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Project Title: Computational and Experimental Investigations of Wormlike Micellar Fluids for Enhanced Oil Recovery

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The first-year goal of this project is: (1) experimental investigations on the fluidic behavior of wormlike micellar fluids passing through a sudden contraction microchannel and (2) numerical investigation on the wormlike micellar fluids in porous media.

1. Experimental investigations on the wormlike micellar solutions

Wormlike micellar solutions (WMS) have attracted a considerable amount of interest in enhanced oil recovery (EOR) applications. However, the structural formations and behavior of WMS in the porous media of oil field need further investigations. Rheological conditions of WMS in the oil field influence the fluidic response to different types of shear and extensional forces that apply on WMS. Microfluidic devices provide a versatile platform to study WMS under different flow circumstances and confined geometries. We employ a microchannel with sudden contraction (upstream channel ≈ 1,000 × 500 μm, downstream channel ≈ 250 × 500 μm, width contraction ratio = 4:1), which provides different rheological flow regimes. Injecting a viscoelastic fluid through such a microchannel provides localized regions in which fluid are under shear and extensional forces [1]. The Microchannel was fabricated on polymethylmethacrylate (PMMA) by a two-step method. First, the designed geometry was directly milled on the PMMA chip using a high precision computerized numerically controlled (CNC) micro milling machine (MiniTech). Then, the milled chip was covered by a PMMA cover slip (thickness of 1 mm) using a thermal bonding method. The experimental investigations are carried out using a cetyltrimethyl ammonium bromide (CTAB) and sodium salicylate (NaSal) in de-ionized water where the molar ratio of salt to surfactant is fixed at Cs= [NaSal]/[CTAB] = 0.32. WMS were seeded by 0.01 wt% of fluorescent polystyrene particles (Fluoro-Max™, Ex: 530 nm, Em: 607 nm, diameter = 10 μm). Streakline images of the polystyrene particles represent the flow behavior of WMS over different flow rates. After a series of 300 to 900 images was acquired using an inverted fluorescence microscope (IX70 Olympus) equipped with a high-speed camera (NX-4, IDT) at capture rates of 30 to 90 fps, the images were stacked to obtain the streakline images using ImageJ software (see Fig. 1).

While relatively small vortices termed as Moffatt vortices are reported for Newtonian fluids in the upstream of the contraction region in a microchannel, nonlinear viscoelastic flow phenomenon is represented by the dynamics of the large recirculation regions in the upstream region, which appear in the corner of contraction (so-called corner

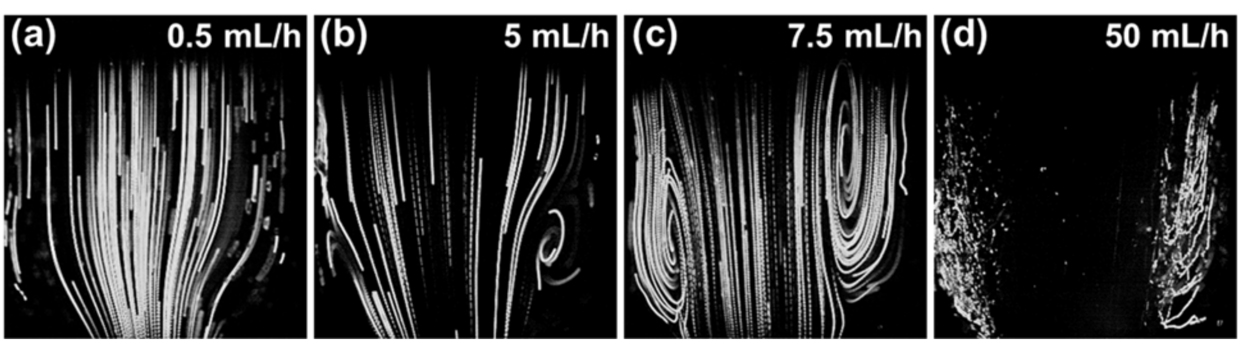

Figure 1. Streak images of particle seeded WMS ([CTAB] = 50 mM, Cs=0.32). (a) stable flow, (b) onset of recirculation flow, (c) asymmetric flow and time dependent vortex growth, and (d) jerky flow.

