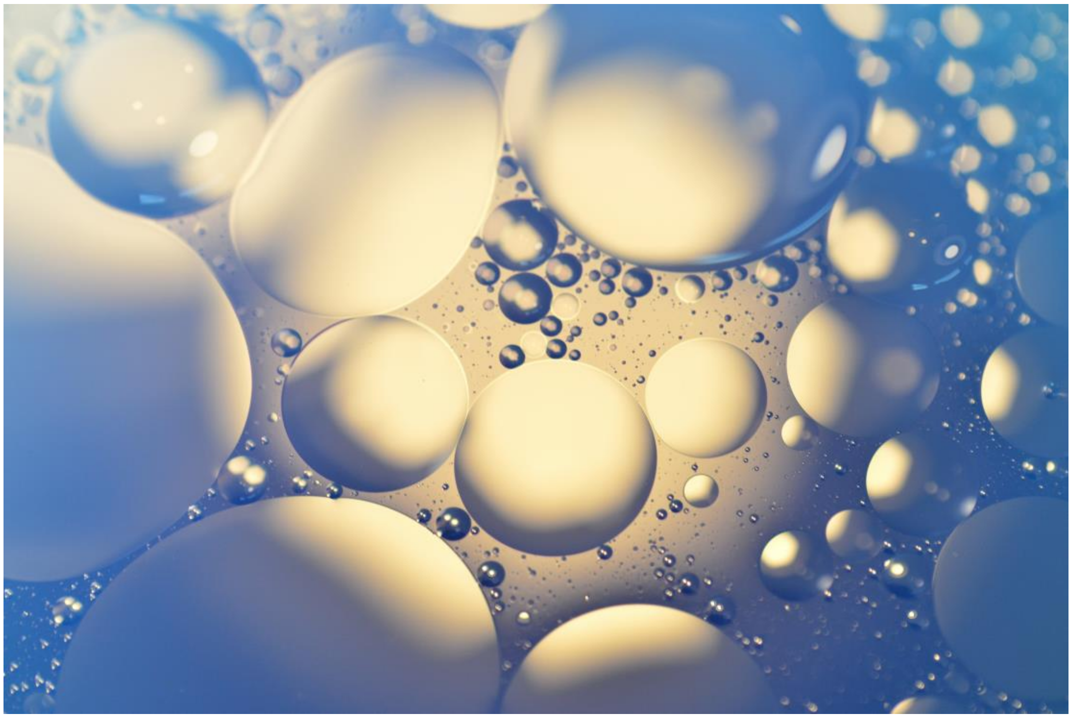
Cameron Sprenger

MCEN 5151

Get Wet Assignment



Background

This is the first assignment for MCEN 5151 Flow Visualization. The goal is to gain an understanding of basic camera operation and set up, as well as techniques when setting up experiments to produce the desired flow or fluid effect that will be photographed. It took quite a while to decide what I was going to try to photograph for this project because there are endless types of fluid flow and fluid interactions. I tried dripping dye into water, creating a boundary layer between a saline solution and water, creating convection cells with a heating element, mixing two opaque fluids to form vortices, capturing water droplets midair, and the total internal reflection on an air-water boundary. Each time, either the resulting fluid flow was underwhelming, or the photographs weren't able to capture what I was seeing. What I ended up photographing was the aftermath of one of my previous experiments where I was dripping vegetable oil and milk into dyed blue water. Since the milk was soluble, it mixed into the water making for a nice light blue color while the insoluble oil sat on the surface and formed drops. The interaction between the oil and water formed crisp and contrasting borders which I found to be very visually appealing. The scale of the droplets were small, so I had to use a macro lens to get close enough to see the tiny details. The larger droplets in the photo are approximately 6-8 mm. in diameter.

Physics of the Flow

There are three main forces at play in the formation of the oil bubbles seen in the picture. First being the polarity of the water and oil molecules, the surface tension of the two liquids, and the buoyant forces resulting from the difference in densities of the water and oil. The oil formed drops on the water/milk surface instead of mixing into the water because water is a polar molecule, while the oil is nonpolar. There is a common adage, "like dissolves like" which means polar things mix well with other polar things, such as salt in water, and non-polar things mix well with other non-polar things. In the case of water and oil, the water forms hydrogen bonds with itself, since it is a polar molecule, which the oil is not able to break, so instead of trying to break these bonds the oil is forced out from between the water molecules and clumps to itself which forms drops that rise to the surface due to the difference in densities (Figure 1).

