MCEN 5151 Team Second: Died Bubbles of Alcohol ”Pop” in a Suspension of Oil

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ABSTRACT

A companion to Team First: Alcohol Suspended in Oil Floating at a Density Barrier. In this demonstration we capture a dyed bubble ”popping” and record the resulting outflow. Some text is borrowed from the companion report, as similar dynamics were at play. In this report, I choose to focus on flow and flow response times as opposed to bubble formation.

Keywords: Flow Visualization, Stokes Number, Immiscible Bubbles

INTRODUCTION

The image in Figure 1 is a still from a slow-motion video produced for MCEN 5151 and the second team project. The same image is presented in the negative in Figure 2, which makes certain features easier to identify. The team consisted of myself and classmates Sami Algoosi and Alessandro Sanchez. This project is a companion to the first team project where I accidentally suspended dyed bubbles of aguardiente in a density column. With this project I sought to intentionally produce those same bubbles and record one of the bubbles popping in slow-motion. While the colors and framing may be of artistic interest, the primary goal was the record a brief moment of Stokes Flow as the surface tension holding the bubble together collapses.

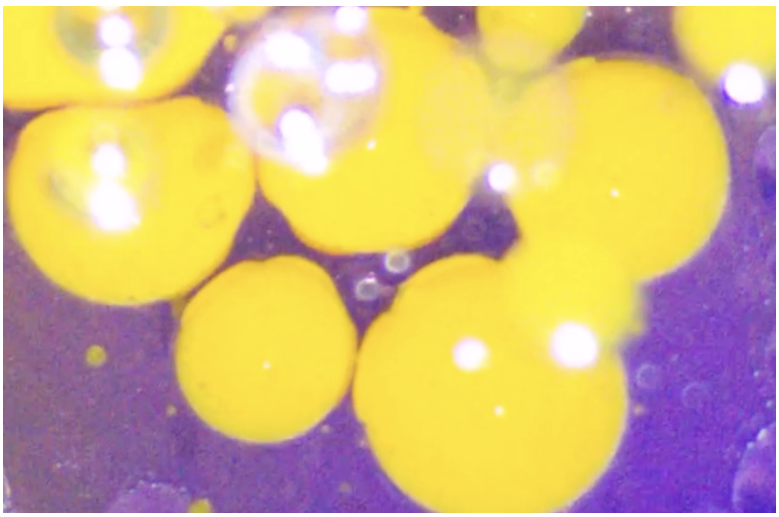


Figure 1. Real color of bubbles of aguardiente (yellow) suspended in canola oil (clear) sitting atop dyed water (purple).

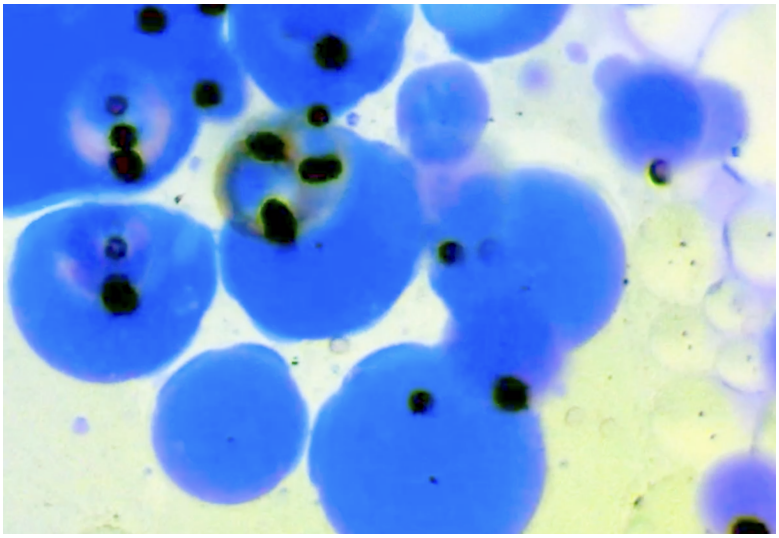


Figure 2. The same image as Figure 1, but in the negative.

