Oil Droplets Reflecting Light

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Get Wet Assignment

MCEN 5151: Flow Visualization

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1 Introduction

The image in this document aids in the visualization of fluid mechanics and phenomena, specifically droplet motion and light reflection. This image was taken using techniques discussed in MCEN 5151: Flow Visualization, fulfilling the requirements of the Get Wet assignment. It developed from a prior visualization of rain droplets on a window, demonstrating light refraction of the window screen through the droplets. The primary goal of this iteration was to visualize the motion of hydrophobic liquid droplets on water and focused light reflection across the droplets. Artistically, this image demonstrates the beauty of natural light and color captured through different fluids; small star-like droplets create a pseudo-galaxy in contrast to the large streaks. Oil, blue food coloring, and water were mixed together on a saucer plate, then captured using macro-photography techniques. The final image captured movement of a large non-spherical droplet, a focused reflection of the window on the smaller droplets, and aesthetic appeal.

2 Flow Phenomena

The multitude of sizes of the droplets will allow us to study the effect of size and shape of the droplet as it relates to droplet motion and reflectivity.

When examining this image, it is notable that many of the oil droplets are spherical or near spherical; however, there is one large tail-shaped droplet near the top of the image. To understand the shape of this non-spherical droplet, we begin by defining this flow as immiscible, or a flow which does not form a homogeneous mixture. This flow can be defined as immiscible because the oil is hydrophobic, which does not combine with water absent of an emulsifier agent. At the instant this image was taken, the droplet was moving counter-clockwise across the surface of the water; this motion is defined as shear flow, or parallel fluid flow of varying velocity through each layer. When understanding the motion and shape of the droplets, it is important to consider the Capillary number; this is a dimensionless quantity that describes the ratio of viscous forces to surface tension. This number can be mathematically described as follows.

$$Ca = \frac{\mu^{\text{ext}}\,\dot{\epsilon}\,a}{\gamma}$$

Where: μ^{ext} is the fluid viscosity of the ambient surface, $\dot{\epsilon}$ is the shear rate, a is the initial droplet radius, and γ is the resistance of surface tension between the two surfaces (Gounley 2016). For the large droplet, we can estimate the Capillary number using a viscosity of 1.00e-3 Pa*s, shear rate of 1 cm/s, initial radius of 2 cm, and gamma of 0.03 N/m:

$$Ca = \frac{1.00 \times 10^{-3} \cdot 0.01 \cdot 0.02}{0.03} = 6.67 \times 10^{-6}$$

A higher Capillary number means that the viscous forces are dominating the surface tension, which would result in a more deformed droplet shape. In considering the varying Capillary numbers of the droplets in this image, all variables can be estimated as roughly constant, save the initial radius, a. The viscosity of water is unchanging, the droplets were all moving at roughly the same rate along the surface, and the two surfaces had a constant resistance of surface tension among the droplets. Therefore, the smaller droplets in the image have relatively low Capillary numbers, while the larger droplet near the top and the ellipsoidal droplet near the bottom demonstrate higher Capillary numbers because of the initial radii values.

Another value to consider in the formation of droplet shape is the Boussinesq numbers; these are dimensionless quantities that describe the shear and dilational surface viscosity. These can be represented numerically as follows.

$$Bq_{\text{s}} = \frac{\mu_{\text{s}}}{\mu^{\text{ext}} a} \quad \& \quad Bq_{\text{d}} = \frac{\mu_{\text{d}}}{\mu^{\text{ext}} a}$$

Where μ_s and μ_d are the shear and dilational surface viscosity, and μ^{ext} and a are the same as in the Capillary number. When $Bq_s = Bq_d$, it becomes a single value, the Boussinesq number, Bq (Gounley 2016). Since the shear and dilational surface viscosities require force data to calculate, we will analyze this only theoretically. A larger Boussinesq number represents a greater influence of the surface viscosity of the droplet, and therefore, a more spherical shape. When considering the Boussinesq number in the context of this image, the primary variable among different droplets is the initial radius; a smaller initial radius represents a relatively larger Boussinesq number and vice versa.

