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Visualization of Bubble Dynamics in Oil Water Gas Interface The Effect of Rheology

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ABSTRACT

Dynamics of bubbles at quiescent oil/water interface is visualized using high speed imaging system and particle image velocimetry (PIV). In addition, comparison with CMC (Carboxymethyl cellulose) dissolved in water is considered. In this work we describe experiments done in a transparent test cell at the University of Stavanger. These experiments are done with silicon oil overlying an aqueous still fluid. Air bubbles are injected from the bottom of the cell and multiple bubbles aggregate at the interface. When the buoyancy force is sufficiently high to overcome capillary forces at the interface, multiple bubbles are detached and move upward through an envelope of aqueous phase. Transport and dynamics of entrained aqueous liquid through the oil phase is clearly visualized in the experiments. When the air bubbles finally are released at the upper oil surface, aqueous liquid coalesce as droplets - they detach and fall down through the oil phase. At the water-oil interface in the oil a layer is formed of distinct water droplets. They will gradually coalesce and grow and after some time fall down back into the water phase. There is thus a continuous process of water droplets falling from the top of the oil into this apparent mixture or "mid-phase" of oil-water droplets. This process can eventually be understood in terms of population dynamics theory, based on a creation-destruction model. In this way we can consider the experiments to be one of the simplest prototype examples of oil-gas-polymer mixing in still liquids.

INTRODUCTION

The mixing of two liquids, in this case oil and water, leads to a dispersion where either water or oil is continuous and the other phase dispersed as droplets[1]. Studies of fluid transport by such a bubble cluster necessitate a general understanding of the bubble dynamics associated with the motion of single bubble. The mixing between these two liquids is reported to be greatly accelerated by bubbling gas through the system. The mixing of immiscible liquids is an important phenomenon both in nature and in technology. For example, oil water and gas mixtures in petroleum industry for efficient recovery of oil is important. To identify the different mechanisms that make mixing of fast flow processes understandable, visualization using high speed systems is important.

As the bubbles rise and travel through the interface the fluid transport is characterized by a local drift and a reflux across the flow volume[2]. Fig. 1 illustrates the drift of a solid particle moving through an oil water interface. Water is then dragged together with the particle but will fall down (reflux) back to the interface. When bubbles are injected in the same way they will transport the water along the direction of their motion. The water uplift and transport is referred to as drift. An important phenomenon in fluid dynamics and many industrial processes involves such changes at the interface between two immiscible fluids. A filament of water is formed and

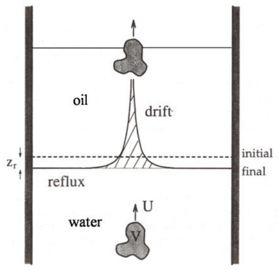

Figure 1: Schematic representation of Darwin's model of fluid displacement by a rigid body crossing the water oil interface. Reproduced and modified from Bush and Eames[2].

many droplets are generated due to the instability of the filament. Fig. 2 illustrates such a system. Some bubbles stay or slow

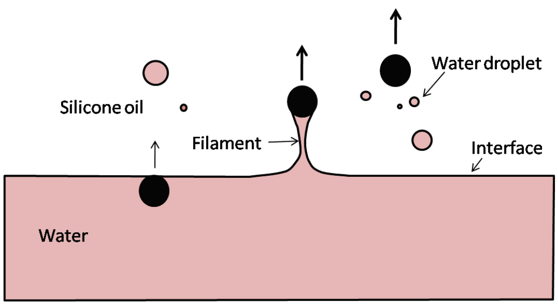

Figure 2: Illustration of traveling bubble through the interface between water and silicone oil.

down at the interface for some time and form a coated aqueous dome that protrude into the upper oil phase. These bubbles also drift the aqueous phase into the upper oil phase as mentioned earlier. Firstly, this entrainment occurs in the form of a film around the bubbles to create an envelope. Later on, the film breaks down in the oil phase. After the film ruptures the bubbles continue their rise in the oil phase and coalesce with the upper surface.

The present study is to get knowledge of the nature and characteristics of bubble dynamics in immiscible liquid mixture induced by gas injection. High speed video systems is used in order to understand the details during the passage of the bubbles through the interface between the water and oil.

