IV1 - Chlorophyll Drops in Water

Cole Smith
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Context and Purpose

The intent of my video, visible at https://vimeo.com/747212205, was to demonstrate the fluid flow phenomena exhibited over time by small quick moving drops falling into a stationary water medium. Additionally, the purpose of this video was to do so with chlorophyll, a fluid that is non-conventional in that it is both organic and, to my knowledge, original in terms of intentional flow visualization setups in either this class or otherwise. The specific fluid physics phenomenon that I was attempting to demonstrate with my experimental setup were Rayleigh-Taylor instabilities. I went through three attempts of videoing this process, the first two of which failed because of inadequate lighting, incongruent backgrounds, and phasing effects captured on video because of specific types of lights used. Additionally, I attempted to use a strobe light to implement an intentional sort of 'phasing' effect, but I was unable to get this to work because of inconsistent flash timing with the specific strobe light that I was using. Overall, the purpose of this video is to demonstrate a physics event that many of us have seen but don't fully understand. I was inspired to use chlorophyll specifically by, in the past, observing the interesting and unique effects of putting chlorophyll into water for taste and nutritional benefit. In this report, I will lay out the phenomena, techniques, and insights behind this beautiful process.

Flow Apparatus

Below in Figure 1 is a diagram of the flow visualization apparatus used for this video. The apparatus is extremely simple compared to some others used for the IV1 project, as it just consists of a clear circular glass filled nearly to the top with cold filtered water. The flow principles are self-contained within the water and occur as soon as the chlorophyll drops contact the water surface. I let the water sit for a period of ~5 minutes after pouring it into the glass to ensure that it was fully or nearly-fully stationary so that the only phenomena being observed were those caused by the drops of chlorophyll entering the water, namely the Rayleigh-Taylor instabilities and momentum. The dropper releases approximately 0.05 mL [4] of chlorophyll in each droplet and the total dropper is 1 mL in volume. While I didn't measure how many droplets were released into the water, or what the total volume of chlorophyll added was, it shouldn't matter because in the rest of this report I will examine the phenomena occurring on an 'individual-

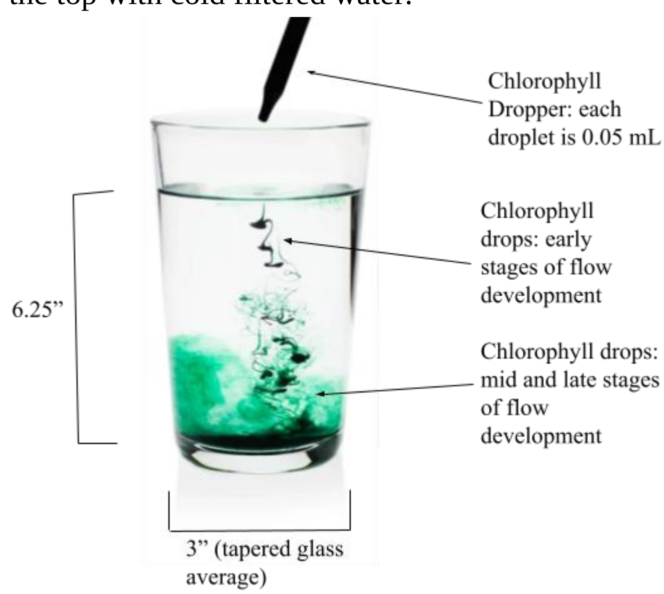

Figure 1: Flow visualization apparatus used for chlorophyll in water experiment.

droplet' level. This individual specific case can then be elaborated to the large-scale experiment theoretically to describe the aesthetic and physical happenings during the video.

Fluid Phenomena

In terms of the flow of the chlorophyll within the water the two main principles at play are momentum and the Rayleigh-Taylor instability. The relevant forces acting on the fluids within the framework of these principles that cause the flow to look this way are viscous forces, friction forces, gravitational forces, and buoyancy forces. The two relevant non-dimensional numbers to these phenomena are the Reynolds and Atwood numbers. These are calculated below for the chlorophyll drops when they contact the water, assuming that they're spheres at this moment, and therefore, based on a volume of .05mL, their diameter and characteristic length is .0046m. Using a value of .155m (~6in) for the height above the water from which the drops are released, the velocity of the drops upon impact is given by the following equation:

$$mgh = \frac{1}{2}mv^2 \;\rightarrow\; \sqrt{2 * 9.81\frac{m}{s^2} * .155m} = v = 1.73\frac{m}{s}$$

