NARRATIVE PROGRESS REPORT
AMERICAN CHEMICAL SOCIETY - PETROLEUM RESEARCH FUND

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Title: Effect of Contact Forces on Displacement of Immiscible Fluids Through a Porous Network
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The goal of this project is to investigate the effect of sharp geometries on the propagation of an immiscible liquid interface through a porous medium. This topic is fundamental to understand the dynamics and transport of multiphase flow through porous rocks with applications to enhanced oil recovery, its modelling, and its simulation. We want to address the following questions: how does the pore geometry affect the *contact forces* and the *streamwise propagation of the liquid-liquid interface*? What is the impact of sharp vs. round edges on the *residual oil saturation* in the porous medium? During the second year of the grant, we have continued our work on flow through porous networks with sharp and rounded edges, and the penetration of falling spheres, smooth and spiky, through an oil-water interface.

In the first year of the grant, we investigated porous media flows through quasi-two dimensional networks in 3D-printed models via a Stratasys printer. In this case, the minimum radius of curvature for sharp edges was ~0.2 mm. We have since switched to a Form2 printer that allows more efficient printing with sharper edges. We have also switched to more simplified geometries that eliminate sidewall edge effects and developed a novel visualization method. We are currently completing parametric tests in these models looking at multiple fluid pairs subject to varying flow direction and Capillary number. The oil phase is visualized using a combination of fluorescing dye and ultraviolet illumination. This method allows reliable visualization of the presence and absence of thin films along pore surfaces. A snapshot extracted from an image sequence is shown in Figure 1. In this example, the interior of the model is initially filled with silicone oil. The silicone oil is then displaced by an aqueous solution using a syringe pump with fixed calibrated flow rate. The image reveals not only trapped oil volumes, but also the presence of oil films on the bounding surfaces. In addition to the direct visualization, the results are analysed based on the known volumetric flow rate and a mass balance to determine the volume of trapped fluid. These results, which will be presented at the upcoming 2018 APS DFD meeting, document the effect of sharp edges on film breakage as well as trapping within porous structures.

Figure 1. a) Top view of aqueous solution in process of displacing dyed silicone oil 20 cst. Flow is from left to right.

Separate experiments were performed to study the motion of smooth and rough spheres falling onto a flat oil-water interface. This auxiliary configuration helped us identify the effect of surface irregularities on a more simplified 3D geometry. The experiments were performed by Luuk Altenburg (Visiting Student from TU Delft, Netherlands) and Diogo Barros (Postdoctoral Associate, University of Minnesota). A sketch of the apparatus is presented in figure 2.a, where the oil-water interface is created inside an acrylic tank.

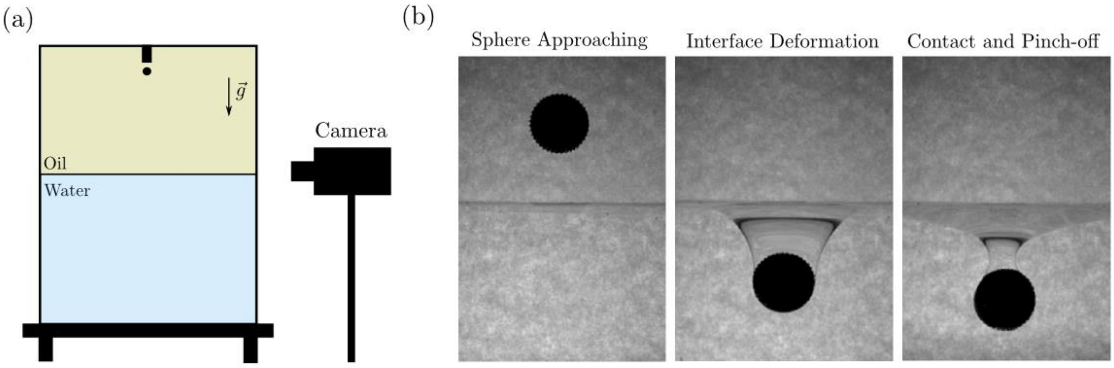

Figure 2. Motion of a sphere through an oil-water interface. a) Sketch of the experimental apparatus. b) Steps during the falling of a *rough* sphere through the interface captured by a high-speed camera.

After release at the top of the oil domain, the sphere settles under gravity, deforms the interface, and continues to sink for certain parameter combinations (see figure 2.b). The dynamics of this process was investigated over Bond numbers (computed using liquid-liquid density difference and sphere radius) in the range 0.2-1.05 and fluid-fluid viscosity ratios of 0.05-15. The ratio of solid-oil to water-oil density difference varied over 1.6-21. The influence of inertia in the problem was also considered by releasing spheres from multiple heights to account for variable approach Weber and Reynolds numbers up to 26 and 174 respectively. We have acquired comprehensive data sets over these ranges and presented the work at the APS DFD meeting in November 2017. We are preparing a journal article on this work. Key conclusions thus far are that inertia, surface wettability, and surface roughness all can affect whether particles float or pierce the boundary and sink.

Both sets of experiments described will provide key ingredients for future models of multiphase flow in porous media accounting for geometrical features. Our investigation has made significant impacts on the careers of the post-doc and two students who participated. Dr. Diogo Barros broadened his research expertise into a new direction and obtained an Assistant Professor position at Aix-Marseille University in France. Luuk Altenburg, participated as an ‘intern’ from TU Delft, where our work on falling particles has formed the basis of his master’s thesis (to be completed in January 2019) and helped initiate a broader collaboration between University of Minnesota and TU Delft. Jonathan Siles Garner participated as an undergraduate researcher and has gained significant experience in design, experimentation, and analysis.