PRF# 57552-ND9
Project Title: Computational and Experimental Investigations of Wormlike Micellar Fluids for Enhanced Oil Recovery
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1. A stable viscoelastic flow at high Weissenberg numbers

Flows of viscoelastic fluids in microscale are under study for a variety of applications such as chemical enhanced oil recovery (cEOR). At the microscale, the characteristic laminar flow of a Newtonian fluid with a quite low Reynolds numbers (Re) is well understood. Nevertheless, the strong elastic characteristic of viscoelastic fluids shifts the onset of instabilities to very-low Re (<< 1) [1]. Applying high deformation rates to the viscoelastic fluids, which is characterized by high Weissenberg numbers (Wi), results in high elasticity (El=Wi/Re) in the fluidic motion. Hence, a microchannel with a sudden change in geometry (i.e. contraction in entry flows) provides a platform applying high deformation rates, in turn promotes elastic instabilities in flows of viscoelastic fluids [2]. The contraction flow patterns of many viscoelastic fluids such as polymer [3] and DNA [4] solutions have been studied. Those solutions have shown the formation of vortices that turned to flow instabilities at high Wi. This work reports a unique contraction flow pattern of WMS that remains stable even under high Wi. For this project, a microchannel with 8:1 planar contraction is directly machined on a polymethylmethacrylate (PMMA) chip by using a 5-axis CNC micro-milling machine (Micro Mill/GX, Minitech Machinery). Two distinct WMS (Solutions A: WMS-A and Solution B: WMS-B) in terms of their rheological characteristics were prepared (see Table 1).

Figure 1 shows a series of streak images of WMS-A. The flow pattern at low Wi was Newtonian-like (a). At Wi = 0.7, symmetric vortices appeared in upstream corners (b). Increasing Wi led to the growth of vortices in length (c). For Wi ≥ 2.9, elastic instabilities occurred, and spatiotemporal variations were observed in the flow pattern (d). These transitions from a Newtonian-like to the time-dependent unstable flows are similar to pervious reports on contraction flows of viscoelastic solutions [3]. In contrast, WMS-B did not show vortex formations. Instead, regions with no-flow condition were observed in upstream corners. Increasing Wi only led to the growth of regions with no-flow condition and the flow pattern remained stable up to the highest Wi applied to the fluid in this experiment (see Figure 2). The results of this experiment and further investigation on fluids that show stable flow pattern even at high Wi can promote applications of viscoelastic fluids where flow instabilities are not desired.

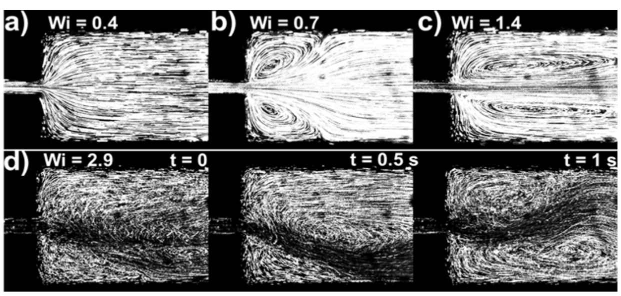


Figure 1. Streak images of WMS-A at (a) Wi = 0.4, the image represents the Newtonian-like behavior of flow which is observed for Wi < 0.7, (b) Wi = 0.7, in which symmetric vorticities formed at channel upstream corners, (c) Wi = 1.4, For 0.7 ≤ Wi < 2.9, the vortex length is increased as a function of Wi, and (d) Wi = 2.9 where the flow patterns showed time-dependency and spatiotemporal instabilities.

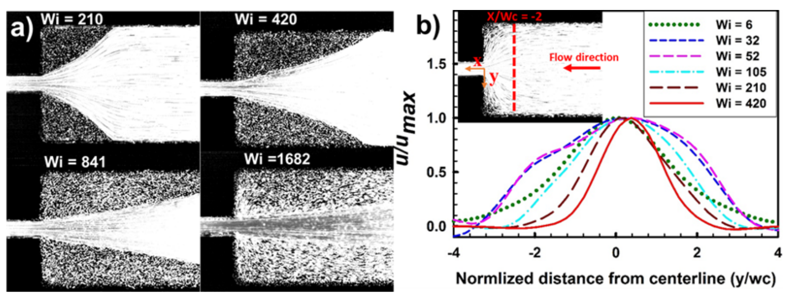


Figure 2. (a) Streak images of WMS-B at different Wi. Regions with no-flow condition are presented at upstream corners. The length of regions with no-flow condition increases as a function of Wi. (b) Normalized velocity profiles where velocities are divided to the maximum velocity (u_{max}) of fluid at each Wi show that the area of regions with no-flow condition increases with higher Wi. Velocity profiles were extracted along a line fixed in the channel upstream at $\frac{x}{w_c} = -2$ (where $w_c \approx 250\mu m$ is the width of downstream channel). Inset image of Figure 2(b) shows the origin of coordinates (x and y directions), the flow direction, and the position of fixed line at $\frac{x}{w_c} = -2$.

Table 1. Concentrations and rheological characteristics of WMS where R is the molar ratio of sodium salicylate (NaSal) to cetyltrimethylammonium bromide (CTAB), τ_R is the single relaxation time, and η_0 is the zero-shear viscosity.