It is important to consider the interplay between the Capillary number and Boussinesq number when examining a droplet. A spherical droplet is predictable when both the Capillary number is low and the Boussinesq number is high. When the droplet's Capillary number grows above the critical Capillary number, the droplet is more likely to be deformed. This critical Capillary number increases with the Boussinesq number (Gounley 2016). Applied to this image, it is concluded that the larger droplets have high Capillary numbers relative to their Boussinesq numbers due to their larger initial radii, leading to less stable, deformed droplets.

Another key feature of this image is the reflection visible in many of the smaller droplets. The window frame and tree are visible most sharply in the smaller droplets, and become more blurred and magnified in the larger droplets. The surface tension of the oil causes the droplets to be lens shaped, and we are able to examine the scattering of light against varying thickness lenses using the law of reflection (Nikolov 2017). The incidence angle, θ_i, is defined as the angle between the incidence beam, direct sunlight in our case, and the unit vector orthogonal to the surface of the droplet. The light is then reflected across that unit vector by the same angle of θ_i (Rodrigues 2014). Larger, thicker droplets have a steeper slope of curvature around the edges, leading to a steeper gradient of orthogonal unit vectors against the surface.

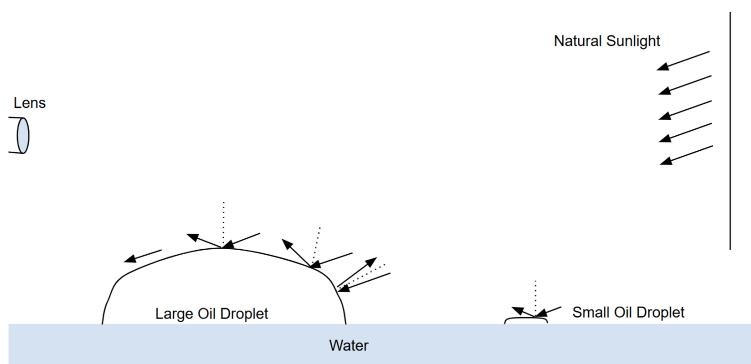

Figure 1: Sketch of light reflection on small versus large droplets

Considering that the source of light does not move, these larger droplets have a larger variety of angles of reflection compared to smaller, flatter droplets. This effect results in broader scattering of the reflected beams, leading to a blurrier image than the smaller, flatter droplets produce. This concept is sketched below to illustrate the even reflection of light on small droplets relative to the uneven reflection on large droplets.

Studying the shape and size of the droplets pictured allows us to better understand the physics of this flow visualization. Larger droplets interact with water and light much differently than smaller droplets; however, this can be understood through application of the same principals described above.

3 Visualization Technique

This visualization was created using Johnson's Baby Oil, Market Pantry's Food Coloring & Egg Dye (blue), water, and a small white saucer. The saucer was filled one third of the way with baby oil, then blue water was poured over the oil until the saucer was roughly three quarters filled with liquid. The water was poured at a approximately 50 mL/s, ensuring that none of the liquid overfilled while still creating a disturbance to the oil. This image was taken immediately after the pour, while the fluids were in motion from the disturbance. Various iterations of this visualization experimented with location of the water pour, stirring the liquids with a whisk after the liquids settled, and pouring the solution into a cup then back into the saucer. All of these methods resulted in similar fluid flow, although the best visualizations occurred immediately following the disturbance of the initial pour.

Figure 2: Visualization setup

Natural sunlight was used to produce this final image, with the saucer about two feet away from a window and the camera a foot away on the other side. This led to the half-illuminated effect on the bubbles, since the light was only hitting one side of each droplet. It is notable that the window frame is visible (as well as a tree outside the window) in some bubbles. Natural lighting was selected to maximize the illustration of this effect, as one of the primary motivators of this investigation is the law of reflection. Other lighting sources tested include an indoor overhead light and a focused spotlight floor lamp, although neither produced images as desirable as the daylight. This photograph was taken mid afternoon, to get the most direct natural daylight through the window without any unwanted shadows.