EXPERIMENTAL SETUP

The experimental apparatus in this study is presented in Fig. 3. Oil and

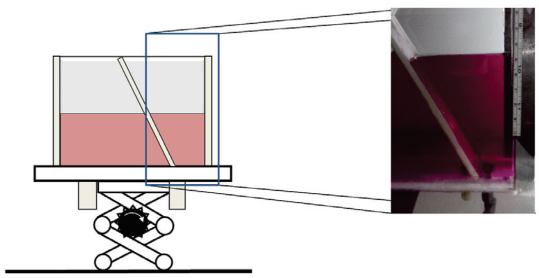

Figure 3: Schematic representation of the bubble facility.

water layers were established. The cell is 20 cm x 20 cm in cross section and 5 cm in width. It was mounted on an acrylic bottom plate and placed on a jacket platform so that manual lifting is made possible. Air bubbles with a volume of 0.5 ml where injected using a syringe from the the bottom of the cell. Also experiments with CMC (Carboxymethyl cellulose) solution in water were used together with silicone oil (viscosity 0.01055 Pa.s and density 930 kg/m^3). The lower liquid layer was dyed using Lissamin red while the upper layer was clear. This was done in order to visualize the mass transport of the heavier water phase to the upper oil layer. Two modes of bubble injection were used. Either as only a single bubble, or continuously from the bottom inlet.

Visualization was obtained using both a low cost camera (Samsung EK-GC 100, 768 x 512 pixels 120 fps in slow motion video mode) and a high speed camera (MiniVis e2, 512x512 pixels, 2500 fps) together with light emitting diodes (LEDs). The high speed camera was computer controlled using the software program MotionBlitz from Mikrotron. The Samsung camera is a simple and inexpensive system that probably can substitute expensive equipment to achieve moderate accuracy as compared with high cost and complex system. This is realistic at least for frame rates up to 120 fps.

RHEOLOGICAL MEASUREMENTS

The non-Newtonian solutions of 0.1 and 0.5 g/L of CMC (Carboxymethyl cellulose sodium salt, low viscosity) from Sigma-Aldrich were dissolved in water. The rheological characterization of the solutions was done using an Anton Paar MCR-302 for shear rates ranging from 1 to 1020 s^{-1}. Cone plate geometry CP50-1 was used for performing the experiments at 20^{o}C. The measurements were repeated several times to get rid of experimental uncertainty. The viscosity as a function of shear rate is graphed in Fig. 4 for these two solutions. It can be seen from this figure that the polymer solutions are shear thinning. Oscillation tests were performed at

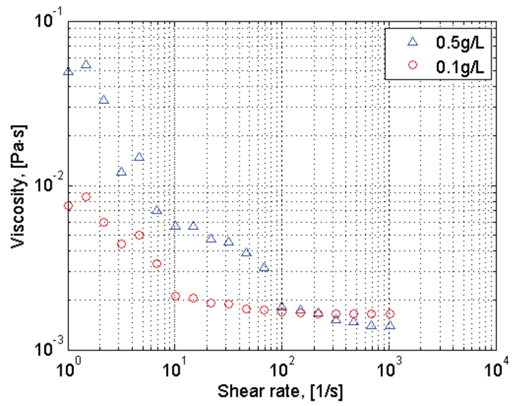

Figure 4: Viscosity as a function of shear rate for 0.1 and 0.5 g/L of CMC.

an angular frequency, ω=10 rad/s. This was conducted in order to evaluate the viscoelastic behavior of the polymer solutions. Only test for the 0.5 g/L of CMC is presented here. Fig. 5 shows the results from this test. It is found that both the storage

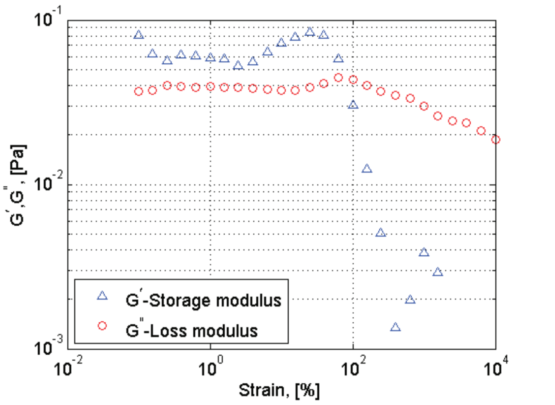

Figure 5: Viscoelastic behavior of 0.5 g/L of CMC. ω = 10rad/s.

modulus (i.e. elastic response G') and loss modulus (i.e. viscous behavior G'') are independent of the strain within the linear viscoelastic regime during the oscillatory measurements.