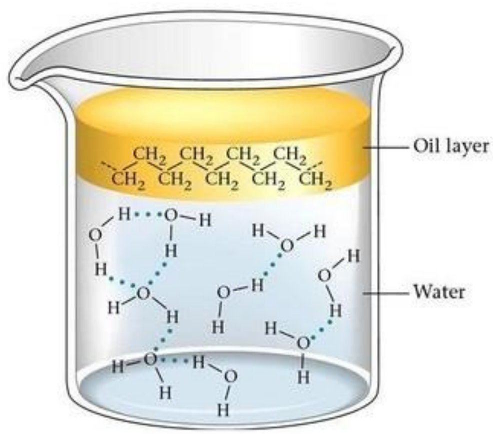


Figure 1.

This shows the interaction between water and oil. Hydrogen bonds are shown as the dotted blue lines between the water molecules. These strong bonds force oil molecules out from between the water and into droplets.

The same hydrogen bonds that hold water molecules together are also responsible for water having high surface tension. When exposed to air, water has a surface tension of approximately 72 mN/m (milli newtons per meter) which is about twice that of oil exposed to air which has a surface tension of around 35 mN/m. The distinction that a liquid is exposed to air is important because the surface tension of a fluid changes if the interface is with another substance due to the differences in intermolecular forces. When water is exposed to air, the hydrogen bonds of the surface molecules are stronger than the bonds of molecules in the bulk because there are less bonds between the surface molecules making for stronger bonds (Figure 2). When another fluid is added to the surface of the water it disrupts the hydrogen bonds at the surface and lowers the surface tension. When oil is added to water, the surface tension of the water decreases to approximately 40 mN/m.

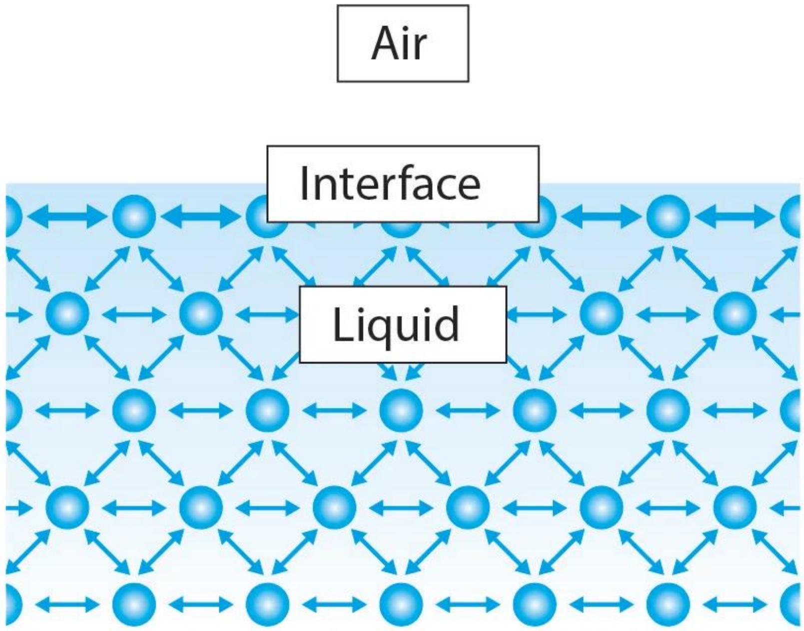


Figure 2.

Force vectors for hydrogen bonds between water molecules with an air interface. The hydrogen bonds on the surface of the water have less adjacent molecules which results in stronger interactions.