Additionally, as the dynamic viscosity of chlorophyll isn't available online, and since visually it exhibits similar characteristics to water, I approximate it to be proportional to the difference in densities between water and chlorophyll, where the density of chlorophyll is $1.079\frac{g}{cm^3}$ [7] and the dynamic viscosity of water is $.0010016\frac{Pa}{s}$, as shown:

$$\frac{\rho_{chlor}}{\rho_{water}} = \frac{\mu_{chlor}}{\mu_{water}} \;\rightarrow\; .0010016\frac{Pa}{s} * \frac{1079\frac{kg}{m^3}}{997.0\frac{kg}{m^3}} = \mu_{chlor} = .0010840\frac{Pa}{s}$$

While I recognize that this is a crude estimate it is backed up by the findings of Kesaulya et. al. that seawater excess viscosity and chlorophyll concentration are significantly positively correlated.[1] While the behaviors of salt water and fresh water can vary quite a bit, this research shows a strong and convincing enough correlation that I feel confident in directly relating these variables in the context of this report. Additionally, this is the soundest solution that I was able to find, and it was necessary to do so to calculate the flow-descriptive nondimensional values as follows:

$$Re = \frac{\rho UL}{\mu} = \frac{1079\frac{kg}{m^3} * 1.73\frac{m}{s} * .0046m}{.0010840\frac{Pa}{s}} = 7900 \text{ [9]}$$

$$A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} = \frac{1.079\frac{g}{cm^3} - .997\frac{g}{cm^3}}{1.079\frac{g}{cm^3} + .997\frac{g}{cm^3}} = .039$$ (Where ρ_1= density of heavy fluid, ρ_2= density of light fluid) [3]

Since the Reynolds number is 7900 the chlorophyll drops are very likely to fall into turbulent flow as soon as they contact the water [9], which is consistent with what is observed in the video as some non-smooth vortex finger clouds expand out in unpredictable directions. Dalziel states that there are a wide variety of mechanisms which may lead to the formation of an unstable density stratification, leading in turn to the development of the Rayleigh-Taylor instability, redistribution of the density, mixing, and ultimately stable stratification.[2] As described by Sharp, during the second stage of Rayleigh-Taylor instability, namely redistribution of density, the amplitude of perturbation grows nonlinearly and this development is strongly influenced by three-dimensional effects and the value of the Atwood number, or functionally the density ratio.[3] While I would qualitatively attribute the three-dimensional forces mentioned to vortices, this specific topic is beyond the scope of this report. However, in regard to the Atwood number Sharp asserts that if $A \geq 0$, which is true in my setup, patterns visualized are reminiscent of two sets of interpenetrating bubbles, often described as symmetric “fingers” of fluid.[3][8] This description is quite clearly corroborated by viewing my video and noticing that the chlorophyll droplets quickly develop into bubble like shapes which expand out into the water around them during the Rayleigh-Taylor redistribution of density stage occurring from 0:08-0:22 in the video. Next, the mixing stage occurs from about 0:22-0:55 in the video and eventually begins to shift into stable stratification from 0:55 onwards. This progression in Rayleigh-Taylor instability phases demonstrates that the forces driving the chlorophyll flows will change with time because of the differences in density, and the system as a whole over time will near stable stratification.[2][8] Stable stratification of fluids occurs when one layer, “is less dense than the one below it,” and is perpetuated and preserved due to buoyancy forces.[6] Qualitatively, based on unused trials the time required for the flow to fully develop and reach stable stratification with no visible movement is ~5 minutes, and the spatial resolution of the glass used was adequate to allow for proper demonstration of this full development.

