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Viscoelastic effects on residual oil distribution in flows through pillared microchannels

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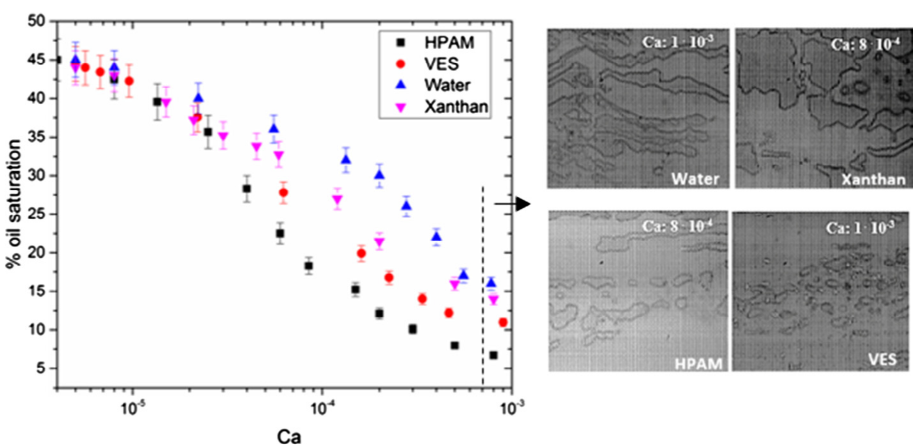
GRAPHICAL ABSTRACT



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ABSTRACT

Hypothesis: Multiphase flow through porous media is important in a number of industrial, natural and biological processes. One application is enhanced oil recovery (EOR), where a resident oil phase is displaced by a Newtonian or polymeric fluid. In EOR, the two-phase immiscible displacement through heterogonous porous media is usually governed by competing viscous and capillary forces, expressed through a Capillary number Ca, and viscosity ratio of the displacing and displaced fluid. However, when viscoelastic displacement fluids are used, elastic forces in the displacement fluid also become significant. It is hypothesized that elastic instabilities are responsible for enhanced oil recovery through an elastic microsweep mechanism.

Experiments: In this work, we use a simplified geometry in the form of a pillared microchannel. We analyze the trapped residual oil size distribution after displacement by a Newtonian fluid, a nearly inelastic shear thinning fluid, and viscoelastic polymers and surfactant solutions.

Findings: We find that viscoelastic polymers and surfactant solutions can displace more oil compared to Newtonian fluids and nearly inelastic shear thinning polymers at similar Ca numbers. Beyond a critical Ca number, the size of residual oil blobs decreases significantly for viscoelastic fluids. This critical Ca number directly corresponds to flow rates where elastic instabilities occur in single phase flow, suggesting a close link between enhancement of oil recovery and appearance of elastic instabilities.

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1. Introduction

Multiphase fluid flow through porous media is of high importance in a large number of industrial and physical processes, such as enhanced oil recovery, soil remediation, geophysical, biological and engineering applications [1,2]. The flow of a single-phase Newtonian fluid through a porous medium is well understood within the framework of Darcy's law in the creeping flow regime. However, multiphase flow through porous media involving non-Newtonian fluids are much more complex in nature [1]. In enhanced oil recovery, both water and polymer solutions are pushed through the porous media, to displace oil from reservoirs. Because the pore length scales and fluid velocities are small, the Reynolds number is usually small. However, two other non-dimensional numbers become very critical in such immiscible transport processes. The first one is viscosity ratio (M), defined as the ratio between the viscosities of displacing and displaced fluid. A value of M > 1 is considered favorable, while M < 1 is unfavorable for displacement because of appearance of viscous fingering instabilities. The second important number is the capillary number Ca, defined as the ratio of viscous and surface tension forces $Ca = \mu u/\sigma$. Here μ is the viscosity of the displacing fluid, u is the Darcy velocity, and σ represents the interfacial tension between the displacing and displaced fluid. Substantial experimental and numerical work has been done by researchers to understand the influence of Ca, M, and wettability on displacement efficiency [3–13].

In case of water flooding, the viscosity ratio, M is generally <1. Thus, after water flooding a large amount of oil remains non-displaced. Large disconnected islands of oil, called ganglia, remain trapped in the porous medium. In such cases, due to the heterogeneity of the rock structure and difference in permeability, preferential flow paths for the water are formed, which causes less recovery. As a next stage of oil recovery, non-Newtonian fluids are injected into the oil reservoir. One of the features of such fluids is that the viscosity depends on the local shear rate. Thus the Ca number is redefined as $Ca = \mu(\dot{\gamma})u/\sigma$, where $\dot{\gamma}$ is a typical (or dominant) shear rate in the porous medium. The viscosity ratio $M = \mu(\dot{\gamma})/\mu_d$ also changes, depending on the local shear rate. Here μ_d is the viscosity of the displaced fluid. Non-Newtonian fluids that are commonly used in enhanced oil recovery include hydrolyzed polyacrylamides (HPAM), xanthan gums, and viscoelastic surfactants (VES) [2,14]. The typical Ca numbers in oil field applications range from 10^{-5} to 10^{-3} [2,5]. Generally, with increasing Ca the displacement efficiency increases. However, a non-monotonic dependence of Ca number on residual oil saturation was recently reported [3,15]. Non-Newtonian fluids are found to recover more oil than their Newtonian counterparts [16] *for a similar range of Ca numbers*.

