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Effect of Confinement on Drop Coalescence: Lab Model Study of Oil Drop Coalescence for Enhanced Oil Recovery

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During the first year of the grant, we made significant progresses towards the goals of the project as described below. The graduate students working on this project are gaining valuable experience in experimental techniques necessary for interfacial fluid mechanics research.

Establishment of the Hele-Shaw cell setup

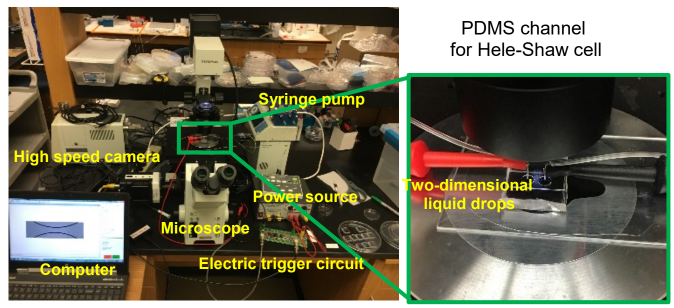

Figure 1. Left: experimental setup for the project. Right: Hele-Shaw cell device made of PDMS.

During the first year of the project, we improved the Hele-Shaw cell setup, which that we made for preliminary experiments before the beginning of the grant, for precise observation and analysis of drop coalescence (Figure 1). First, the Hele-Shaw cell (straight channel of a constant height with open ends) was fabricated using polydimethylsiloxane (PDMS)-based soft lithography for better control of the gap height of the Hele-Shaw cell (the inset of Figure 1). Second, two-dimensional (2D) drops were grown in the Hele-Shaw by injecting a working liquid through steel needles with a syringe pump. It was possible to control the size of the two drops by adjusting the distance between the needles and to control the growth speed of the drops by adjusting the flow rate of the syringe pump. Third, electric trigger was employed to synchronize the beginning of high-speed imaging with the initiation of drop coalescence. For this purpose, water and glycerol solutions were used as the working liquid, and salt is added to create conductive solutions. The needles of the Hele-Shaw cell were connected to the electric trigger circuit, and voltage was applied between the needles. When the drops made a contact, the circuit triggered the high-speed camera. Last, a bright field inverted microscope was used for magnified imaging of drop coalescence. The improved setup enables reproducible coalescence of 2D drops.

Drop coalescence in gas in confinement

After finishing the Hele-Shaw setup, we investigated coalescence of 2D drops of glycerol solutions. The improved setup enabled capturing and analyzing the dynamics of the drop coalescence in detail. Once the two drops formed in the Hele-Shaw cell made a contact, they began coalescence, but the coalescence was limited to the neck region between the drop because of the confining walls of the cell (the top figure in Figure 2). Surface wave was observed to develop on the meniscus of the drops while the neck grew, but the wave disappeared because of high viscous shear stress caused by the narrow confinement of the Hele-Shaw cell. Also, a bubble was observed to generated at the center of the coalescence neck.

We developed a MATLAB-based image processing method to automatically measure the width r of the growing coalescence neck (Figure 2 top) as a function of time t ($t = 0$ s indicates the initiation of coalescence). Data obtained from repeated experiments with different conditions were plotted together using dimensionless variables: $r^* = r/(R_{avg}w)^{1/2}$ and $t^* = t/\tau_c$, where R_{avg} is the averaged radius of the two drops, w is the gap height of the Hele-Shaw cell, and τ_c is the capillary time scale [$= (w^3\rho/\gamma)^{1/2}$]. Here, ρ and γ are the density and liquid-vapor surface tension coefficient of the used glycerol solution. Although conditions were different, scaled data collapsed on a single curve (Figure 2 bottom), which shows transition in the scaling exponent α of $r^* = (t^*)^\alpha$. The early part of the curve seems to show the inertia regime of drop coalescence because α is close to 1/2, and the later part shows negligible growth of the neck due to viscous dissipation. We expect the viscosity-dominant regime for the very early moment of coalescence when the neck is three dimensional, so we plan to adjust experimental condition to capture it.

