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Effect of Fluid Rheology and Sandstone Permeability on Enhanced Oil Recovery in a Microfluidic Sandstone Device

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Abstract:
Maximizing oil recovery from current reserves is becoming more important as global usage continues to rise. In this paper, we present the development of two microfluidic sandstone devices of high complexity and differing permeability capable of quickly and inexpensively testing the oil recovery performance of fluids with different rheological properties. Our initial baseline experiments were performed by displacing oil with water over a wide range of flow rates. Next, a commercially available fluid thickener, Flopaam 3630, was tested. Flopaam is both shear thinning and viscoelastic and was found, due primarily to its large viscosity, to recover more oil than the water and increase the oil recovery substantially in both the larger and smaller permeability microfluidic sandstone devices. Finally, a shear-thickening nanoparticle solution was studied. The shear-thickening solution was designed to thicken at a shear rate of about 10 s^{-1}, a typical shear rate in the oil reservoirs. These shear-thickening fluids were found to be an excellent enhanced oil recovery fluid, especially when the shear rates within the microfluidic sandstone devices closely matched the shear rates associated with the shear-thickening regime. For the high permeability sandstone devices tested, when the appropriate choice of shear-rate-dependent viscosity was used to define a capillary number, the oil recovery obtained from both the Newtonian and non-Newtonian fluids were found to collapse quite well onto a single master curve. This, however, was not the case for the lowest permeability sandstone devices where the increased complexity was found to negatively affect the performance of the viscoelastic fluid when compared to either the Newtonian or the shear-thickening fluid. Finally, it was shown that these oil recovery results are insensitive to whether a single-stage recovery process or a more complex two-stage recovery process that starts with an initial water flood followed by a flood with a secondary fluid were used.

Key words:
enhanced oil recovery, shear thickening, microfluidics, sandstone, permeability

1 *INTRODUCTION*

The recovery of oil from a well generally takes place in three stages: primary, secondary, and tertiary or enhanced oil recovery (EOR) [1]. In the primary stage, approximately 10 % of the total oil in the well is recovered using the internal pressures within the well. In the secondary stage of oil recovery, a driving or pumping fluid, typically water, is used to displace an additional 20 – 40 % of the oil in the reservoir. As a result, between 50 – 70 % of the original oil still remain in the oil field after the secondary recovery [1]. Even so, an oil well is often considered exhausted at this point because enhanced oil recovery techniques can be too expensive to justify their use. However, as the global oil supply decreases and the expense of oil increases, the developing of EOR fluids and methods to efficiently and inexpensively access and recover all of the remaining oil trapped within a well are becoming increasingly more important.

The methods of enhanced oil recovery can be categorized into three main approaches: thermal, gas, and chemical [1 – 7]. All three approaches have been used for decades and aim to ease the recovery of the oil, either by changing the properties of the oil, the imbibing fluids, or the material properties of the sandstone itself. Here we will focus on chemical methods. Chemical methods increase the effectiveness of water floods by modifying the water used to displace the oil. These methods can include reducing the interfacial tension between the imbibing fluid and the oil with the use of surfactants, increasing the viscosity of the imbibing fluid through the addition of polymer or wormlike micelle additives, and using additives to modify the wettability of the oil fields substrate to make it lyophobic [1, 2, 4]. One of the greatest challenges with chemical methods is the variability in the properties of the oil and the rock between reservoirs or even within a given reservoir. As a result, to maximize oil recovery the chemistry and

