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Victor	Torrealba	King Abdullah University of Science & Technology
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Abstract

Polymers have been successfully deployed in the oil&gas industry in various field implementations, including mobility control in waterflood, flow divergence, and well conformance control. However, lab and field applications of polymer injections often encounter polymer-induced formation damage related to pore-throat clogging from polymer entrapments, leading to permeability reduction. This phenomenon manifests as a loss of injectivity, which can diminish the recovery performance. The first principles of polymer interaction with porous rocks are poorly understood. In this work, we use microfluidics to assess formation damage induced by polymer flood. Microfluidic techniques offer convenient tools to observe polymer flow behavior and transport mechanisms through porous media. The microfluidic chips were designed to mimic the pore-size distribution of oil-bearing conventional reservoir rocks, with pore-throats ranging from 1 to 10 μm . The proposed fabrication techniques enabled us to transfer the design onto a silicon wafer substrate, through photolithography. The constructed microfluidic chip, conceptually known as “Reservoir-on-a-Chip”, served as a two-dimensional flow proxy. With this technique, we overcome the inherent complexity of the three-dimensional aspects of porous rocks to study the transport mechanisms occurring at the pore-scale. We performed various experiments to assess the mechanisms of polymer-rock interaction. The polymer flow behavior was compared to that of the water-flood baseline. Our observations showed that prolonged injection of polymer solutions could clog pore-throats of sizes larger than the measured mean polymer-coil size, which is consistent with lab and field observations. This finding highlights a major limitation in some polymer screening workflows in the industry that suggest selecting the candidate polymers based solely on their molecular size and the size distribution of the rock pore-throats. This work emphasizes the need for careful core-flood experiments to assess polymer entrapment mechanisms and their implication on short- and long-term injectivity.

Introduction

Water injection into subsurface rocks is a common technique for oil recovery. However, the displacement efficiency of waterflood is limited when the mobility ratio is larger than one (Aronofsky, 1952; Aronofsky & Ramey, 1956; Dyes et al., 1954). This problem manifests in reservoirs with a high viscosity oil, a preferentially hydrophilic rock, or heterogeneous layered systems with high contrast in permeabilities. One effective solution to decrease the displacement mobility ratio (i.e., the ratio between the mobility of

the displacing fluid to that of the displaced fluid) is to add polymers to the injection water to increase its phase viscosity (AlSofi et al., 2019; L. Lake et al., 2014). The first principles of polymer interaction with reservoir rocks are not well understood. They are typically inferred indirectly in lab experiments from the measured injection pressure and the effluent compositions. These indirect measurements can capture the response of the polymer interaction with the rock at the injection and production points but are not fit to assess the polymer/rock interaction mechanisms at the pore-scale. Microfluidic experiments are suitable to capture the dynamic processes taking place at the pore-scale under high throughput conditions. The fabricated micromodels should honor the representative dimensions at the pore-scale, including the pore-throat sizes and the nature of rock porosities with variable pore-size distributions. The heterogeneity in the pore-throats introduces other mechanisms related to inaccessible pore-volume (IPV) for polymer and permeability reduction (Hoteit et al., 2016; L. W. Lake, 1989; Lotfollahi et al., 2016; Seright et al., 2009). The IPV may alter the flow tortuosity and pathways of the polymer molecules compared to other tracers, such as salt, resulting in compositional segregations and different breakthrough times (Dominguez & Willhite, 1977; Pancharoen et al., 2010; Santoso et al., 2020; V. A. Torrealba & Hoteit, 2019).

