PRF#: 56921-ND9
Project title: A CFD study of micro-emulsion formation and transport in a porous media
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Project summary: This research seeks to perform a computational study to develop methods that improve sweep efficiencies through chemically enhanced recovery of oils from porous media that make up most land-based oil wells. The PI is considering the micro-rheological behavior of a micro-emulsion that spontaneously forms at the interface separating two nearly miscible liquids in order to develop a firm understanding of these type of displacements which are relevant to the efficient removal of oil from porous media. The porous media will be modelled using an axisymmetric tube geometry. The term chemically enhanced is a generic phrase used to denote an aqueous phase that contains surfactants, solvents and/or possibly alkaline salts that are used to reduce the interface tension between it and an oil such that the two species can be considered miscible. We are particularly interested in what happens at the oil/water interface in the presence of surfactants or surfactant producing chemical reactions. The reason is that at the interface a micro-emulsion can form which has physical properties that are vastly different from either continuous phase fluid. In terms of modelling, the micro-emulsion can be considered a third species with its own physical properties. A schematic of the setup appears below (see Fig. 1).

To solve the problem mathematically we seek to understand the interplay between momentum and possible species transport.

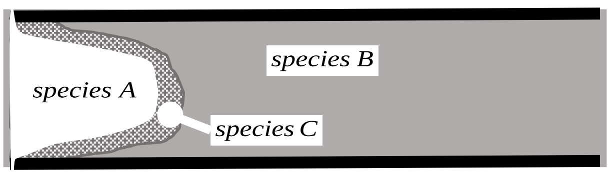

Figure 1. Problem Schematic.

We began the study by developing a firm understanding of emulsion rheology. While there are many published studies on emulsion rheology we were not convinced of generalizability of these prior results. Our results (see Fig. 2) for shear viscosity of emulsion containing aqueous sodium hydroxide and corn oil suggest that that emulsion thickens when sheared. Note the conditions under which these measurements were made (sheared in a viscometer) do not exactly match those that occur during displacement.

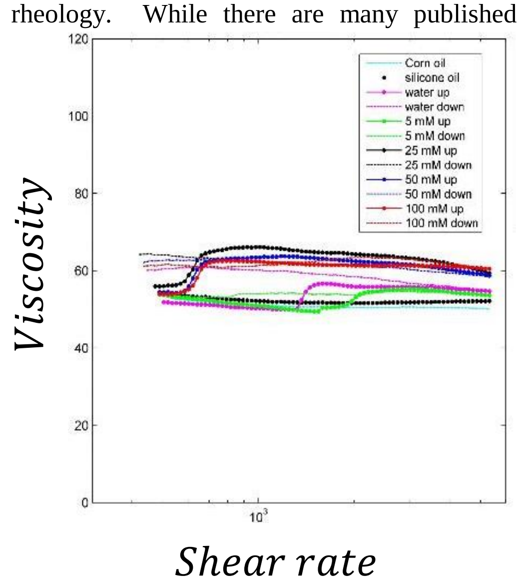

Figure 2. Shear viscosity (cP) versus shear rate for a sodium hydroxide and corn oil emulsion.

The curves are somewhat novel, even though the data itself is not, as most of these measurements are presented at a single shear viscosity value. But the collective trends seem to suggest a shear thickening region with two Newtonian plateaus at high and low shear rates similar to what is observed for shear thinning fluids via a Carreau fluid model:

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty) \cdot [1 + (\lambda|\dot{\gamma}|)^2]^{(n-1)/2} \quad .$$

The Carreau model is excellent for modelling viscosity over a wide range of shear rates since it has limiting values for high and low shear rates. This led us to explore properties of the Carreau fluid model, since we would need to connect model parameters of a Carreau fluid with those of a shear thickening emulsion.

Impact: We are currently performing experiments to remove shear thinning fluids (dilute aqueous polymer solutions) from capillary tubes as a way to explore Carreau fluid properties, and this has resulted in the discovery of a new instability as a function of the Carreau fluid parameter; which is similar to the Weissenberg number used for non-Newtonian fluids where the elastic fluid response time is replaced with the Carreau fluid characteristic time. This has been an exciting development, even though it is not directly related to the problem of immiscible fluid displacement.

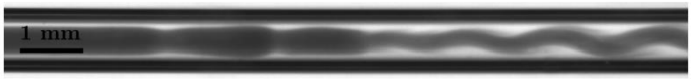

Figure 3. Water displacing aqueous carboxmethyl-cellulose (0.75%). Corkscrew-like instability forms after a critical length. Flow of displacing fluid is from right to left.

Shown left is an example of this instability that occurs for Carreau numbers greater than unity. As can be seen there is, what appears to be, a corkscrew type instability. It is not clear if this is a corkscrew since imaging is only 2D. We have been able to characterize this instability as a function of Peclet, Reynolds and Carreau number. Peclet numbers tend to determine the instability wavelength where there is a direct relationship between the two. Reynolds numbers also play a role; and this role deals with the length of displacing fluid that is required until the instability appears. This is illustrated in the picture above (see Fig. 3) where approximately half the tube shows axisymmetric type instability and the other half does not. The Carreau parameter is the main culprit for the appearance of this instability, where $Cu = \lambda a/U$, with λ the Carreau fluid characteristic time, a the tube diameter and U the mean velocity.

Exp	Pe $X10^4$	Re $X10^{-1}$	Image		Cu_0
1	8.85	2.47		$\mu_0 = 303.1$ cP	66.2
2	17.71	4.95		$\mu_0 = 1369$ cP	132.4
3	14.75	1.51		$\mu = 5$ cP	

Figure 4. Displacement images for a 0.5% polymer solution (carboxymethyl-cellulose) displaced by dyed water. Experiments performed at Reynolds, Peclet and Carreau numbers as shown (zero Carreau number for experiment 3. Mixing occurs in experiments 1 and 2.

This instability becomes stronger as tube diameter decreases as shown in Fig. 4 where the tube diameter is approximately half that of the tube used for experiments shown in Fig. 3. The fluids appear to mix in a non-laminar fashion despite the small Reynolds numbers.

<u>Career and student impact:</u> The funds from the ACS-PRF have had a positive effect on the PIs research goals. With these funds we have been able to focus attention on the underlying physicochemical phenomena associated with chemically enhanced fluid recovery. We believe that the work will result in important contributions to this field that will be beneficial to others studying similar problems. So far we have produced one publication (in press), one paper under revision, one paper under review and one in paper currently in production.

The funds have also had a positive impact for the PIs research group. We have been able to expand the project and have added two additional graduate students (previously there was only one graduate student). These funds have supplemented the salaries for these additional students who also work as teaching assistants. There projects will produce papers in addition to the ones mentioned above.

To conclude it is necessary to mention one of the overall, but maybe underappreciated goals of the research. There are practical benefits to increasing sweep efficiency. Since water is typically used as the displacing fluid, mainly because of its perceived abundance, then improving sweep efficiencies can also reduce its usage.

We would like to thank and acknowledge support from the ACS and PRF.