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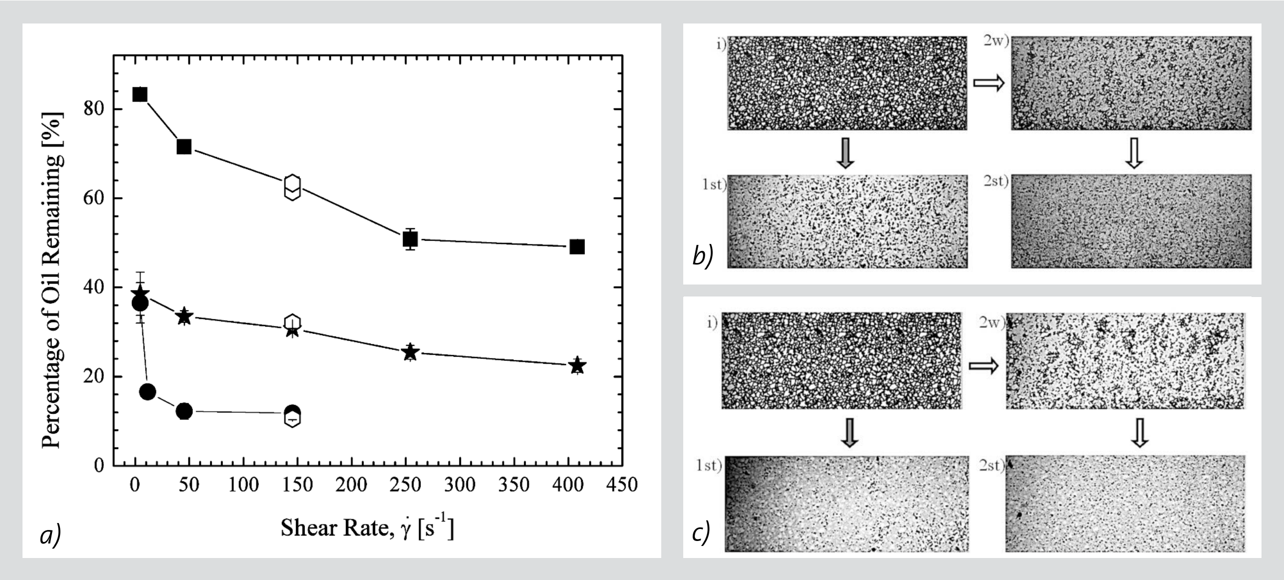

Figure 10: a) The percent oil remaining as a function of flowrate for ■ water, ● shear-thickening solution, and ★ Flopaam 3630 for the SMD-73D. The octagons indicate two stage recovery residual oil, starting with a water flood in each case and followed by either a secondary shear-thickening solution or a secondary Flopaam flood. b) The initial oil filled SMD-73D geometry (i) and comparing the steady-state results after flooding with only the Flopaam 3630 solution (1f) against flooding first with water (2w) and a secondary flood with the Flopaam solution (2f). c) The initial oil filled large SMD-73D geometry (i) and comparing the steady-state results after flooding with only the shear-thickening nanoparticle solution (1st) against flooding first with water (2w) and a secondary flood with the shear-thickening solution (2st).

4 CONCLUSIONS

The field of Enhanced Oil Recovery is becoming a more important and necessary field. In this work we present efforts towards developing a microfluidic platform for quickly testing the ability of EOR fluids with different rheological properties for the recovery of oil from hydrophobic sandstone of various permeabilities. Water was tested in the microfluidic sandstone device as a baseline for oil recovery comparison in both devices. Additionally, a commercially available viscoelastic fluid thickener and a shear-thickening fluid were both examined for their ability to increase oil recovery. Two microfluidic sandstone devices were developed with different permeability and complexity and compared to a much simpler device published previously in Nilsson et al. [13]. In all three microfluidic sandstone devices, at a given flow rate, the viscoelastic Flopaam solution outperformed the water, but was in turn out performed by the shear thickening fluid. This observation is a direct result of the large viscosity of the viscoelastic fluid and the shear thickening transition observed for the nanoparticle suspension. If the data is renormalized as a function of the capillary number using the appropriate shear-rate-dependent viscosity, nearly all the data collapse onto a single master curve independent of fluid and the permeability of the sandstone device. The lone exception was the case of the viscoelastic Flopaam solution. For these fluids, decreasing the microfluidic sandstone permeability resulted in a 15 % reduction in the amount of oil recovered. Finally, it was demonstrated that a two-stage recovery process using water and a secondary fluid can recover as much oil as a single stage recovery with the secondary fluid in this larger, more complicated device. These measurements demonstrate that microfluidic sandstone devices can serve as a quick diagnostic tool to investigate the ability of enhanced oil recovery fluids to recover oil. They represent a viable, cost effective alternative to core floods for determining the effectiveness EOR fluids.

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