Fluids @ 20C	Canonical Density ($kg \cdot m^{-3}$)	Canonical Viscosity ($Ns \cdot m^{-2}$)
Water	992	1.001
Canola (Rapeseed) Oil	900	0.118
Alcohol (Ethanol, pure)	790	$118 \cdot 10^{-6}$
Aguardiente (30% ABV, estimated)	931	N/A

Table 1. Relevant properties for fluids pictured. Canola oil values are from *Properties of Food Processing* (Fellows). Aguardiente density approximated assuming the labeled 30% alcohol-by-volume.

FLOW PHYSICS

0.1 Density

Canonical densities and viscosities at 20 degrees Celsius are presented in Table 1.

0.2 Stokes Number and Flow

It is worth mentioning the Bond number and Morton number, considering the return to viscous bubbles and the relevance of surface tension. The Bond number is a dimensionless number that encodes the ratio of gravitational to surface tension forces and is as follows:

$$\mathrm{Bo} = \frac{\Delta\rho g L^2}{\gamma} \tag{1}$$

It can be thought of as "Mass Component divided by Surface Tension Component" and relates gravitational and exterior fluid pressures to self-stabilization by surface tension. Large Bond numbers indicate that gravity dominates over surface tensions, either "popping" a bubble over the surface it sits on, or dragging the upper phase through the surface of another, forming a bubble. Despite small length scales, we see both the formation of bubbles as aguardiente sinks through canola oil the form bubbles, and then eventually pop after settling near the water layer. This seems to indicate that the oil and aguardiente exist in the unstable bubble regime described by (Park et al.).

The Morton number relates viscosity drag and surface tension of a bubble moving through a stagnant fluid, characterizing bubble speed and helping to approximate shape.

$$\mathrm{Mo} = \frac{g\mu_c^4\Delta\rho}{\rho_c^2\sigma^3} \tag{2}$$

Here μ_c is the viscosity of the host fluid, ρ_c denotes density of the host fluid, and σ is the surface tension at the boundary. $\Delta\rho$ and g retain their meaning. For circular bubbles like we see in Figure **??**, bubble

velocity is primarily influenced by viscous forces, so a large Morton number would correspond with a slow-moving bubble (Pfister and Hager). With small Morton numbers, we expect rapid movement of bubbles, which makes sense considering the low viscosity of canola oil.

Of particular interest in this report is the Stokes number:

$$\mathrm{St} = \frac{t_0 u_0}{l_0} = \frac{\rho_p d_p^2 u_0}{18 \mu_0 l_0} \tag{3}$$

The Stokes number relates the stopping time or response time of a particle embedded in a fluid to the stopping time or response time of the host fluid (**?**). Small Stokes numbers, $\mathrm{St} << 1$, describe particle motion that is well coupled to the host fluid and follows it closely, while a large Stokes number, $\mathrm{St} >> 1$ describes a poorly coupled particle who's movement is dominated by inertia. Subscripts of $_p$ indicate characteristics of the particle, and subscripts of $_0$ indicate characteristics of the host fluid, which in this case is the augardiente. Symbols carry their typical meaning: ρ_p is particle density, d_p is particle diameter, u_0 is the flow velocity of the fluid, μ_0 is the viscosity of the host fluid, and l_0 is a characteristic length. Estimating the particle characteristics of the tattoo ink/dye is based on ink particles from ink-jet printers and food-grade titanium dioxide TiO_2 (1; Geiss et al.).

