers.

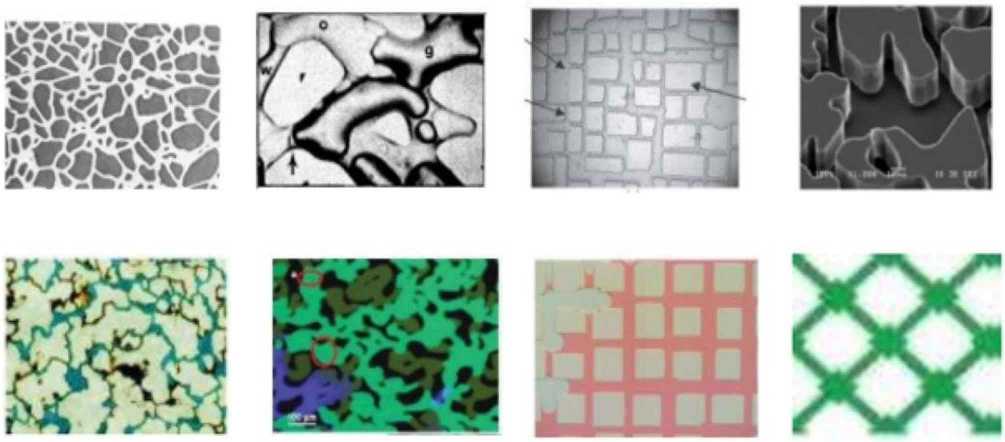

Figure 1. Micromodel Pore Patterns
(Source: (Hosseini & Foroozesh, 2019)

METHODS

The laboratory tests have been performed on purpose for observing the properties of both polymer and micromodel. Polymer used in this experiment is HPAM polymer, which has powder form before solved. The micromodel was built by acrylic laser cutting method, which in this research the micromodel was provided by the vendor. Therefore, the micromodel was bought from the vendor and ready to be tested.

Micromodel Manufacturing

The homogeneous micromodel was designed with perfectly regular geometry model which the pore has a square shaped, thus the micromodel would have homogenous flow pattern. Polymethylmethacrylate usually known as acrylic was used as the material to fabricate the micromodel. Soft material such as PMMA is suitable for making inexpensive micromodels fast. PMMA is a good substitute for glass which the surface is slightly hydrophobic but it can be treated by using oxygen plasma to get water wet medium. 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 acrylic plate with flow pattern on the surface was covered by another acrylic plate. High temperature (175°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.

Polymer Rheology Test

This laboratory test records the polymer rheology properties. Polymer product used in this experiment is FP3630S as HPAM polymer. The test is including polymer viscosity measurement in various shear rate and concentrations. The instrument used in this test is Viscometer Brookfield LVDV3T with Spindle CV40. The principle of this instrument is measuring the resistance of fluids for various shear rate based on torque occurred. It gives result shown by Figure 2 as properties of FP3630S polymer for various concentrations. This result was used as a benchmark for polymer concentrations injected in a micromodel.

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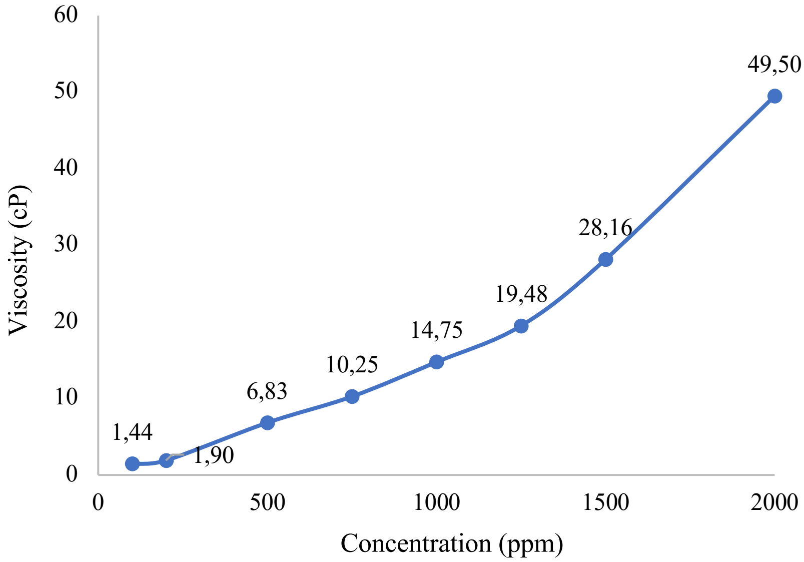