Visualization Technique

The primary visualization technique that I used to capture the liquid chlorophyll drops falling into cold water was primarily a ‘dye-based’ marked boundary technique. It was a marked boundary technique because a singular source of bright light from the right side of the frame lights the background as well the water inside of the cup and contrasts against the dark chlorophyll inside the water. The chlorophyll initially absorbs much of the light contacting it and doesn’t let it past to the camera sensor for the most part. However, later in the video when the chlorophyll disperses and dilutes enough light begins to be able to pass through it and reach the camera. This, when contrasted with the transparent water which scatters light to the camera but doesn’t really absorb much light, allows us to clearly visualize the boundary between the water and the chlorophyll. As is described in the Flow Visualization textbook to be necessary for this technique to work, these two fluids are very similar in density and presumably in viscosity.[5] As mentioned in the text, “contrast is heightened by keeping the rest of the room as dark as possible,” [5] which I was sure to also implement as I both did the visualization at night and used only one light source. Additionally, “shining additional light on this dark ink would not enhance the contrast, but adding light to just the backdrop would,” [5] which I also found to be relevant as a second LED light positioned on the opposite side of the glass only washed out the contrast provided by the previously mentioned primary light. In terms of sourcing of materials, the chlorophyll used was non-diluted NOW Foods Liquid Chlorophyll, the water and glass used were household and non-novel, the light was a high-powered shade-directed LED standing house lamp, the background was constructed from white printer paper taped to my wall and my white desk pushed against this paper to provide uniformity. The camera was on a tripod approximately 3 feet away from the subject and was slightly looking down from an elevated angle towards the subject, the subject was approximately 4 inches from the background behind it, and the light originated from approximately a foot to the right of the subject.

Photographic Technique

The abstract technique that I used was taking a video of the flow visualization experiment with a zoomed in perspective. The size of the FOV was approximately 12 by 7 inches and the distance from the object to the lens, as stated previously, was approximately 3 feet. The lens focal length was 31mm and the other lens specs are a thread diameter of 40.5mm, however I didn’t use any lens filters. My camera is a Sona a-6500, it’s a digital camera, and in its highest resolution video mode it exports MP4 files, so my original and final video sizes are the same at a width and height of 1080 and 1920 pixels respectively. The audio sample rate of the video was 48 kHz using stereo 2 channel. The aperture was 5.6, shutter speed is an irrelevant measurement because it's a video, and ISO was set on auto but hovered around 32000. For my video the frames per second as shot was 60 FPS but was exported and viewed in playback at 30 FPS. In terms of post-processing on my video I didn't do anything in aftereffects or color-correction, and all editing was for the title section, credits section, transitions, and the music in the background. The FOV, video size, and aperture were all the recommended settings given the zoom and focus settings used in my cameras video mode. The frame rate was restricted by my camera's capture rate and the size of file that I was able to export off of the memory card used. The ISO was chosen in order to maximize the amount of visual contrast between the chlorophyll flows and the white background. The distance from the object to the lens was chosen as a combination of being the closest I could get the tripod without running into the desk the glass was on, but not being able to put the camera on the desk because it would have been closer than the minimum allowable focal length of the lens I had on my camera. Finally, the focal length was chosen through experimentation to get the middle of the glass in the clearest focus possible throughout the video.

Video Insights

As stated in the Fluid Phenomena section this video reveals the beauty of the interpenetrating bubbles and fluid fingers created by the fluid physics combination between momentum and Rayleigh-Taylor instabilities. The main aspect I like about this video is how it allows the viewer to see the progress of the flow artifacts throughout all the stages of Rayleigh-Taylor instabilities except for the very early phases.[8] Not only is it captivating in a scientific and engineering sense because of this, but it is also beautiful to be able to both appreciate the aesthetic qualities of the flow and understand their fundamental causes. The fluid physics are shown very well in the video format that I've used, and the only part of the Rayleigh-Taylor instabilities that aren't visible to the audience in this video are the small wavelength perturbations at the interface between the droplets and the water upon first contact.[8] In terms of further questions I have, I'm curious as to why, in the beginning of the interaction, some of the chlorophyll tends to stick around the top right edge of the glass in the form of bubbles that eventually pop and release little chlorophyll splashes into the water below them? Besides this, I have fully fulfilled my intent in terms of providing a window for myself and others into understanding the physics behind the beautiful shapes and gradients chlorophyll makes in water. In terms of improving the video in future iterations I would change the framing of the video to include the bottom of the glass as well. I would experiment with a shorter and wider water receptacle with a squarer video aspect ratio, and I would even consider using a vertical video orientation in order to better use the visual real estate. I would also experiment with taking a longer video and then potentially speeding up the stable stratification stage of the flow to get a more complete and engaging view at the long-term behavior of Rayleigh-Taylor instabilities and this beautiful flow.

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