If you look closely at the bubbles of oil on the water, you can see they are reflecting light differently based on their diameter. This is because the curvature of the top surface is directly related to the diameter of the bubble because the units of surface area are force over cross-sectional length. The two main forces acting on the bubbles are gravitational and surface tension. The outward pressure due to gravity is a function of the fluid's density, volume, and hydraulic head pressure, whereas the tension is only related to the length of the cross section of the bubble. This relation does not scale linearly as the mass of the droplet is increased, so larger bubbles will be flatter compared to smaller bubbles because of the greater gravitational force relative to the surface tension. The figure below shows the force balance on the surface of a fluid of varying size (Figure 3). The smaller bubble takes on a more rounded shape as the surface tension tries to decrease the length of the surface of the fluid, while the larger bubble forms a flatter shape as the pressure due to gravity increases more quickly than the surface tension.

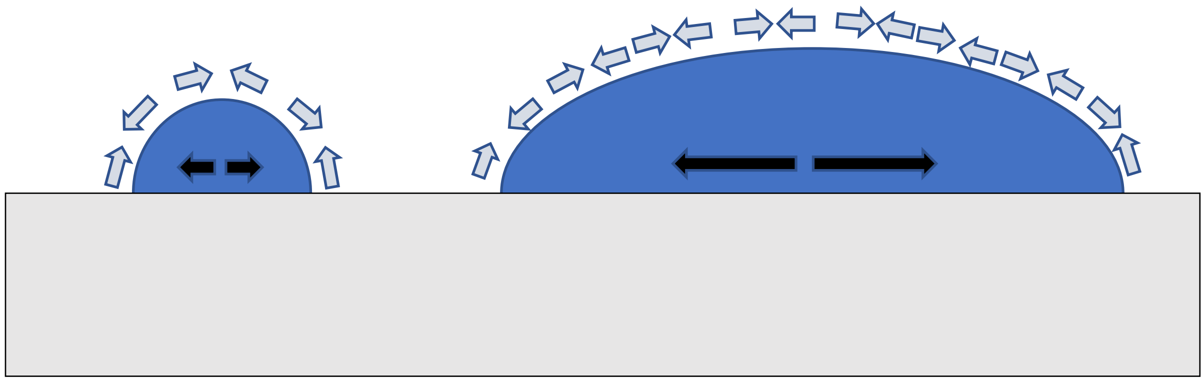


Figure 3.

Shown above are two cross sections of bubbles that are different sizes and the resulting shape. The black arrows show the outward pressure due to gravity inside of the bubble and the light blue arrows are the force vectors due to the surface tension acting tangent to the surface.

The maximum thickness of the oil bubbles on the water can be calculated using the equation below which assumes the contact angle between the water and oil is 180°. In reality, this angle is probably slightly off because the water does not form a perfectly flat surface that the oil sits on, but instead is slightly depressed, but as an approximation it will work. The equation is in terms of surface tension, gamma (γ), gravity, and the density of the fluid, rho (ρ) which for vegetable oil is .91 $\frac{g}{cm^3}$.

$$h = 2 \cdot \sqrt{\frac{\gamma}{g \cdot \rho}}$$

Solving for *h* with the surface tension of .035 N/m and the above density, we find that the max height the oil bubbles can reach is 3.9 mm.

Experimental Conditions

The set up of the experiment was relatively basic in terms of equipment and the fluids that were used to create the photo. Initially, I was attempting to drop milk into a cup of water that was dyed blue to capture the moment the droplet rebounded but hadn't mixed with the water. After this experiment resulted in photos I wasn't very happy with, I tried adding vegetable oil into the water just to see if it was visually interesting. I stirred the cup a little to break up the large bubbles of oil and add some motion so each picture would be unique from the previous one (Figure 4). For lighting, I placed the cup on a white poster near a window to allow as much natural light in as possible as well as having two LED lamps pointed directly at the surface which I could control the color temperature of (Figure 5). Since there was some milk in the dyed water, it made an opaque solution which acted to diffuse the surrounding light as well as make a more distinct background for the oil to be shot on. My goal was to capture the boundary between the oil and the water, so I lined one of the LED lights up with the center of the shot to take advantage of the lensing effect of the oil and the direct reflection on the water. Without the light reflecting the way it was, the oil bubbles were much harder to see, and the boundary between the water and oil were less distinct. One of the side effects of using a macro lens is a very shallow depth of field which I used to highlight the relation between the oil and water in the center of the picture. By shooting down at the surface of the water at an angle instead of perpendicularly, I was able to only focus on the region that was ideally lit and have the foreground and background out of focus. The best display of this effect is in the top right of the picture where the oil drops in the background are blurred and create a bokeh effect highlighting the center of the image.