Figure 2. Properties of FP360S Polymer at 25°C (shear rate: 7 1/s)

Polymer Aqueous Stability Test

The aqueous stability testing was performed to observe the endurance of polymer fluids in a certain range of times and temperatures. Polymer should be categorized in good stability, which had no solid sediment during the testing. Aqueous stability test was carried out by observing polymer solution to investigate polymer form solid sediment or not. In this test, the FP3630S polymer was observed in the range of concentrations 100 ppm to 2,000 ppm. The testing was run at temperature 25^{0}C and 60^{0}C for 7 days. The results obtained from this testing is shown by Figure 3 and Figure 4. It can be seen that FP3630S polymer has good stability at 25^{0}C and 60^{0}C indicated by no solid sediment formed. This is a method for selecting polymer as FP3630S is a good candidate polymer for the micromodel flooding test.

Figure 3. Aqueous Stability Result for Seventh-day at 25^{o}C

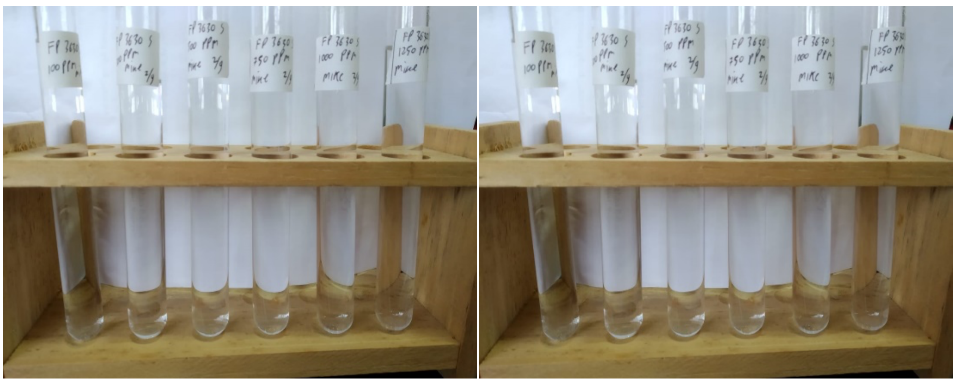

Figure 4. Aqueous Stability Result for Seventh-day at 60^{o}C

Micromodel Flooding Test

The micromodel flooding test was conducted in the order shown in Figure 5. The first step is preparing the micromodel to be ready for injection. The preparation has a purpose to setting-up injectivity tools and micromodel recording equipment. The injectivity tool includes a syringe pump and making the connection for the inlet and outlet. The micromodel recording equipment has two components, namely light source and camera. An overview of the micromodel set-up is shown in Figure 6. Micromodel in Figure 7 was ready to be set in injectivity equipment for flooding test.

The next step of the micromodel flooding test is saturation. 10,000 ppm NaCl brine water was injected into a model to represent the imbibition process in the actual reservoir rock. Therefore, the model was saturated by brine water, and the micromodel pore volume could be obtained (0.46 cc). Further saturation is carried out by injecting light oil (43.278 ^{o}API) as saturating fluid other than the water. The fluids properties and micromodel's characteristic are shown in Table 1 and Table 2, respectively. The residual water saturation was occurred as the irreducible water where there is still some amount of water that could not be displaced by the oil. The next step is waterflooding and polymer injection scenario. Waterflooding step was carried out to represent the visual observation of waterflooding operation in a model. Furthermore, the last scenario is the injection of polymer solution into a model by various concentrations (1,000 ppm and 2,000 ppm). Every step of micromodel flooding test was recorded by the camera to get images of each scenario. Each type of fluids has been coloured to do observation by DIA.