Polymer flooding is a conceptually simple process; however, its implementation at the field scale can be challenging. One of the key hurdles for a successful implementation is to prevent polymer plugging of the formation near the injector wellbore, which may result in a continuous loss of injectivity. For instance, East Coalinga experienced wellbore impairment and injectivity degradation during field tests using biopolymers (Tinker et al., 1976). Pembina experienced injectivity degradation after a polymer pilot using a commercial partially hydrolyzed polyacrylamide polymer (Groeneveld et al., 1977). Shannon reservoir showed a distinct injectivity alteration as a response of the polymer system injected, emphasizing the need for a rigorous understanding of the polymer-rock interactions at the injection well (Doll, 1984). The polymer injectivity at West Coyote was below expectations owing to formation damage, which was later resolved by selecting a lower molecular weight polymer (Shuler et al., 1987). Polymer injection tests at White Castle Q Sand, which is a 2000md-reservoir, did not experience significant injectivity degradation under dilute conditions (Shahin & Thigpen, 1996). Laboratory experiments confirmed the existence of plugging behavior beyond a critical injection rate. A single-well injection/back-production implementation of polymer flooding showed important discrepancies in the polymer retention in the reservoir compared to laboratory tests using crushed material samples and coreflood samples (Juri et al., 2015). Polymer injection tests at the Bhagyam field experienced a steady increase in the injection pressure, possibly due to wellbore plugging (Kaladhar Sharma et al., 2016). Acid stimulation was used to revert the damage, though the injectivity deteriorated further with a continued polymer injection. The results from a biopolymer injection pilot test in Germany also showed a decrease in injectivity with time, which was attributed to sand-face plugging (Behr & Rafiee, 2017). Complex functional polymers have been used recently for an inter-well field trial showing good injectivity behavior since the injection viscosity is similar to that of water (Rashid et al., 2018). The increase in injection pressure showed to be beneficial in inducing fractures in the near-wellbore region, which translates into a higher effective wellbore area that allows for an improved injectivity profile (Song et al., 2018).

Numerous studies have been conducted to understand the transport behavior of polymers through porous media. Many researchers investigated the effect of injection rate on polymer retention in porous media, such as sandstone, carbonate cores, gravel, and beads packs (Al-Shakry et al., 2018; Han et al., 2012; Southwick & Manke, 1988). At high rates, such as those encountered in the near-wellbore region, polymer chains may mechanically degrade and break, causing a reduction in the viscosity of the polymer solution (Seright, 2017; Seright et al., 2009). Permeability is a critical parameter that controls the resistance factor of the polymer solution, which emphasizes the need to consider physically representative pore-throat sizes. Other studies focused on the factors that control polymer injectivity, showing that injection water quality and composition are critical parameters (AlSofi et al., 2018; Fletcher et al., 1992). Also, polymer injectivity was found to be a function of pore-volumes injected, with incremental degradation occurring with the continued injection of polymer solutions (Fletcher et al., 1992; Seright et al., 2009). This point highlights the need to conduct high throughput polymer injection studies. Another objective of

experimental studies is to assess polymer retention using representative conditions to the field of interest (Noik et al., 1994).

One key limitation of coreflood tests is that it is not intuitive how to differentiate between polymer adsorption on the rock and flow-induced polymer retention, which is typically a function of the complex topology of the reservoir rocks. Microfluidic experiments can aid in the understanding of such behavior by simplifying the pore geometry while capturing the fundamental mechanisms of polymer-rock interaction. Microfluidic experiments can be designed such that water injection is resumed after the injection of polymer (Hincapie & Ganzer, 2015). For these cases, the water injectivity is lower than that prior to the injection of polymer; a phenomenon known as the residual resistance factor (RRF). This mechanism reflects an irreversible component of polymer retention in the rock. Further, injection flow regimes may have an effect on polymer injectivity. For example, there is pronounced polymer injectivity difference between linear corefloods and cylindrical corefloods for similar injection rates and polymer solution properties, where linear conditions were found to create higher polymer injectivity degradation (Skauge et al., 2016). On the other hand, there are other utilization of polymers where plugging is the sole objective of the polymer injection (Bryant et al., 1997). In such applications, the polymer is used to shut off high conductivity layers that have been swept by the injection fluid.

Microfluidics experiments have been increasingly used in recent years to assess fluid displacement processes in the subsurface (Fan et al., 2018; Gogoi & Gogoi, 2019; Lifton, 2016; Song et al., 2018; Sugar et al., 2020; V. Torrealba et al., 2019; Wegner & Ganzer, 2017). Studies have looked at the displacement of oil by both water and polymer solutions using geometrical characteristics that resemble a sandstone thin-section, with grain sizes ranging from 50 to 300 μm (Buchgraber et al., 2011). A fabrication-centric study showed a workflow for creating representative reservoir-on-a-chip models based on mapping real 3D pore-structures to 2D networks (Kumar Gunda et al., 2011). Experiments using a commercial chip assessed rheological characteristics of various polymer solutions for porous media applications (Dupas et al., 2013). Experiments on chips with a pronounced permeability contrast, controlled by changing the corresponding pore-throat sizes, showed the effectiveness of foam injection in improving sweep efficiency (Conn et al., 2014). Studies on micromodels composed of 40 μm -cylindrical pillars with pore-throats of 10 μm showed micro-gel polymer retention in the center of pores (W. Yun & Kovscek, 2015). A micro-to-nano dual-scale workflow for the fabrication of chips with dimensions relevant to tight and fractured rocks was presented by (Kelly et al., 2016). Recent studies on the flow instabilities of viscoelastic polymer solutions emphasized the importance of channel dimensions, even in the case of large channels with 34 μm and 68 μm widths. A workflow for dual-porosity and dual-depth media emphasized the importance of considering the duality in porosity to capture representative flow mechanisms that correspond to those of in the subsurface rocks (Wonjin Yun et al., 2017).