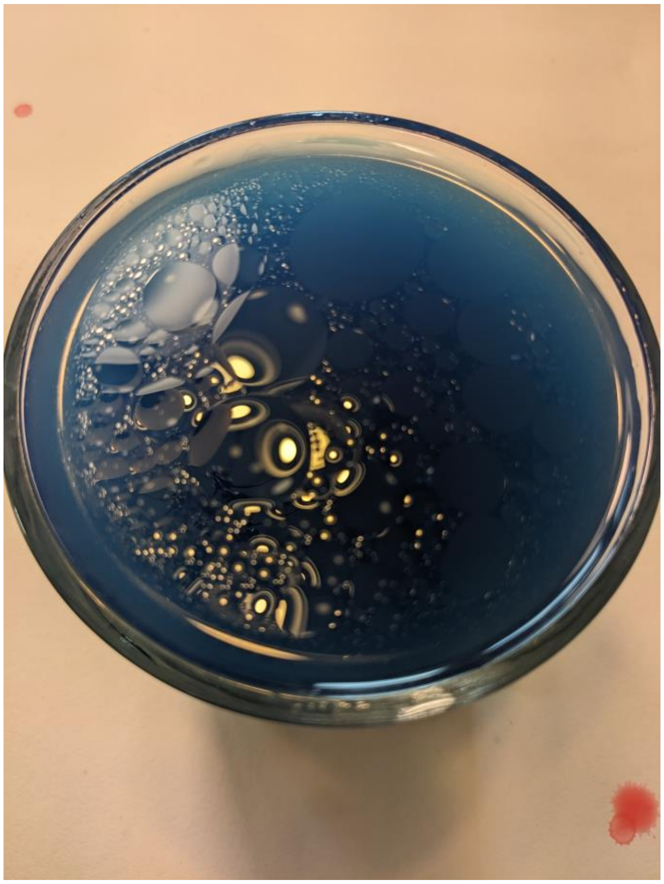


Figure 4.

The cup of water/milk and oil placed on the white poster after stirring.

Picture taken on my phone.

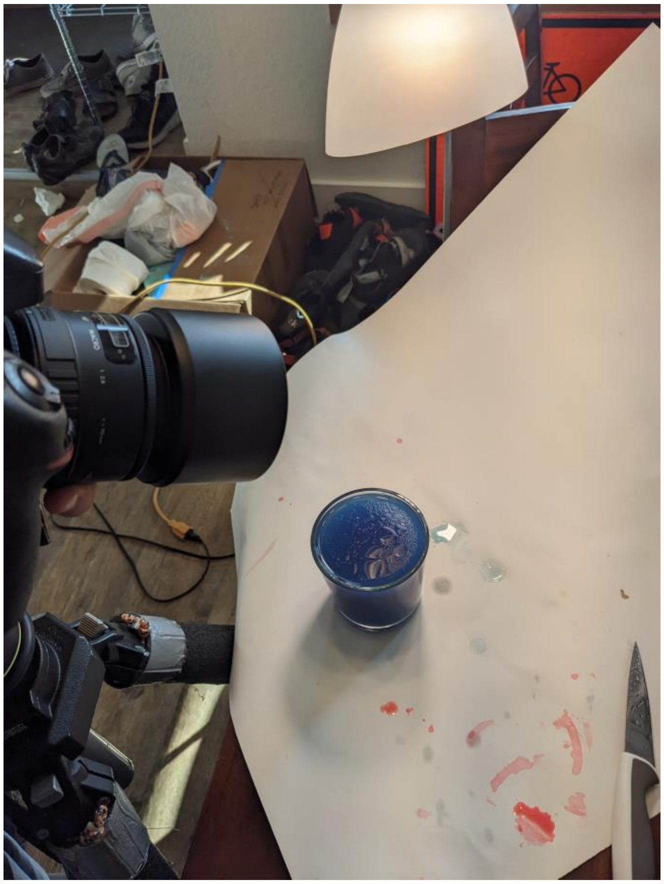


Figure 5.