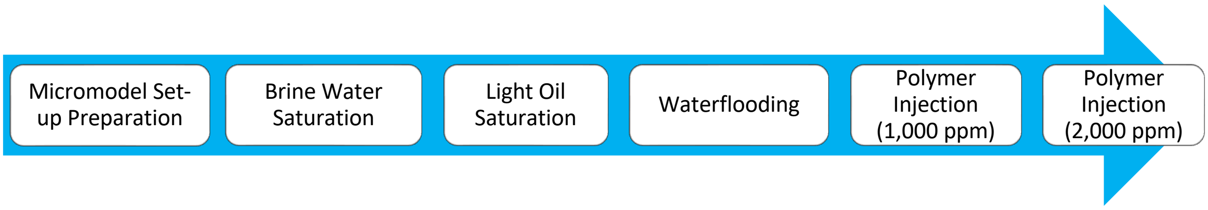

Figure 5. Steps of Micromodel Flooding Test

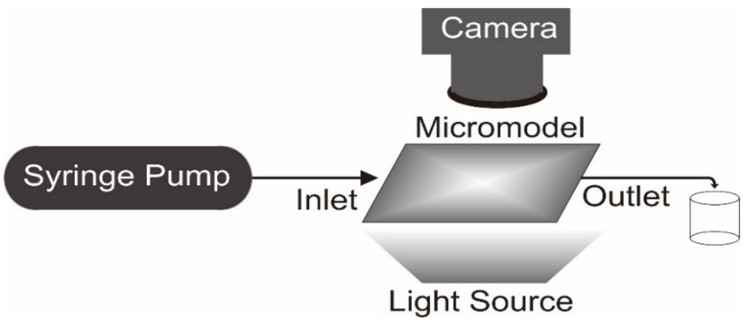

Figure 6. Scheme of Micromodel Injectivity Equipment Set-up

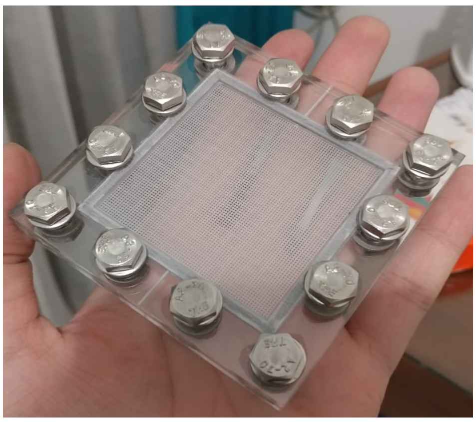

Figure 7. Micromodel Used in Experiment

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Table 1. Fluids Poperties

Sample oil properties (T = 25 °C)		
Specific Gravity	API	Viscosity, cP
0.81	43.3 °API	2.15
Synthetic brine properties		
Composition	Molecular Weight, g/mol	Concentration, PPM
NaCl	58.4	10,000

Table 2. Micromodel Characteristics

Homogenous Micromodel	
Length, mm	50
Width, mm	50
Etching Depth, mm	0.58
Pore Size, mm	0.17
Grain Size, mm	1
Bulk Volume, cc	1.45
Grain Volume, cc	0.99
Pore Volume, cc	0.46
Porosity, %	58.62
Absolute Permeability, D	31.34

RESULTS AND DISCUSSION

Oil Saturation

The micromodel was saturated by brine water as the initial fluid. It represents reservoir condition which the first fluid contained in a reservoir rock is brine water. Then, the oil was injected into micromodel to represent oil migration process in a reservoir. It gives result residual water saturation which was not movable by oil imbibition process.

Figure 8 shows micromodel image for oil saturation process (Inlet is on the bottom and outlet is on the top. Flow direction is from bottom to top). Blue colour is brine water, and the yellowish-brown colour is light oil. There is residual water saturation on the edges of micromodel as blue colour. Light oil dominates in micromodel saturation. Based on DIA, saturation of each fluids was calculated. Light oil has saturation 40.25% as dominant fluid, residual water saturation was 19.5% and air (gas) has saturation 40.25%. According to the result of saturation process, it can be seen that the injected brine could not fully displace the air (gas) in the model so that the remaining gas saturation is still high. It represents reservoir condition in which the actual saturation, there were three types of fluid namely oil, water and gas.