	[CTAB](mM)	[NaSal](mM)	R	τ_R(s)	η_0 (Pa·s)
WMS-A	50	16	0.32	0.02	1
WMS-B	100	32	0.32	5.9	120

2. A mass-conserving finite element method for three species wormlike micellar fluids model.

Using the prior modeling results of WMF, the PIs have prepared for modeling and simulation of contraction flow. Note that the PIs have developed a new model of wormlike micellar fluids that takes into account the generation and break of the gelation and produced successful results for the simple shear flow of WMF, i.e., the shear banding. From what has been observed in contraction flow, it is appropriate to take into account the inhomogeneous distribution of gelation and other micelles. The three species model is given as follows:

$$\partial_t \mathrm{L} + \mathbf{u} \cdot \nabla \mathrm{L} = -\mathrm{c}_1(\dot{\gamma}_x)\mathrm{L} - 3\mathrm{c}_2(\dot{\gamma}_x)\mathrm{L}^3 + \mathrm{c}_3(\dot{\gamma}_x)\mathrm{S}^2 + \alpha \mathrm{c}_4(\dot{\gamma}_x)\mathrm{G} + \varepsilon_{\mathrm{L}}\Delta \mathrm{L} \tag{1a}$$

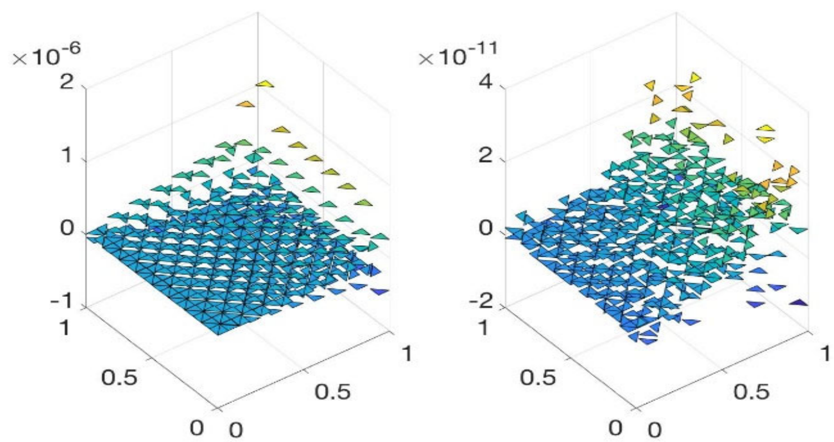
$$\partial_t \mathrm{G} + \mathbf{u} \cdot \nabla \mathrm{G} = \mathrm{c}_2(\dot{\gamma}_x)\mathrm{L}^3 - \mathrm{c}_4(\dot{\gamma}_x)\mathrm{G} + \varepsilon_{\mathrm{G}}\Delta \mathrm{G} \tag{1b}$$

$$\partial_t \mathrm{S} + \mathbf{u} \cdot \nabla \mathrm{S} = 2\mathrm{c}_1(\dot{\gamma}_x)\mathrm{L} - 2\mathrm{c}_3(\dot{\gamma}_x)\mathrm{S}^2 + \beta \mathrm{c}_4(\dot{\gamma}_x)\mathrm{G} + \varepsilon_{\mathrm{S}}\Delta \mathrm{S} \tag{1c}$$

where L is long or cylindrical micelle, S is short or spherical micelle, G is gelation, and $\dot{\gamma}_x$ is the spatially dependent shear rate or velocity gradient. The coefficients c_i for $i = 1, 2, 3$ and 4 are positive functions of $\dot{\gamma}_x$, $\varepsilon_{\mathrm{L}}, \varepsilon_{\mathrm{G}}$ and ε_{S} are diffusion coefficients and α and β are tuning parameters. The populations of species are designed to affect the flow through:

$$\mu_p = \mu_L \mathrm{L} + \mu_G \mathrm{G} + \mu_S \mathrm{S} \tag{2}$$

where μ_L, μ_G and μ_S are L-,G- and S-species viscosity, respectively. The coefficients c_i for $i = 1, 2, 3$ and 4 will be chosen so that the fluids exhibit the shear thinning when the micellar concentration is high while shear thickening transition is obtained for smaller concentration. When it is coupled to flow equation, it is important to numerically solve fluids velocity in such a way that the mass conservation holds true locally. The PIs have designed new local conservative flow solver. To demonstrate the conservation of mass in discrete framework, a Stokes system is solved on a test domain. As Figure 3 shows, unlike the traditional finite element method, our method shows that the local conservation holds true.



Mesh size	Iteration Numbers
$1/2^2$	43
$1/2^3$	45
$1/2^4$	46
$1/2^5$	49
$1/2^6$	49

Figure 3. From left to right, (a) element-wise divergence of velocity obtained by Hood-Taylor FEM and EG-Hood-Taylor FEM, respectively and (b) iteration counts of preconditioned MINRES for solving linear system by EG-Hood-Taylor FEM to reach tolerance 1.E − 10.

Impact of the research on the development of human resources

The ACS PRF ND grant provided PIs and graduate students with the opportunity to carry out novel research and obtain a deep understanding of the behavior of WMS in the porous media under various fluidic conditions. The grant supported a postdoctoral associate, 2 MS students, and a Ph.D. student to accomplish their theses and dissertation as well as preparing them for future careers.

References

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