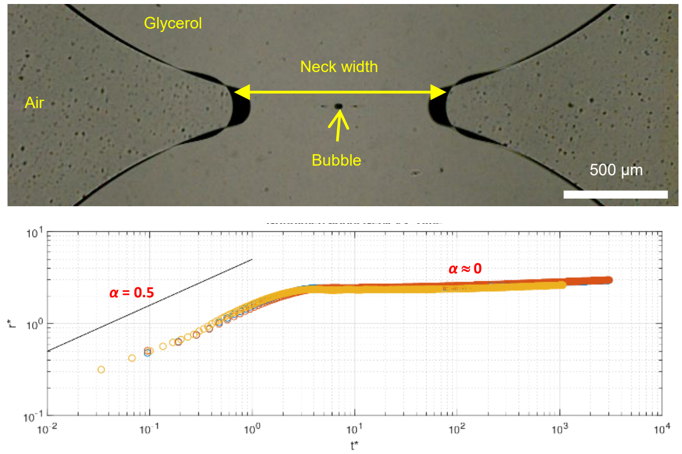

Figure 2. Top: captured image of coalescing glycerol drops in the Hele-Shaw cell, showing the surface wave development on the drop meniscus and the air bubble at the center of the neck. Bottom: dimensionless plot the neck width growth of three different coalescence cases.

Gas bubble entrapment due to the confinement

Bubble generation was observed during the coalescence. By tilting the channel device, we found that actually two bubbles were generated; one near the top wall, and the other near the bottom wall of the cell. Also, when drop coalescence was done on a single glass surface, only one bubble was observed. Therefore, the observed bubble generation is thought to be caused by rapid motion of the bulk liquid outpacing the motion of the contact line (solid-liquid-gas interface) entrapping gas and forming a bubble. This phenomenon is expected to be dependent on the contact angle and contact angle hysteresis associated with the wall.

Contact angle measurement using the meniscus thickness

As shown in the top panel of Figure 2, the meniscus of the drop (i.e., interface between the drop and air) appeared dark because the curved meniscus refracted light. We developed a MATLAB-based image processing code to measure the thickness of the meniscus, and found that the meniscus thickness increased with the gap height of the Hele-Shaw cell while the contact angle of the drop was fixed. After having hypothesized that the meniscus width was determined by the contact angle and the gap height, we developed a simple theoretical model to measure the contact angle using the meniscus thickness of the drop and the gap height of the Hele-Shaw cell. Using a syringe pump to flow the drops, contact angle hysteresis can be measured. The measured values agreed well with the contact angle value measured with a goniometer.

Plan for the second year

In the first year of the project, Objective 1 of the project, "Develop a Hele-Shaw cell laboratory model mimicking oil ganglia" was achieved, and Objective 2 "Analyze two-dimensional (2D) drop coalescence dynamics in air with modulated coalescence conditions" was partly achieved. In the next twelve months, we will examine more cases of drop coalescence in air by changing surface wettability, surface tension coefficient and liquid viscosity, as a part of Objective 2. We will also investigate the coalescence of liquid drops (dispersed phase) in an immiscible liquid (continuous phase) using the Hele-Shaw cell setup. For Objective 3 "Measure the flow velocity field during 2D drop coalescence", we will measure the velocity field in the coalescing drop using particle image velocimetry or particle tracking velocimetry. We expect to obtain the following outcomes at the end of the second year: 1) scaling laws of the neck width growth of drops coalescing in the confinement of the Hele-Shaw cell, 2) flow velocity field of drops coalescing in the confinement, 3) bubble entrapment mechanism during the coalescence, and 4) a new contact angle measurement method based on the meniscus thickness of drops in the confinement. The outcomes of the project will be published in relevant journals in the second year. Currently two manuscripts are being prepared based on the outcome of the first year of the project.