Another essential need for laboratory tests is to elucidate the high throughput behavior of polymer solutions. While at the reservoir scale, processes are designed to be in the order of one pore-volume injected (PVI), the near-wellbore region will effectively encounter a much larger PVI. Therefore, laboratory screening programs should incorporate such extended polymer injection tests (Alexis et al., 2016; Alfazazi et al., 2019; Dwarakanath et al., 2016). While at the coreflood scale, this can be a limitation, here, we show that microfluidics can be used for such high throughput tests. To the best of our knowledge, this is the first time a variable-porosity microfluidics device with representative pore-throat sizes has been used to assess the entrapment of polymer solutions. Our objective is to present an approach that can be used for polymer compatibility screening under extended injection conditions that can reduce the risk of polymer injectivity impairment at the field scale.

The paper is organized as follows: we first introduce the microfluidic device design and fabrication workflow. Then, we briefly describe the fluid characteristics, the experimental setup used for the flow experiments, and the image processing. The results are then discussed, where we describe the used approach for direct visualization of pore-clogging caused by the polymer solution. The last part of the paper focuses on the '*shadowing effect*' created by fine features, characterized by 1 μm pore-throats size,

and its impact on the neighboring downstream area of the coarse features, characterized by $10\mu\text{m}$ pore-throats size. We conclude the paper by summarizing the findings.

Materials and methods

In this section, we describe all relevant materials and methods used in the study.

Microfluidic device design and fabrication

Microfluidic chips serve as a two-dimensional proxy to avoid the complexity of the three-dimensional porous network in rocks, which facilitate isolating and visualizing the mechanisms of interest that occur at the pore-scale. We designed the configuration of a 2D pore-structure micromodel to mimic key features related to the heterogeneous nature of rock pore-throats. We defined a hypothetical rock pore-throat distribution where the large throats are within $10\mu\text{m}$, and the small throats are $1\mu\text{m}$, as shown in Figure 1. The dimensions mimic the pore-size distribution of oil-bearing conventional reservoir rocks (Browne et al., 2019; Gundogar et al., 2016).

Figure 1: Overview of the microfluidic chip, with an area of 2cm^2 for the porous medium. The top-right area shows an enlarged image of the heterogeneous structure of the porous medium, designed to include fine features with $1\mu\text{m}$ pore-throats and coarse features with $10\mu\text{m}$ pore-throats. The pore-throats are defined to be the corner-to-corner distance.

Figure 2 shows the overall workflow of the fabrication protocol used in this study. We transferred the microfluidics chip design on a 5in -chrome mask using a DWL 2000 laser lithography system. We then proceeded to the photolithography step using the AZ ECI 3027 positive photoresist, with the spin parameters such that we obtained a $4\mu\text{m}$ resist thickness on a 4in silicon wafer. The mask alignment and exposure were done with an EVG6200 Contact Aligner system. We performed deep reactive ion etching using a PlasmaLab100 system at a temperature of 10°C . We did a total of 100 cycles of sequential SF_6 etching and C_4F_8 passivation steps, with times of 7s and 5s, respectively. The etched wafer was anodically bonded to a borosilicate 4in -glass wafer using an EVG 520IS bonding tool and then diced using a diamond blade.

Figure 2: General description of the fabrication workflow used to build the microfluidic chips with variable-sized features to mimic the heterogeneous nature of porous rocks.

Figure 3 shows the scanning electron microscope (SEM) image of a small section of the chip centered around one set of fine features. We used the Teneo field emission scanning electron microscope, and the relevant scanning parameters are listed at the bottom of the figure. From SEM, we measured an etched-depth of $36\mu\text{m}$ around the fine features and $37\mu\text{m}$ around the coarse features.