Experimental setup with the camera, one of the LED lights, and white poster. Just out of frame and slightly above the shown light is the second LED light. The window is above the orange sign and is about 5 feet wide and 4 feet tall.

Camera Settings and Imaging Techniques

For this photograph I used a Nikon D800 DSLR body with a Sigma 92 mm macro lens at 8K resolution (7378 x 4924). The lens does not zoom, but instead only has focus adjust, so I had to get close to the surface of the water to fill the frame of the photo. The end of the lens hood was only a few inches away from the lip of the cup to get close to the surface without blocking any of the light. As seen in the picture, the total field of view is approximately 3 inches wide which is slightly less than the diameter of the cup. Below are the settings the photo was taken at if you would like to recreate the set up.

Camera Mode	P (Program Auto)
ISO	1250
F-Stop	5.6

Exposure	1/125

The unedited picture captured almost exactly was I was aiming for, so I did minimal photo editing in Darktable. I cropped the image ever so slightly because in one of the corners you could see the lip of the cup, and I added a slight S-curve to the color space curve to increase the contrast between the oil and water. The dimensions of the cropped image are 6680 x 4448 and the images before and after postprocessing are shown below.

Image before processing

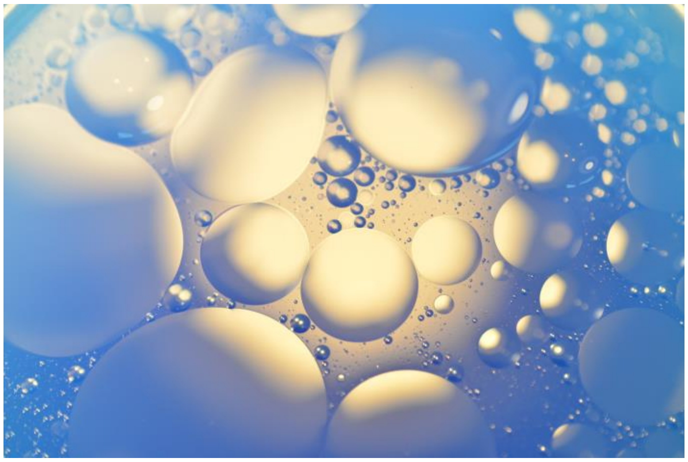


Image after processing

Conclusion and Reflection

In the end I am very happy with how this photo came out. The composition of large and small oil bubbles are balanced and add dimension to the image, and the bokeh helps draw the viewers focus to the middle where the main fluid interaction is. The lighting at the center of the image highlighted the boundary between the oil and water exactly how I wanted them to, and you can clearly see the difference in curvature between drops of different sizes. Since I used a short pint glass the center of the image is also darker than the border because the water was deeper there, and less light was able to diffuse though which also helps to draw attention to the middle and have the rest of the picture fade into the background. The only element of the fluid physics that this photograph does not show is the cross section of the bubbles which would let us analyze the physics more by directly viewing the curvature of the top and bottom of the oil as well as how high in the water the oil sits. But that would have to be incorporated into a second photo because it would take away all the visually pleasing elements of this picture. Additionally, the oil stayed very pure and free of defects like tiny water drops or bubbles, so the reflection on the top of each drop of oil is perfectly uniform and reflects the light from above very nicely.

The dye pack that I bought had three color options, blue, red, and yellow, and I am glad I chose blue because I feel like it makes the picture more natural to look at because it is the same color as water. A red or yellow image would be more visually striking but would be too distracting and create less contrast between the water and yellow oil.

If I were to redo this project, there isn't a lot that I would try to change. In terms of the photographing, I think it captured everything I wanted it to from an artistic standpoint, and it showed as much of the fluid physics as I would be able to capture with that set up. It may have been interesting to add some more motion to create a more interesting flow phenomenon, but as an introductory assignment, the scope of what I did felt right.

Sources:

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