EXPERIMENTAL RESULTS

The bubble dynamics has been visualized at four regions; in the water phase, at the oil-water interface, in the oil phase and finally at the top surface of the oil. But most results presented here are at the interface between the oil and water.

Visualization in Newtonian system

Visualization in the water phase

The bubble was injected from the bottom of the cell using a syringe. As the bubble rises a zigzag motion of the bubble was observed.

Visualization at the oil-water interface

According to the image sequences in Fig. 6 the following stages describe the bubble passage through the oil and water interface:

- rising of the bubble from the aqueous phase, t = 0 s

- entrance of the bubble at the interface (t = 32 ms) where the bubble was slowing down and the interface started to deform. This situation is consistent with the model made by Darwin (1953), see Fig. 1 published in Bush and Eames[2], where the upward filament drawn upward behind the bubble is referred to drift.

- at t = 192 to 1232 ms the water film started to drain around the bubble. The bubble stretched the interface and deformation of the bubble shape, as seen from Fig. 6. This observation is in accordance with Reiter and Schwerdtfeger[3]

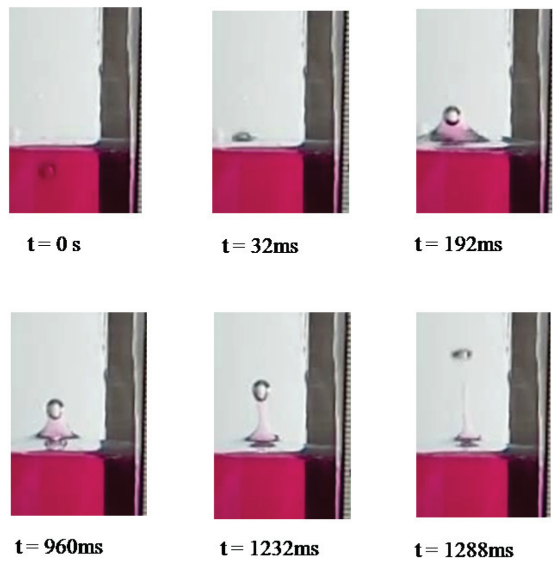

Figure 6: Image sequences of the bubble through the interface. The heavier fluid is water.

- at t = 1288 ms the water film ruptures. This is seen in detail on the right in Fig. 7. This is a zoomed in snapshots of the bubble interface. Numerous water droplets broke out from the ruptured water film. This film rupture has also been observed by others[4,5] in the literature. Additionally, as seen in the left photo in Fig. 7 ripples were formed on the outer interface of the water film around the bubble. This is caused by interfacial tension[5].

Figure 7: Selected snapshots from the high speed images of the bubble shape at the interface. Left: liquid drainage on top of the bubble. Right: the bubble drifts in a thin filament

- from t = 1288 ms the bubble continues to rise the silicon oil. The bubble shape becomes oblate

Visualization at the oil-air interface

When the bubble reaches the interface between silicon and air, air bubble eventually breaks and the attached water falls down to the oil water interface.

The position of the air bubble as a function of time in water is presented in Fig. 8. As mentioned, when single bubble was released to the water it traveled in a zigzag manner. Its time position is shown as a linear motion. From time between 1520 ms to 2720 ms the bubble stayed at oil water interface and from 2720 ms the bubble left the interface and traveled through the oil in a rectilinear manner. This different type

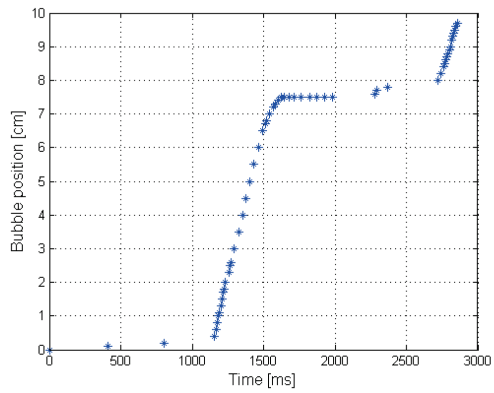

Figure 8: Bubble position as a function of time.

of motion in the water phase and in the oil phase is probably due to a combined effect of higher oil viscosity and the extra load of attached water on the bubble.

Visualization in non-Newtonian system

The same pattern was also obtained in 1g/L CMC solution. The bubble was also stretched but the length of the filament was shorter than in the water case at the interface and deformation of the bubble shape, as seen from Fig. 9.