Figure 3: Scanning electron microscope image showing variable-sized features in the micromodel chip. The image confirmed that the etching depth near the fine features is around $36\mu\text{m}$, and near the coarse features is around $37\mu\text{m}$, as designed.

Fluid characterization

For the water injection experiments, we mixed 100ml of distilled water solution with one droplet (0.05ml) of dyed red aqueous fluorescent microsphere beads. For the polymer injection experiments, we prepared solutions with 100ppm of high molecular weight (20MDa) partially hydrolyzed polyacrylamide synthetic polymer, following the standard protocol recommended by the manufacturing company. For the imaging step of the polymer injection, we mixed 100ml of the polymer solution with one droplet (0.05ml) of the fluorescent beads.

Figure 4 shows the measured particle size distribution of the fluorescent beads and the polymer chains using the Zetasizer Nano-ZS dynamic light scattering instrument. The size distribution of the

fluorescent beads was centered around 400nm, with the sizes of the smallest and largest fluorescent particles were around 300nm and 600nm, respectively. The size distribution of the polymer coils was centered around 2 μ m, and the smallest and largest polymer coils were measured at around 800nm and 5 μ m, respectively. Based on these size distributions, we note that the fluorescent beads are smaller than both the designed small and large pore-throats of the micromodel, and therefore they should be accessible to the entire pore-volume. Most polymer coils have lengths larger than the small pore-throats, while all coils have smaller lengths than the large pore-throats.

Figure 4: Dynamic light scattering characterization of the fluorescent bead particles and the partially hydrolyzed polyacrylamide polymer. The mean diameter of the beads is 400nm, and the mean polymer coil length is 2000nm.

Experimental setup

The inlet and outlet holes for fluid flow in the micromodel were laser-drilled in between the photolithography and the dry etching steps, where a PLS6MW 40W Ytterbium fiber laser was used. We fabricated the chip holder by laser cutting different 1mm layers of poly (methyl methacrylate) with a VLS 3.50 30W CO₂ laser, and carefully bonded them together using small volumes of chloroform. We secured two metallic tubes with 2mm outer diameter to facilitate the flow into and out of the chip. For all flow experiments, we connected a syringe pump to the inlet port and a fluid collection system to the outlet port. The syringe pump was controlled with a constant injection rate at 10 μ l/min, while the fluid collection system was at the ambient conditions. From the microfluidic chip design, the 2-dimensional porosity is 66.2%, which corresponds to chip pore-volume (PV) of 10 μ l and an injection rate of 1PV/min.

Image processing

The image acquisition was made using a fluorescence microscope. The recorded snapshots of the flow experiments and the subsequent analysis correspond to the injection of the fluids with the fluorescent beads. We processed the raw images using a well-known image analysis software, Fiji-ImageJ (<https://fiji.sc/>). For enhanced visualization, the acquired images were converted to the RGB scale. This approach enabled us to highlight different fluorescence intensity levels, where the blue color was used to reflect low intensity (i.e., no fluorescent material), while green and red correspond to moderate and high-intensity levels of the fluorescent beads, respectively. The flow direction for both the water and the polymer experiments was unchanged throughout the entire duration of the experiments.

Results and Discussion

In this study, we conduct two sets of microfluidic experiments on separate chips: a water injection experiment and a polymer injection experiment. The water-flood experiments were performed to determine a baseline for the analysis of the polymer-flood experiments. For the water injection experiments, we started by injecting one-third of the total volume of water in the absence of fluorescent beads and then switched to the mixture of water and the fluorescent beads for the remaining two thirds. The total injection volume is 50 PVI. However, for the polymer injection experiment, we began by injecting 50 PVI of polymer solution in the absence of fluorescent beads. We then switched to polymer injection with the fluorescent beads for an additional 50 PVI. For the polymer case, we doubled the magnification compared to the water injection case to get a better observation of the low-porosity region. By using this injection scheme, we could assess the flow behavior of polymer within the fine and the coarse features, mimicking different pore sizes.