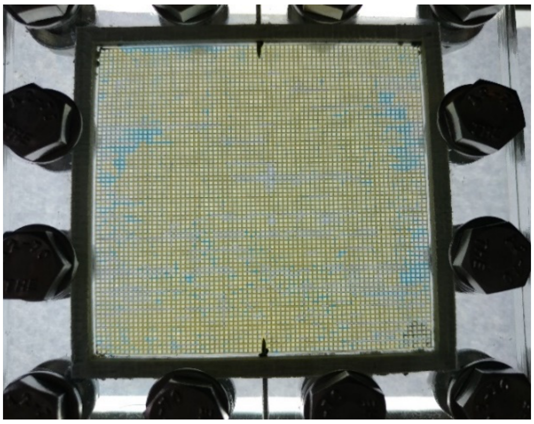

Figure 8. Captured Micromodel Image for Oil Saturation

Table 3. Fluid Saturation at Initial Condition

Fluid Type	Fluid Saturation, %
Oil	40.25
Water	19.5
Gas	40.25

Waterflooding

The waterflooding scenario was carried out to observe the behavior of water flow direction in order to displace oil. Figure 9 shows the result of waterflooding scenario in micromodel (Inlet is on the bottom and outlet is on the top. Flow direction is from bottom to top). DIA gives result for oil saturation became 13.82%, water saturation was 50.4% and gas saturation was 35.78%. This result represents decreasing of oil saturation and increasing of water saturation. Flow direction of injected water which has been recorded, shows the viscous fingering of waterflooding operation. It is indicated by uneven distribution of injected water. There was unswept zone of oil saturation.

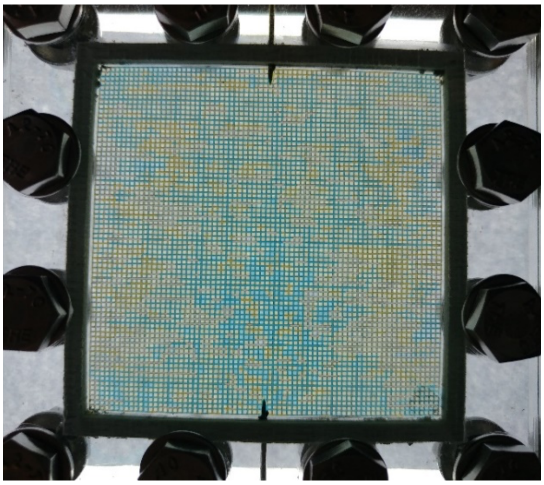

Figure 9. Captured Micromodel Image for Waterflooding

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Table 4. Fluid Saturation after Waterflooding

Fluid Type	Fluid Saturation, %
Oil	13.82
Water	50.4
Gas	35.78

Polymer Injection

The main scenario of this experiment is polymer injection. Firstly, this scenario was done by 1,000 ppm polymer solution. The second section of polymer injection was run by 2,000 ppm polymer solution. Polymer injection scenario has purpose to observe the flow direction of polymer to displace oil as tertiary recovery stage of oil production. This scenario gives visual result on how polymer displace oil by improving sweep efficiency to recover waterflooding viscous fingering.

Figure 10 represents the 1,000 ppm polymer injection. Red colour fluid is 1,000 ppm polymer which had been injected into micromodel. Image was analysed by DIA to calculate saturation of each fluids. The result obtained is micromodel was saturated by 12.23% of oil, 17.22% of water, 19.97% of gas and 50.58% of 1,000 ppm polymer. The oil saturation was reduced from 13.82% (waterflooding) to 12.23%. It indicates that polymer injection gives incremental oil production based on reduction of oil saturation. Qualitatively, it can be seen that injected polymer has more even distribution than waterflooding.

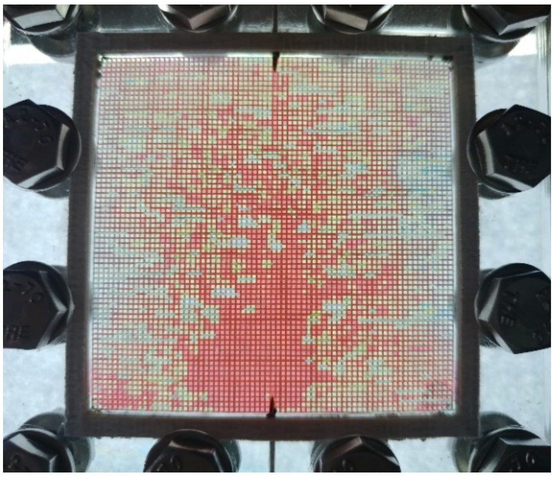

Figure 10. Captured Micromodel Image for 1,000 ppm Polymer Injection

Table 5. Fluid Saturation after Polymer Injection (1,000 ppm)