Previous research suggested that flooding by non-Newtonian fluids can only improve the macroscopic sweeping [17], i.e. displacement of oil on scales much larger than that of individual pores. However, current research work [18–22] and field studies [16] suggest that non-Newtonian fluids might increase oil recovery by microscopic oil displacement on the scale of a single or a few pores, sometimes referred to as micro-sweep. Of course, even for a Newtonian displacement fluid such as water, mobilization of the ganglia may occur beyond a critical Ca number [23]. However, for non-Newtonian displacement fluids, viscoelastic effects can mobilize the oil ganglia at *lower* Ca numbers. Viscoelastic effects already occur during *single* phase flow of non-Newtonian fluids through porous media. The important non-dimensional number characterizing the importance of elastic effects is the Deborah number De, defined as the ratio of the fluid relaxation time and a characteristic time scale of the flow experiment. Non-Newtonian fluid sometimes exhibit time dependent velocity fluctuations in the flow fields which are reminiscent of turbulence, however they occur at very small Reynolds number, a phenomenon called elastic turbulence [24–26]. Elastic instabilities occur when the De number is sufficiently large, as reported experimentally for both polymeric [24,27–32] and wormlike micellar solutions [33–39]. Numerical simulations also show the presence of such spatial and temporal elastic instabilities [26,40–42]. Our recent simulations of viscoelastic flow through symmetric and asymmetric set of cylinders and through a random porous medium show that the origin of these instabilities are more related to the viscoelastic shear stress than to extensional contributions [25,43]. Recent findings by Clarke et al. [18], Avendano et al. [44] and Nilsson et al. [45] show the possible effects of viscoelasticity in enhanced displacement. Rodriguez de Castro et al. [46] very recently showed effects of shear thinning fluids on residual oil formation. However, a complete picture regarding the residual oil size distribution and its correlation with viscoelasticity is still missing.

In this work, we will show that the enhanced oil recovery by micro-sweep observed in *two-phase* flows through porous media is strongly correlated with the appearance of elastic instabilities observed in *single phase* flows of the same displacement fluid through the same porous medium. Our work therefore suggests that *elastic* instabilities, rather than e.g. shear-thinning or other quasi-Newtonian effects on the viscosity, are responsible for the enhanced micro-sweep for the set of fluids investigated in this study.

Displacement experiments are often performed on fully three-dimensional rock core samples. However, detailed visualization of the phases on the level of the rock pores is extremely difficult. Instead, we use a microchannel with a strategic arrangement of cylindrical pillars, ensuring that the time and length scales are similar to those occurring in actual rock structures [47]. Several researchers have shown that multiphase flow studies are possible (and relevant) in such microchannels [3,48,49]. In this study, we compare a Newtonian fluid (water) with three types of non-Newtonian fluids, namely a slightly elastic shear thinning fluid (xanthan), a viscoelastic shear thinning polymer (hydrolyzed polyacrylamide - HPAM), and a viscoelastic surfactant (VES), for their ability to displace oil in the microchannel in a similar range of Ca numbers. The reader should note that in the definition of Ca number the viscosity $\mu(\dot{\gamma})$ is obtained from the single phase microfluidic experiments. A detailed analysis of the ganglia size distribution shows that both HPAM and VES are able to fragment large oil ganglia to smaller microstructures. The Ca number where the micro-sweep increases significantly corresponds to flow rates where increased flow resistance and elastic instabilities are observed in single phase viscoelastic fluids. Water and xanthan showed no such micro-sweep displacement patterns for similar Ca ranges.

This paper is organized as follows. In Section 2 we detail the microfluidic setup, give details of the bulk rheology of the fluids used in this study, and explain the experimental procedure. In Section 3 we show and discuss our results. In Section 4 we end with our conclusions.

2. Material and methods

2.1. Microfluidic setup

The displacement experiments are performed using a pillared microchannel. A porous medium is mimicked by strategically placing an array of cylindrical pillars in a hexagonal pattern from the entry to the exit of the microchannel, as shown in Fig. 1. These pillars act as obstacles in the flow path, creating continuous contraction and extension of the displacing fluid. The straight