Water-flooding

We assessed the flow characteristic of the water-flood, with emphasis on the plugging effects, by performing image-based analysis to the data acquired during the injection experiments of the water with fluorescent beads. Figure 5 shows the cumulative trailing particle pathways for the water injection experiment for two injection-intervals, each computed over a stack of 1000 images. The reported PVI corresponds to the start of water injection seeded with the fluorescent beads. Figure 5a shows the cumulative streamlines for the first 16.7 PVI, while image Figure 5b shows the cumulative streamlines for an additional 16.7 PVI. The mixture of red and green colors, corresponding to moderate and high fluorescence intensity, indicating the existence of many uniformly distributed streamlines within the entire area. The similarity in the color shades in both images suggests that the flow streamlines remained relatively uniform and unaltered during the two injection intervals. These results indicate that water and the transported fluorescent particles could flow freely within the whole pore-space, fine and coarse with no flow obstruction. This behavior is expected, owing to the small size of the fluorescent beads compared to the pore-throat sizes of the model. Therefore, the accessible pore-volume stayed unchanged during the whole experiment with no apparent induced plugging.

Figure 5: Images from the micromodel showing the fine and coarse solid features colored in white. The cumulative trailing particle pathways (green particles with brownish background) for the flow up to 16.7 PVI of water with fluorescent beads is shown in image a). The cumulative trailing particle pathways between 16.7 PVI and 33.4 PVI are shown in image b). These images show no significant change in the flow behavior during the recorded injection period, indicating no plugging.

We performed a quantitative analysis of the fluid flux to substantiate the flow behavior observed in the cumulative trailing particle pathways from Figure 5. The flux of water with the transported fluorescent beads was quantified using the Multi ROI Profiler functionality in ImageJ. Three areas were

chosen to be investigated, comprising of two fine-feature zones and one coarse-feature zone, located between them, as shown in Figure 6-left. Figure 6-right shows the normalized mean pixel intensity as a function of PVI, corresponding to the three zones investigated. The fluctuating behavior in the fluorescent signal is related to the random distribution of the fluorescent beads in the water, as expected. The normalized mean pixel intensity variation with the PVI, for all three zones, exhibits a relatively constant trend, indicating a nearly constant flux of fluorescent beads within all zones. These results show similar flow behavior between the two fine-feature zones and between the coarse-feature zone and the fine-feature zone. This observation is in agreement with the flow characteristics obtained by the cumulative trailing particle pathways from Figure 5. Therefore, the entire porous medium in the microdevice was fully accessible to the fluorescent beads with no obstruction for flow.

Figure 6: The caption on the left highlights three investigated areas on the chip, two fine-feature areas, and one coarse-feature, which were considered to quantify the fluid flux behavior. The plot on the right shows the corresponding normalized mean pixel intensity variation with PVI, indicating a relatively constant trend for the fluxes of the fluorescent beads within all three areas. These results confirm that water flow with beads occurred in all zones with no obstruction.

The results of the water-flood experiments showed no apparent induced plugging in the porous media by bead/solid interactions. Therefore, the water-flooding experiment was considered as a baseline for the polymer-flood experiments.

Polymer-flooding

We assessed the flow characteristic of the polymer-flood, with emphasis on plugging effects, by performing image-based analysis to the data acquired during the injection experiments of the polymer with the fluorescent-beads solution. Figure 7 shows the cumulative trailing particle pathways, in green and red, over the entire injection period, which is divided into four injection intervals: 0-5 PVI, 5-16.7 PVI, 16.7-33.4 PVI, and 33.4-50 PVI. In this case, the reported PVI corresponds to the start of the polymer injection with the fluorescent beads, after the injection of 50PVI of bead-free polymer. The blue regions, based on the RGB scale of the images, indicate no fluorescence signal, and therefore no polymer plugged regions. Figure 7a illustrates the cumulative trailing particle pathways of the first 5 PVI, showing two large blue regions near the entrance channel, emphasizing prior polymer plugging and forcing the beads to flow around them. There is very low seeding density around the fine-feature zone, likely owing to the streamlines of the polymer solution by-passing the low porosity region. However, there is still a presence of fluorescent particles in the low porosity region as they are mostly transported by diffusion. The middle of the fine-feature region has the lowest seeding density, in agreement with the observation that the polymer solution streamlines are by-passing the small features. An additional plugging feature occurred near the top of the observation window, as shown in image Figure 7b, which illustrates the cumulative trailing particle pathways from 5 to 16.7 PVI. The emergence of this added plugging feature caused a decrease in the seeding density of the fluorescent beads in the porous medium. The trailing particles