Fluid Type	Fluid Saturation, %
Oil	12.23
Water	17.22
Gas	19.97
Polymer	50.58

Figure 11 represents the 2,000 ppm polymer injection. Green colour fluid is 2,000 ppm polymer. DIA gives result that residual oil saturation by 2,000 ppm polymer injection is 7.02%. The other fluids have saturation of water 9.83%; gas 14.97%; 1,000 ppm polymer 8.91% and 2,000 ppm polymer 59.27%. It represents that higher concentration of polymer would give higher oil recovery. The residual oil saturation was reduced from 12.23% (1,000 ppm polymer) to 7.02%. Visually, 2,000 ppm polymer injection gives improvement in sweep efficiency indicated by more even distribution compared to 1,000 ppm polymer. Viscoelasticity of a HPAM polymer could play an important role in reducing residual oil saturation, which is not reported in classic Capillary Desaturation Curve (CDC). The capillary number itself can be contributed from several factors such as increasing velocity, reducing Interfacial Tension (IFT) or alter wettability and increasing displacing fluid viscosity (Hakiki et al., 2017). In this case, the effect of polymer concentration on incremental oil recovery is observed. Based on the micromodel flooding results, it can be concluded that the higher concentration would provide better sweep efficiency due to more favorable mobility ratio which resulting in higher oil recovery factor. In other words, the increasing of polymer concentration could improve capillary number indicated by the decreasing of residual oil saturation where the injection of polymer with higher concentration could decrease residual oil saturation more significant.

Overall, this experiment gives visual observation of the polymer injection scenario. The analysis was done by DIA to ensure that the polymer works by reducing residual oil saturation. Qualitative analysis could be done by investigating captured images to analyse the distribution of fluids.

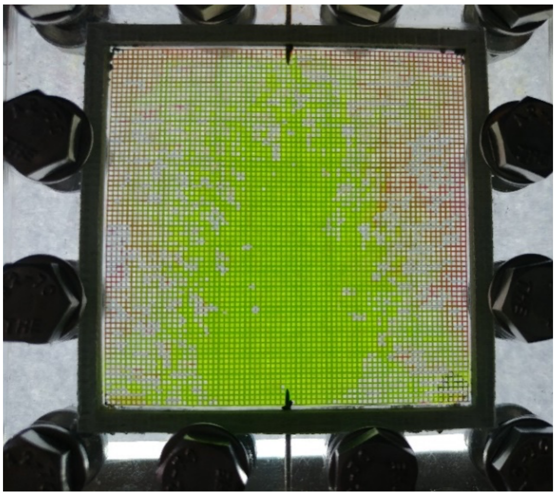

Figure 11. Captured Micromodel Image for 2,000 ppm Polymer Injection

Table 6. Fluid Saturation after Polymer Injection (2,000 ppm)

Fluid Type	**Fluid Saturation, %**
Oil	7.02
Brine	9.83
Gas	14.97
Polymer (1,000 ppm)	8.91
Polymer (2,000 ppm)	59.27

CONCLUSIONS

Based on the experimental study of poymer injection in micromodel that has been conducted, it can be concluded as follows:

- Different scenarios were performed to compare and observe the oil recovery obtained from waterflooding process and polymer injection with different concentrations.
- The result from the micromodel flooding test shows that waterflooding could displace oil in the micromodel until the oil saturation became 13.82% from 40.25% (initial condition) and for polymer injection with a concentration of 1,000 ppm could give incremental oil recovery that can be indicated from the reduction of oil saturation from 13.82% (waterflooding) to 12,23% (1,000 ppm polymer injection).
- The incremental oil recovery obtained from polymer injection indicates that polymer injection has better sweep efficiency compared with waterflooding due to front stability and the reduction of viscous fingering effect. Therefore, polymers were used to overcome the viscous fingering problem occurred in the waterflooding process.
- The last scenario was injecting polymer with a concentration of 2,000 ppm, in which the residual oil saturation was reduced from 12.23% (1,000 ppm polymer injection) to 7.02% (2,000 ppm polymer injection). It can be concluded that the higher concentration of polymer would give higher oil recovery. Thus, front stability and good distribution of polymer will result in better sweep efficiency, then higher oil recovery will be achieved.

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