vortex) and/or near the re-entrant lips (so-called lip vortex) [2]. At low flow rates, a stable regime of Newtonian-like flow was observed (Fig. 1a). In this regime, no vorticities were observed on the upstream of the contraction region because flow inertia surpass the vortex growth. Increasing the flow rate led to the onset of steady viscoelastic flow in the corners of contraction upstream areas (Fig. 1b). In this regime, a lip vortex started growing and turned to corner vorticities with the increased flow rate. Corner vorticities become asymmetric and the vortex lengths are time dependent by further increasing of flow rate (Fig. 1c). At very high flow rates (above 50 mL/h, Fig. 1d), an unstable regime was observed in which particles were showing a back and forth time dependent movement.

2. Expanded mixed finite element for Darcy law, fast solver and its extensions.

In consideration of the coupled nonlinear system, the expanded mixed finite element method (EMFEM) has been employed. EMFEM starts at formulating the steady Darcy law as follows:

$$\nabla \cdot \mathbf{u} = q^*, \quad \mathbf{u} = \boldsymbol{\kappa}\hat{\mathbf{u}}, \quad \text{and} \quad \hat{\mathbf{u}} = -\nabla p \quad \text{in } \Omega, \tag{1}$$

Unlike the standard mixed finite element method, EMFEM introduces three unknowns, p, $\hat{\mathbf{u}}$ and $\mathbf{u}$. While it led to a large system, it was shown to have many advantages; (i) the coefficient $\boldsymbol{\kappa}$ doesn't need to be inverted in the solution process and (ii) an optimal convergence rate can be obtained for certain nonlinear problems. The former (i) is quite useful in the case when $\boldsymbol{\kappa}$ is very ill-conditioned, typical in the reservoir simulation. The latter (ii) is expected to be particularly important for coupled nonlinear systems considered in this proposal. A fast solver has been developed for EMFEM, which seems that there are not many works on such an issue. Arbogast et al. discussed the EMFEM with the lowest Raviart-Thomas element on a square triangulation of Ω and were able to reduce the system into a cell-centered finite difference method for p by using special quadrature rule [3]. To deliver the results, we rewrote Eq. (1) in an operator from as follows: with I being an identity operator,

$$\mathcal{E}\chi = \mathcal{F}, \quad \text{where } \mathcal{E} = \begin{pmatrix} 0 & I & \nabla \\ I & -\boldsymbol{\kappa} & 0 \\ -\nabla\cdot & 0 & 0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \mathbf{u} \\ \hat{\mathbf{u}} \\ p \end{pmatrix}, \quad \text{and } \mathcal{F} = \begin{pmatrix} 0 \\ 0 \\ -q^* \end{pmatrix} \tag{2}$$

In this setting, it can be shown that the operator ε can be spectrally equivalent to

$$\hat{\mathcal{E}} = \begin{pmatrix} A & 0 \\ 0 & -\nabla\cdot\boldsymbol{\kappa}\nabla \end{pmatrix} \quad \text{with} \quad A = \begin{pmatrix} 0 & I \\ I & -\boldsymbol{\kappa} \end{pmatrix} \tag{3}$$

This formulation shows the advantage of EMFEM over the standard mixed finite element methods (MFEM). On the other hand, the operator can be handled by a solver developed for the MFEM. After the successful design of a fast solver, it will be extended to solve transports by employing the Euerian-Lagrangian method for the temporal discretization.

Impact of the research on the development of human resources

Projects objective is to stablish an understanding of the behavior of WMS in the porous media of oil fields. The ACS PRF ND grant provided PIs and graduate students with the opportunity to initiate new research and obtain a deep understanding of roles of wormlike micelles in EOR. The grant supported a postdoctoral associate and 2 MS students to accomplish their MS theses as well as preparing them for future careers.

References

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