The Stokes number is typically used with continuous flows, like a stream or gas moving through space (Murray et al.). To approximate the bubble popping as a continuous flow, we need to zoom in on small length and time scales. The next section contains more details on the video and camera techniques, but for calculating length and time scales, the bubble in Figure 3 is approximately 0.1 cm and 1 frame corresponds to approximately 0.01 seconds. To calculate a representative Stokes number, we use a representative 50 nm in radius particle of titanium dioxide to approximate the dye. We take a representative length of 10 mm, approximately the size of the bubble, and notice that when the bubble pops, auguardiente flow approximately 50 mm in 25 frames for a characteristic velocity of 0.02 $\frac{\mathrm{m}}{\mathrm{s}}$. Approximating aguardiente as the viscosity of water, we get:

$$\mathrm{St} = \frac{(3{,}000\mathrm{kg}\cdot\mathrm{m}^{-3})(50\cdot 10^{-9}\mathrm{m})^2(0.02\mathrm{m}\cdot\mathrm{s}^{-1})}{18(1.67\cdot 10^{-6}\mathrm{m}^2\cdot\mathrm{s}^{-1})(0.01\mathrm{m})} = 0.0000005 \tag{4}$$

An extremely small Stokes number indicates a high responsiveness to the flow of the host fluid. This can be seen in Figures 6 and 5. In these images we can see a cleft that has formed in the dyed aguardiente as the canola oil that had comprised the surface of the bubble settles into the aguardiente that spilled out of the bottom of the bubble. As they aguardiente is displaced, the dye readily follows even small movements of the host fluid.

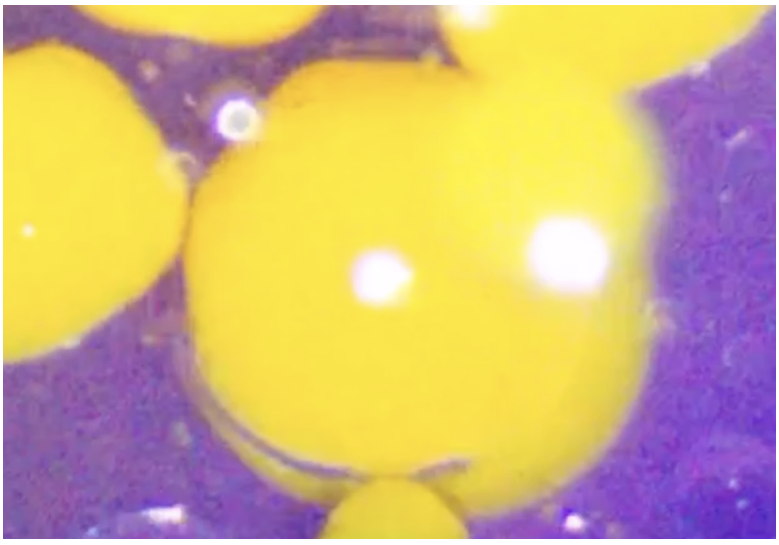


Figure 3. A photo of the bubble "mid pop". The temporal resolution was able to capture some aguardiente outflow while the surface tension of the bubble collapses.

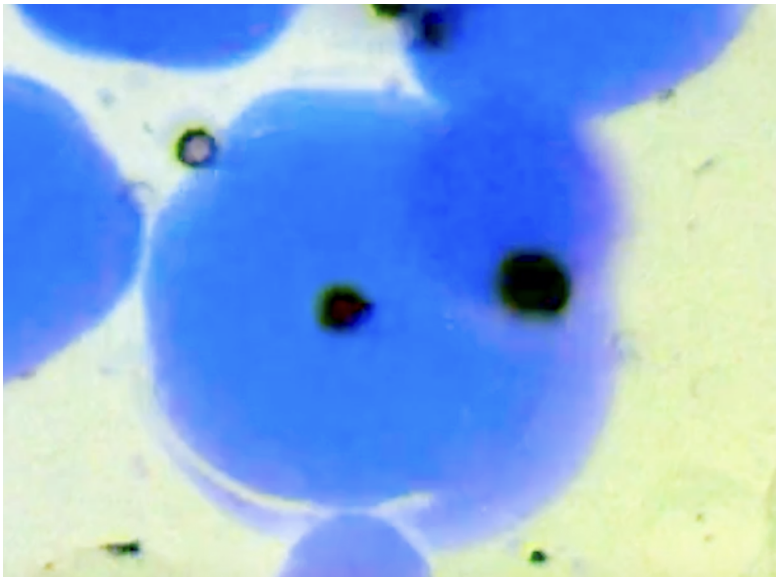


Figure 4. Same image as Figure 3, but in the negative.

