X-Ray Computed Microtomography:

Accurate Liquid Volume Metering

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Syringe Pump Application Note
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Introduction

Aqueous gels have often been used to reduce excess salt water production from oil and gas wells. An ability of gels to reduce permeability to water much more than to oil is critical for successful applications of gel treatments in oil production wells if hydrocarbon strata are not protected during gel placement.[1,2] If gelant penetrates into an oil zone and gel forms, some time will be required before the oil penetrates through the gel bank and significant restoration of permeability to oil can occur.[3,4] The dependence of oil permeability on oil throughput (i.e., fluid volume injected per flow area) determines how long it takes for a production well to "clean up" or restore productivity after a gel treatment. This report uses a Teledyne Isco Model 500D Syringe Pump with X-ray computed microtomography (XMT) to understand the throughput dependence of recovery in oil permeability.

In our previous work,[5] XMT was used to establish why pore-filling Cr(III)-acetate-HPAM gels reduced permeability to water much more than to oil. (A "pore-filling" gel is simply a gel that occupies all of the aqueous pore space.) Our results suggest that permeability to water was reduced to low values because water must flow through gel itself, whereas oil pressing on the gel forced pathways by dehydration or collapse of the gel—leading to relatively high permeability to oil. Those studies involved obtaining 3D X-ray images after forcing large volumes (20 pore volumes) of oil or water through the core after gel placement.

Experimental Procedures

We were interested in how the gel dehydration process progresses as a function of oil throughput. We were particularly interested in whether oil paths develop preferentially in large pores versus small pores. To answer this question, we saturated a hydrophobic porous polyethylene core (~8 darcy original permeability) and a hydrophilic Berea sandstone core (328 mD original permeability) with a Cr(III)-acetate-HPAM gelant and allowed the gel to form. This gel contained 0.5% Ciba Alcoflood 935™ HPAM, 0.0417% Cr(III) acetate, 1% NaCl, and 0.1% CaCl2. A diagram of the experimental setup is shown in Figure 1.

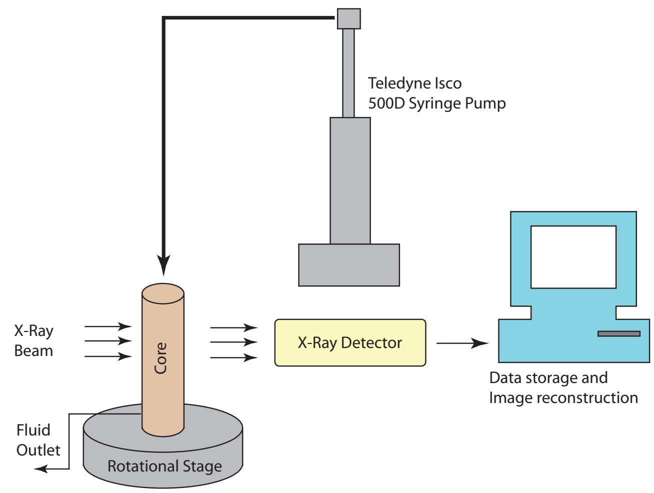

Figure 1: Diagram of experimental setup

The cores were then imaged using ExxonMobil's X2B X-ray beamline at Brookhaven National Laboratory. A previous publication[5] described this procedure. For each of the ~10,000 pores in our image volumes, we followed oil and water saturations as a function of throughput.

Achieving images at selected intermediate throughput values requires precise control of the volume of injected fluid. Our core pore volumes were only 0.26 cm^3 for Berea sandstone and 0.52 cm^3 for porous polyethylene. We wished to inject precise oil volumes to achieve a logarithmic scale of throughput values ranging from 0.1 to 100 pore volumes (PV). Using a Teledyne Isco Model 500D pump, precise volumes of oil were injected into the core (Figure 1). For example, in the case of Berea sandstone, we first injected 0.026 cm^3 (0.1 PV) of oil using a constant rate of 0.26 cm^3/min for six seconds. X-rays passing through the core were detected to form 2-D patterns for each of 1200 angles between 0 and 180°. These 2-D patterns were then reconstructed into a 3-D image. Further analysis of the images identified pore locations and oil, water and gel saturations within each pore. After obtaining the data associated with the first image, another 0.1 PV of oil was injected to reach a total oil throughput of 0.2 PV. This process was repeated in stages to obtain images at total oil throughput values of 0.1, 0.2, 0.3, 0.5, 1, 2, 5, 10, and 100 PV for the case of Berea sandstone, and 0.2, 0.3, 0.5, 1, 2, 5, and 10 PV for the case of porous polyethylene.

Average Saturations in the XMT Image Volume

Figure 2 plots the average saturations in the XMT image volume as a function of PV of oil injected. One surprising aspect of the results was that the average saturation from the XMT data was noticeably greater than expected from the oil throughput data. For example, in the polyethylene core, the average oil saturation in the image volume reached 54% after injecting only 0.2 PV of oil. Also, in the Berea sandstone core, the average oil saturation in the image volume reached 77% after injecting only 0.1 PV of oil. On first consideration, these findings do not seem possible. One would expect that the average oil saturation in the core could not exceed 10% after injecting 0.1 PV of oil and 20% after injecting 0.2 PV of oil. However, remember that the saturations were measured *in the image volume*. The image volume was only 12 mm^3 in the center of a 1,300 mm^3 core. The mobility ratio was extremely high during oil flow through the gel (i.e., the 2-cp oil was much less viscous and more mobile than the million-cp gel). A finger of oil could reach a given location within the core with a very small throughput. Consequently, it is quite possible that the image volume may be flooded to high oil saturation at an earlier time than the average for the core. By the same logic, it is possible that the oil fingers might completely miss the image volume, so that oil saturations remain low until very high throughput values. Thus, some degree of “luck” or random chance led to the particular saturation levels seen in Figure 2. Nonetheless, within a given image volume, the distribution of oil in small, medium, and large pores is of interest.