pathways in the coarse-feature zone show a little discrepancy, marked by increased blue-colored regions. This indicates a reduced flux, and therefore a plugging effect. A key difference in the streamlines can be observed in the fine-feature zone, which shows flow divergence and signs of an early polymer plugging in the center of the zone. The green color of the pathways indicates that the streamlines are relatively uniformly distributed throughout the available flow areas. Figure 7c, showing the cumulative trailing particle pathways from 16.7 to 33.4 PVI, is characterized by a shift in the color-code, showing increased fluorescence intensity. This implies that the concentration of flowpaths in specific regions is a result of the increased polymer-plugging in the pore-network and outside. In the low porosity zone, the streamlines by-pass the central area through the periphery of the zone, with flow mainly occurring in the high-porosity zone through two wide preferential pathways. Figure 7d shows the cumulative trailing particle pathways for the last 16.7 PVI, highlighting unexpected flow behavior induced by excessive polymer-plugging of the porous media and the inlet region. The cumulative streamlines are indicative of a high degree of clogging of the entire porous media and the inlet regions, which are captured by the flow paths that are almost inexistent in both the low- and high-porosity regions.

Figure 7: Captions showing cumulative trailing particle pathways, in red and green, during a total of 50 PVI of polymer solution with fluorescent beads, following 50 PVI of a beads-free polymer solution. The cumulative trailing particles pathways are shown for 4 injection intervals: a)0-5 PVI, b)5-16.7 PVI, c)16.7-33.4 PVI, and d)33.4-50 PVI. The images show a significant change in the flow behavior during the recorded injection period, indicating a polymer plugging effect.

Figure 8 shows the surface plots of the cumulative trailing particle pathways for the last 33.3 PVI, from 16.7 to 33.4 PVI and from 33.4. to 50 PVI, corresponding to Figure 7c and Figure 7d, respectively. The surface plots represent the normalized pixel intensities in 3D of the cumulative trailing particle

pathways. The surface plots cover the entire field of observation captured during the experiments. The plots show the preferential flow path of the polymer solution, where the red scale represents the highest concentration of pathways, and the blue represents the lowest. Figure 8a shows the presence of flow only through the high-porosity zone of the coarse-features, indicating a plugging in the low-porosity zones. With more PVI of polymer, Figure 8b shows that both the low- and the high-porosity regions underwent excessive polymer plugging after an extended injection of 100 PVI of the polymer solution.

Figure 8: Surface plots in 3D representing normalized pixel intensities of the cumulative trailing particle pathways for two injection intervals, from 16.7 to 33.4 PVI in a) and from 33.4 to 50 in b), respectively. The low-intensity signals (green and blue) are indicators of reduced flux and clogging. Polymer clogging appears to accumulate with continuous injection of polymers.

We performed a quantitative analysis of the fluid flux to obtain a deeper understanding of the polymer-induced plugging observed in the low and the high-porosity zones, as shown in Figure 7. The flux of polymer solution seeded with the fluorescent beads was quantified using the Multi ROI Profiler functionality in ImageJ. Two areas were chosen to be investigated, consisting of a fine-feature area and a coarse-feature area located apart to avoid any flow interference effects, as shown in Figure 9-left. Figure 9-right shows the normalized mean pixel intensity as a function of PVI, corresponding to both selected areas. The normalized values were obtained by dividing the mean pixel intensities by the average value of each individual data set. The fluctuating behavior in the fluorescent signal is related to the random distribution of the fluorescent beads in the polymer solution. The normalized mean pixel intensity variation with PVI shows significant dissimilarities in the polymer flow behaviors between the coarse-feature zone (zone 1 in red) and the fine-feature zone (zone 2 in black). The normalized mean pixel intensity for the coarse-feature zone shows a slowly declining trend, indicating a slow reduction in the flux and, therefore, a slow build-up of polymer plugging. In contrast, the normalized mean pixel intensity for the fine-feature zone exhibits a fast decreasing trend throughout the entire injection period, indicative of a significant reduction in the flux, and therefore a faster build-up of polymer clogging. These results are in agreement with the polymer solution flow characteristics obtained in Figure 7.