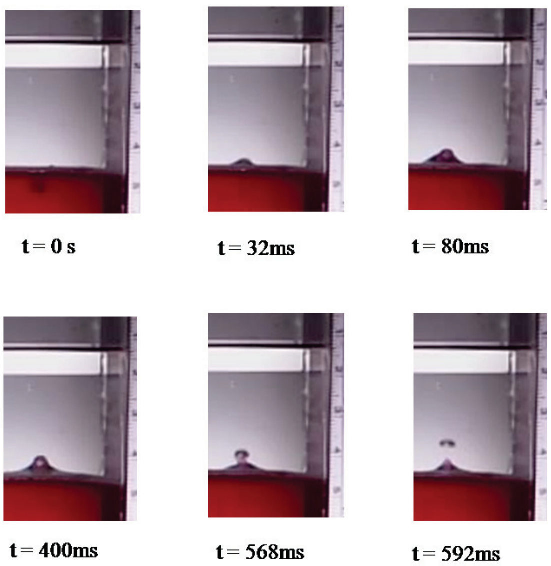

Figure 9: Image sequences of the bubble through the interface. The heavier fluid is 1g/L CMC.

The result from bubble positions obtained from 1 g/L of CMC added in water is presented in Fig. 10. The retention time of the bubble at the interface seems to be shorter (from 960 ms to 1120 ms) compared to the Newtonian case. This could be interpreted as a hydrodynamic effect related to the bubble size. But it could also an effect of rheology or interfacial tension. It was difficult to obtain identical bubbles of the same size from experiment to experiment. Any distortion during injection of the bubble could also lead to disturbance of the oil and water. The ripples at the interface be-

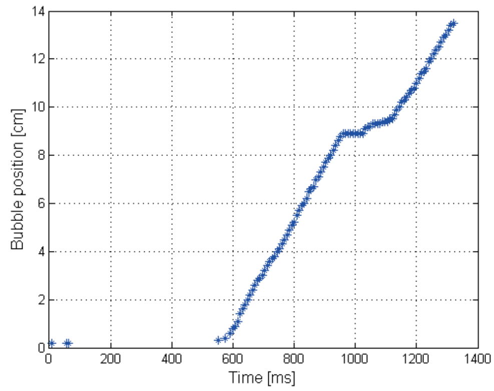

Figure 10: Bubble position as a function of time obtained from 1 g/L of CMC.

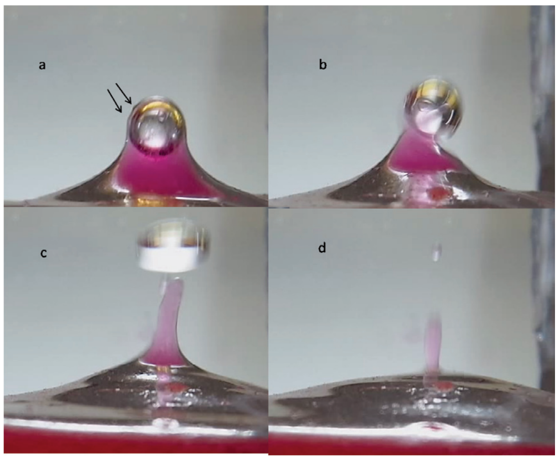

Figure 11: Sequence images of single bubble at the interface between 1 g/L of CMC and silicon oil. The arrows on top left point the ripples position. The time between the images is 8 ms.

tween polymer solution and oil are still visible but clearly damped. This can be seen as indicated by the arrows in Fig. 11a. Substantial drift of uplift of the colored polymer is also clearly seen. In Fig. 11d the bubble continues to rise, detaches from the polymer and traveled through the oil layer. Eventually, the bubble reaches the oil air interface and residue of heavier polymer solution falls back through the oil layer to the polymer oil interface.

CONCLUSIONS

Experiments with air bubbles moving through still oil and water-based layers were studied. Both tap water and CMC polymer solution were used. An intricate behavior of the air bubble transport in water or polymer through the oil was observed. Several mechanisms seem to be involved in the updrift of the heavier water phase. Also the use of a fairly inexpensive camera for imaging the bubble and flow dynamics is of some importance. This is of particular interest for research and teaching for low cost applications where traditional PIV apparatus are not affordable. Nevertheless, high speed camera system would definitely be more appreciable due to its powerfulness and high accuracy.

In this way we can consider the experiments to be one of the simplest prototype examples of oil-gas-water (or polymer) mixing in still liquids.

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