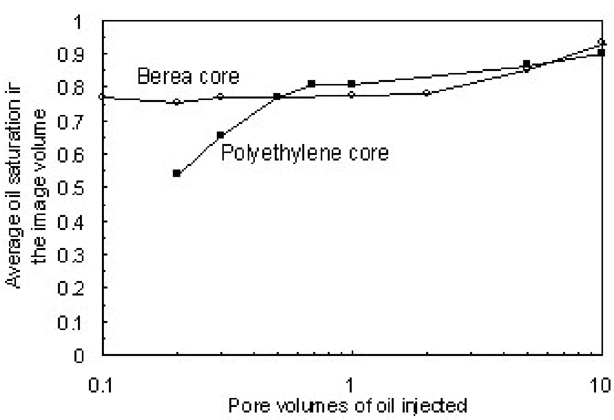

Figure 2: Average oil saturations in the image volumes versus oil throughput

XMT Results for the Polyethylene Core

Figure 3 shows the distribution of oil saturations as a function of pore size and oil throughput in the image volume of the polyethylene core. The smallest polyethylene pores (10-6-10-5 mm^3) filled rapidly with oil. Oil saturations jumped to almost 60% in these pores after injecting only 0.2 PV of oil. We speculate that the hydrophobic polyethylene pore walls provided an effective conduit to imbibe oil through the porous medium. Presumably, growth of an oil film on the pore walls led to compression of the gel. This compression forced a small amount of water to flow through the gel structure to the outlet end of the core (i.e., gel dehydration). Also presumably, this slight loss of water caused a small increase in concentration of polymer within the gel.[5,6]

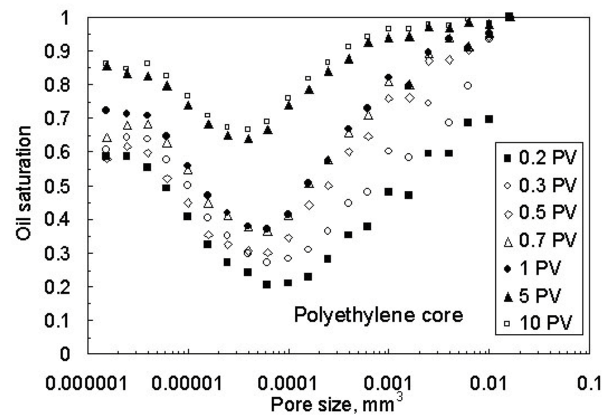

Figure 3: Oil saturation versus pore size and oil throughput: polyethylene core

In contrast, oil saturations rose much more gradually for the most common or intermediate-sized pores. For pores with sizes around 4x10-5 mm^3 (i.e., the peak in the pore-size distribution), oil saturations were 0.24 at 0.2 PV, 0.38 at 1 PV, and 0.64 PV at 5 PV. Conceivably, the slower rise in oil saturations could be responsible for the gradual increase in permeability to oil for this core. There are so many pores within the size range around 4x10-5 mm^3 that the oil must flow through these pores in order to get through the core. Thus, these pores provide the critical resistance that determines the overall permeability.

The largest pores filled quite rapidly with oil. For pores larger than 0.0063 mm^3 (accounting for 61% of the total pore space in the image volume), the oil saturation was over 90% after injecting only 0.3 PV. Although it is possible that gel dehydration was responsible for the gains in oil saturation in these pores, we are inclined to believe that the responsible mechanism was more likely ripping or gel extrusion. In sand packs with permeabilities comparable to our polyethylene core, data from the University of Kansas[5,6] supports ripping or extrusion mechanisms for creating oil pathways.

XMT Results for the Berea Core

Figure 4 shows the distribution of oil saturations as a function of pore size and oil throughput in the Berea sandstone core. For any given oil throughput, the oil saturation was fairly independent of pore size. Why did the smallest Berea pores not experience large increases in oil saturation, as was observed in the polyethylene core? Presumably, the answer is that the water-wet Berea rock had no propensity to imbibe oil, as did the hydrophobic polyethylene. Why did the largest Berea pores not show large increases in oil saturation, as was observed in the polyethylene core? The porosity of the Berea rock was about half that of polyethylene. Perhaps the ripping and extrusion mechanisms were more prevalent in the high-porosity polyethylene.

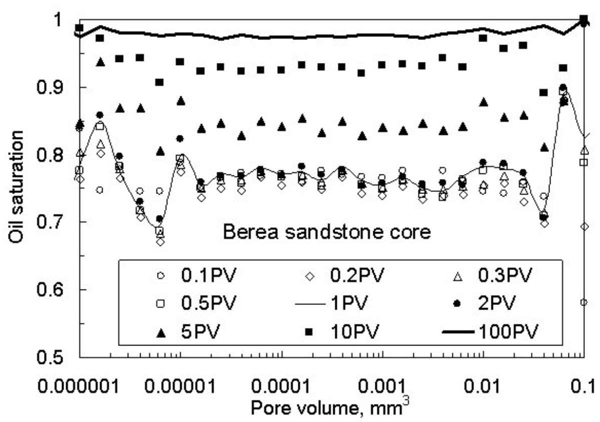

Figure 4: Oil saturation versus pore size and oil throughput: Berea core

References

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