Figure 9: The caption on the left highlights two areas, a coarse-feature area, and a fine-feature area, both considered for the quantitative analysis of the flow flux. The corresponding normalized mean pixel intensity variation with PVI, on the right plot, shows a slowly declining trend in zone 1, indicating slow clogging of the pores, and a fast-declining trend in zone 2, indicating a fast clogging of the pores.

We performed particle tracking velocimetry analysis to assess the polymer flow behavior on a variable-porosity pore-network under high throughput of PVI, a characteristic of the near-wellbore area. With pore-throats ranging in size from $1\mu\text{m}$ to $10\mu\text{m}$ and the experimentally-measured $2\mu\text{m}$ -polymer coils, we anticipated an inaccessible pore-volume effect around the small features only. However, our results showed that the continuous entrapment and build-up of polymers could reduce the effective pore-throat size of the porous medium leading to extended inaccessible pore-volume within the high-porosity zones.

The investigated areas are shown in Figure 10, where we emphasize the ‘*shadowing effect*’ as one of the factors that may contribute to the flow behavior in the high-porosity region. We define the ‘*shadowing effect*’ as the effect of pore-connectivity when a high-porosity zone is accessible to flow mainly through a low-porosity zone. This phenomenon reflects an induced impact of the low-porosity area on the fluid flow through a neighboring high-porosity area, located downstream. Figure 10 shows a high-porosity area (zone 1) located downstream of a low-porosity area (zone 2). This configuration aims to mimic the heterogeneous nature of reservoir rocks, where high-porosity regions could be solely connected through low-porosity regions.

Figure 10: Caption highlighting two areas of investigation, one of a high-porosity zone (zone 1) represented by the coarse-feature area, and one of a low-porosity zone (zone 2) represented by the fine-feature area. The high-porosity area is situated downstream of the low-porosity area.

The particle tracking velocimetry (PTV) was conducted using the TrackMate functionality in ImageJ, based on the images captured during the polymer-flood experiments. The tool could identify the fluorescent particles (beads) seeded in the polymer solution, where individual beads were segmented into multiple frames, and their corresponding tracks were reconstructed. This technique can construct the flow streamlines of the fluorescent beads and calculate their transport velocities based on the particle locations, the frame rate, the frequency of the captured frames (Tinevez et al., 2017). The velocities were not constant over time. Consequently, we divided the 3000 captions into three stacks corresponding to the injection intervals from 0 to 16.7 PVI, from 16.7 to 33.4 PVI, and from 33.4 to 50 PVI, respectively.

Figure 11 illustrates the streamlines during the three injection intervals, shown for the entire field of observation as well as for zone 1 and zone 2, as highlighted in Figure 10. The cumulative streamlines over the entire field of observation, during the three injection intervals, support the results obtained by the cumulative trailing particles pathways from Figure 7. The density of streamlines appears to diminish in the second injection interval (16.7-33.4 PVI), compared to the first one (0-16.7PVI). Moreover, the increased size of polymer accumulations at the inlet of the porous media is noticeable from the distribution of the streamlines, as flow divergence is observed. The streamlines over the last injection interval, 33.4-50 PVI, concentrate outside the porous media with only sparse streamlines through the porous media, emphasizing a significant polymer-induced plugging.

The PTV functionality allowed us to analyze the polymer plugging evolution separately within the high and low-porosity zones. In zone 1, the streamlines throughout the three injection intervals exhibit a decreasing trend, where the last interval shows that the streamlines are substantially reduced as well as the flow area. Therefore, the flow of the polymer solution was dramatically diminished over the last 16.7 PVI injected. In contrast, the streamlines in the low-porosity zone (zone 2) show a significant reduction in the number of streamlines from the first to the second injection interval. The center of the fine-feature zone appears to be poorly flooded in the second injection interval. This observation implies an earlier plugging of the low-porosity zone compared to the high-porosity zone, manifested after only 16.7 PVI. The third injection interval, 33.4-50 PVI, exhibits a further reduction in the number of streamlines, with the flow occurring almost exclusively at the periphery of the low-porosity zone.

Figure 11: Captions of the streamlines corresponding to the fluorescent beads within the entire field of observation (top row), within the high-porosity zone (middle row), and the low-porosity zone (bottom row) during a 50 PVI of the polymer solution. The streamlines are shown during three intervals corresponding to 0-16.7 PVI, 16.7-33.4 PVI, and 33.4-50 PVI, respectively, from left to right.