VISUALIZATION TECHNIQUES AND PHOTOGRAPHIC SPECIFICATIONS

Brightly colored tattoo dye was used to color water and aguardiente to be visible against each other and in canola oil. A flash light of approximately 280 Lumens was held above the container of oil and aguardiente at approximately 30 degree away from the normal, and directly manually by myself. The video was recorded on an AmScope MU203Bi with a ”kludge-y” assortment of lenses and optics pieces that were threaded appropriately to fit the camera, but the exact specifications of which have been lost to poor record keeping. An aluminum optical setup was arranged to manually bring the image into focus, approximately 20 cm above the surface of the container.

The AmScope MU203Bi is capable of recording at 140 FPS, and with the lighting conditions, exposure, and gain, the presented video was captured at approximately 110 FPS and slowed in post processing; approximately 1.5 seconds of real-time in 7 seconds of video. The presented video shows the bubble popping, a reverse of the same, and then both forward and backward time phases in negative. Some features are more readily visible in negative, due to a reduced glare from the light, warranting it’s inclusion. The video was heavily cropped to focus on a singular, popping bubble, and resolve the resulting outflow. Specific pixel information is not readily available in iMovie, but the playback settings turned about 2.3 s of real time into 7.5 s of slow-motion video.

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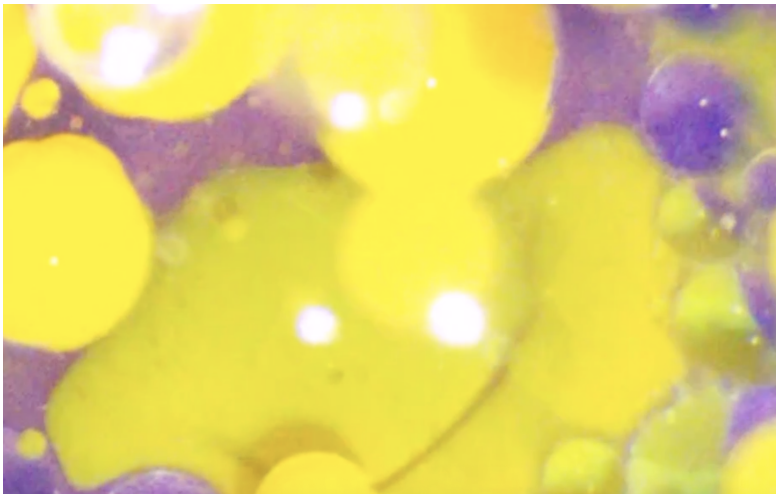


Figure 5. An image taken after a large relaxation time. A cleft in the dyed aguardiente is clearly visible, indicating where canola oil that had formed the edge of the bubble settled into the flow.

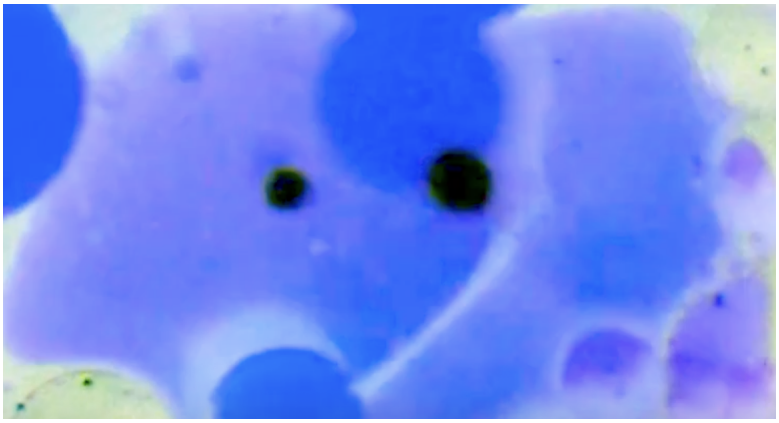


Figure 6. Same image as Figure 6, but in negative.

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