4 Photographic Technique

Captured using a Nikon D810 paired with a macro-lens, this image demonstrates close-up, high definition details of the flow. The Nikon D810 is a full frame sensor DSLR, producing an image size of 7380 x 4928 pixels. The lens used was a Nikon macro lens with a fixed focal length of 105mm and maximum aperture of f/2.8. This macro lens was chosen to magnify the details of the oil bubbles, since the setup was small. The exposure was set as follows: ISO-800, F-stop f/8, and shutter speed 1/60 sec. The aperture and ISO are relatively standard, with a lower shutter speed to balance the light. Since the flow was moving very slowly, motion blur was not a primary concern in the exposure triangle. The field of view in the original image is roughly three inches by two inches, and the camera was about a foot away from the subject. Manual focus was used to control the focus of the lighting and curves of the droplets. The final image was developed using Adobe Lightroom, with a final image size of 5369 x 3583 pixels. Contrast was edited to brighten the highlights and dim the shadows, and exposure was brought up. These edits provided better detail and clarity to the flow in the image. The vibrance of the image was increased, primarily for aesthetic appeal. The original photo is displayed below for reference.

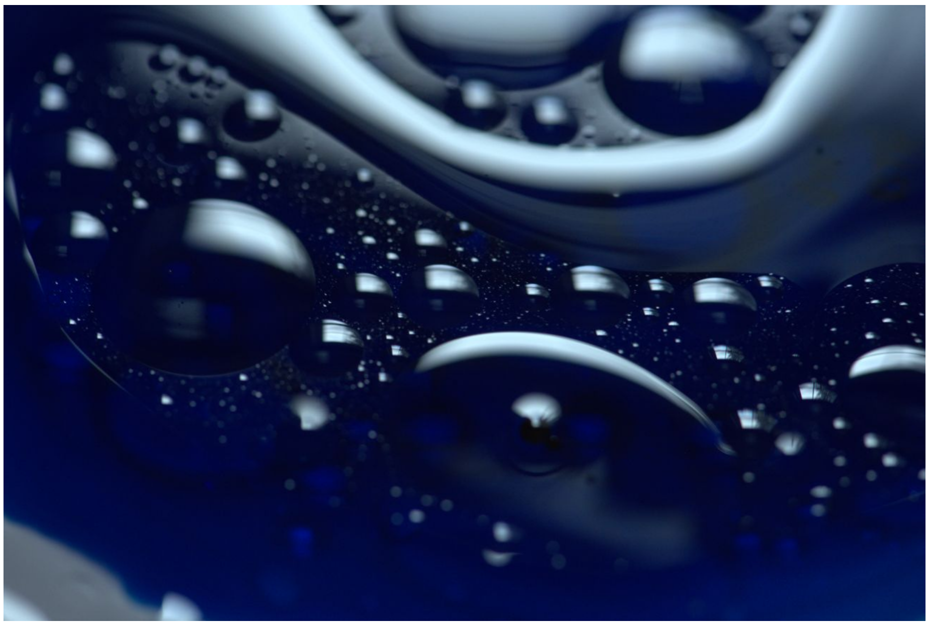

Figure 3: Unedited, original photograph

5 Artists Statement

This photograph is useful in visualizing differences between large and small droplets' interactions with the physical world. It highlights shear droplet motion and surface tension, as well as light reflection. Although this image provides a detailed conceptual understanding of the physics, it proved difficult to estimate any real flow parameters given the lack of datasets. If this experiment were iterated, I would use more equipment to attempt to determine the shear and dilational viscosities. Additionally, I would like to attempt to capture light refraction, as well as reflection, if this were iterated again. There are a few shadows of the droplets that can be seen through other droplets, but I decided to leave that investigation for another experiment that better highlights that effect. Overall, my intent was fulfilled in capturing fluid motion, light reflection, and beauty in our physical world.

6 Citations

Gounley, J., et al. “Influence of Surface Viscosity on Droplets in Shear Flow: Journal of Fluid Mechanics.” Cambridge Core, Cambridge University Press, 22 Feb. 2016, www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/influence-of-surface-viscosity-on-droplets-in-shear-flow/F6179DAA0126660CA250EAEF7890D1F8.

Nikolov, Alex, and Darsh Wasan. “Oil Lenses on the Air–Water Surface and the Validity of Neumann’s Rule - Sciencedirect.” ScienceDirect, 21 June 2017, www.sciencedirect.com/science/article/abs/pii/S0001868616301427.

Rodrigues, M, and P Simeão Carvalho. “Laws of Reflection and Snell’s Law Revisited by Video Modeling.” SPIE. Digital Library, 17 July 2014, www.spiedigitallibrary.org/conference-proceedings-of-spie/9289/928922/Laws-of-reflection-and-Snells-law-revisited-by-video-modeling/10.1117/12.2070784.full?tab=ArticleLink.