We then assessed the behavior of the velocities of the fluorescent beads within zone 1 and zone 2 during the three injection intervals. Figure 12 shows the mean velocity histograms within the high-porosity zone and the low-porosity zone, over the three injection intervals.

In the high-porosity zone, the velocity histograms show a decreasing trend in the mean velocity throughout the three injection intervals. The mean velocity exhibits a decrease of 30%, from 5.17 ft/day during 0-16.7 PVI to 3.60 ft/day during the 16.7-33.4 PVI interval. The velocity exhibits a further decrease with 40% during the last injection interval (33.4-50 PVI), from 3.60 ft/day to 2.18 ft/day. On the other hand, in the low-porosity (zone 2), the velocity histogram shows a decrease of about 15%, from 3.15 ft/day during 0-16.7 PVI to 2.7 ft/day during the 16.7-33.4 PVI interval. Similarly, the mean velocity undergoes a further decrease of about 15% during the third injection interval, 33.4-50 PVI, reaching a value of 2.28 ft/day. The comparable mean velocity in the last injection interval in the low-porosity zone is an indicator of the 'shadowing effect' observation from the streamlines (Figure 11), which reflects the influence of the low-porosity region on the flux through the high-porosity region.

Figure 12: Velocity histograms of the flowing polymers within the high-porosity zone (zone 1) representing the coarse-feature zone, and within the low-porosity zone (zone 2) representing the fine-feature zone, during a 50 PVI of the polymer solution. The injection period was divided into three intervals: 0-16.7 PVI, 16.7-33.4 PVI, and 33.4-50 PVI, respectively, shown from left to right. The particle velocities exhibit decreasing trends in both zones.

Discussion

The experimental results presented in this paper show polymer-induced plugging for high-throughput of pore-volume injected (100 PVI). Significant plugging of the porous network of the microfluidics device was observed during the extended injection volumes of the polymer solution, replicating the flow conditions in the near-wellbore area. Permeability alteration was encountered and represented by the reduction in the flow velocities and the density of particle transport streamlines. This issue occurred in the zones with expected accessible pore-volume for the polymer solution, with 10 μ m pore-throat size, several folds larger than the used polymer coils (2 μ m). This observation raises a limitation of the “5 times” rule of thumb, typically applied in industry. With this rule of thumb, the polymer size selection is mainly based on size exclusion criteria, with the size of the polymer chosen to be approximately five times smaller than the average pore-throat size of the target formation. The significance of this finding is in raising awareness of a major limitation in some polymer screening workflows that rely mainly on the size exclusion criteria. It is, therefore, crucial to emphasize the importance of core-flood experiments to assess injectivity.

Conclusions

We presented an approach based on the design and fabrication of microfluidic chips to study the flow of polymer in a medium with variable porosities. The objective is to assess the polymer clogging mechanisms and their relationship to the pore-throat sizes of the porous formation. The findings are summarized by the following:

- We found that the flow of sub-micron scale beads suspended in water through a variable-porosity micromodel model did not cause any plugging based on image analysis. Therefore, the waterflood case with fluorescent beads was used as a baseline for the polymer-flood experiments.
- The flow of a high-molecular-weight polymer through the designed variable-porosity micromodel caused significant alterations in the flow behavior of the fluorescent beads, owed to polymer-induced plugging.
- The flow model experienced a size-exclusion effect of the polymer within the low-porosity region. The size of the pore-throats in the low-porosity region is comparable to the size of the polymer molecules, and therefore, the clogging observation was expected.
- The high-porosity region, mainly designed to represent the accessible pore-volume for the polymer, exhibited an unexpected reduction in the polymer flux. The clogging behavior within the high-porosity region showed a gradual build-up of polymer entrapment, resulting in permeability reduction, and extended inaccessible pore-volume.
- The ‘shadowing effect’ reflecting the connectivity of high-porosity to low-porosity zones was investigated, where we observed that polymer clogging in low-porosity zones could affect the flow in high-porosity regions. This effect could lead to additional inaccessible pore-volume within the porous formation.
- The results highlight a limitation in some adopted polymer screening workflows that rely solely on the size of the pore-throats and the molecular weight of the polymer.
- The presented approach allows studying high-throughput of hundreds of pore-volumes within a short time, which can complement the traditional fluid compatibility screening process for subsurface applications.

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