Food Dye in Water

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Get Wet Assignment, MCEN 4151

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The goal of the video titled "Food Dye in Water," was to capture the diffusion behavior of food dye in water and to visualize the Rayleigh-Taylor instability that results from mixing the two fluids. Incidentally, the video also visualizes convection currents due to the nature of the lighting used in the setup. Though this was unintentional, it nonetheless gives valuable insight into fluid dynamics and thus will be discussed subsequently. The intent in creating this work was to visualize these principles of fluid dynamics while creating a visually interesting and artistically coherent piece. The video was chosen because of available equipment and expertise, as well as its ability to show the time evolution of the fluid behavior.

To create this video, a very simple setup was used. As demonstrated in Figure 1, a clear glass cup was filled with cool tap water to two-thirds of its height, and a single drop of food dye was deposited into the water. This was done using an inverted bottle whose tip was approximately 2 cm above the top edge of the glass. The dye was then allowed to diffuse into the water for approximately one minute. This process was repeated four times, emptying and cleaning the glass each time. Two of these iterations are present in the video.

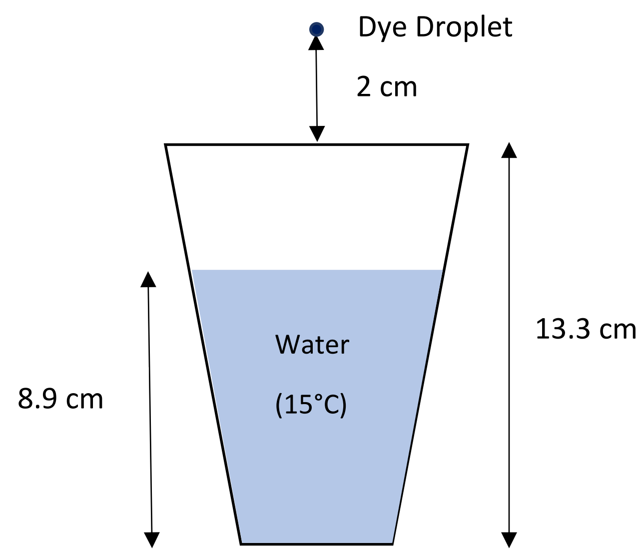

Figure 1. Diagram of Setup (not to scale)

There are three primary behaviors being exhibited in this flow, and they are diffusion, the Rayleigh-Taylor instability, and convection currents. Food dye is specifically designed to dissolve in water, thus it takes advantage of water's molecular properties, namely its polarity. Because of the polarity of water molecules, they tend to attract and "pull apart" molecules from other substances placed into the water, eventually distributing the molecules of the other substance evenly throughout the volume. This is what is occurring with the food dye, as it becomes more distributed throughout the water volume as time passes. The primary force that causes the dye to spread throughout the volume is the intermolecular force exerted on the dye molecules by the water molecules, causing the mean distance between the dye molecules to increase. This occurs until the concentration of dye molecules is constant through the entire volume of water. Since achieving this state takes a long time or the introduction of mechanical forces like stirring, it is not shown in the video.

The Rayleigh-Taylor instability describes the behavior at the interface of two fluids of different densities. This discussion will assume that the fluids are in the configuration presented in Figure 2, where the interface between them is initially a flat plane and gravity (g) acts in the direction shown.

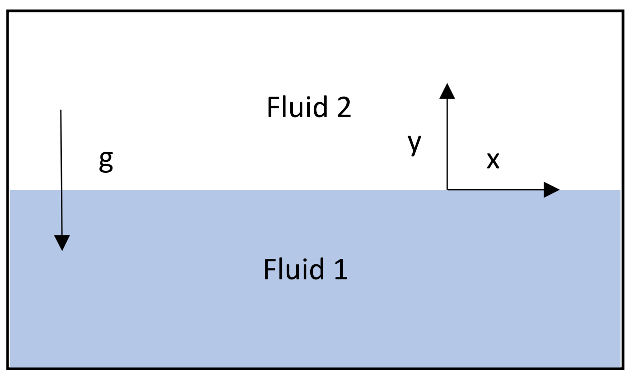

Figure 2. Fluid Configuration for Rayleigh-Taylor Instability

If the fluid on top (fluid 2) is less dense than the fluid on the bottom (fluid 1), then the interface between the two is stable, and no motion will occur (Oakley 2004). If the fluid on top has a higher density than the fluid on the bottom, then the more dense fluid will flow in the direction of gravity (downwards), and the less dense fluid will flow in the opposite direction (upwards). However, if the interface between the fluid is completely flat, no motion can occur. The interface must experience a perturbation, and because the interface is unstable, this perturbation grows exponentially and motion occurs. In the case of this flow, the impact of the dye droplet with the surface of the water creates a significant perturbation in the velocity of the surface, allowing the motion to occur. In addition, the density of water is 1 g/cm^2, while the food dye used consists of primarily propylene glycol, which has a density of 1.032 g/cm^2 (DOW Chemical Company) at room temperature. The full governing equation for the Rayleigh-Taylor instability is highly complex and thus is not given here, but an important quantity used in determining the stability of a fluid interface is the Atwood number, given by:

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

A positive Atwood number indicates that the interface is unstable and a negative number indicates that it is stable (Oakley 2004). The Atwood number for this flow is -0.0157, which is unstable. This aligns with the behavior that is seen in the video; when the dye impacts the water, it is above the water with respect to gravity and it then travels rapidly downward. The "mushrooming" effect of the droplet expanding as it descends is also characteristic of the Rayleigh-Taylor instability. As the flow progresses, it can also be observed that the dye near the air-water interface is also moving downward, though much less rapidly. This is also due to the Rayleigh-Taylor instability, as the denser dye is again on top of the less dense water.

When looking at the video, it is also clear that, in addition to sinking to the bottom of the glass, the dye also rises to the top. This is due to convection currents driven by the exposure of the water to a high-temperature light. This creates regions of water with a slightly higher temperature, and thus slightly lower density, than the rest of the water. These regions are forced upward by the cooler water, creating the upward motion of the dye seen in the video. Once the water reaches the top, it cools and its density increases, so it sinks down to the bottom again.

To visualize the Rayleigh-Taylor instability and convection currents, blue Kroger brand water-soluble food dye was used (see Figure 3). As mentioned before, only a single drop dispensed from the bottle was used for each iteration of the visualization. The lighting consisted of one dim ceiling-mounted incandescent light to provide soft, low-level illumination, as well as a 26 Watt, warm color temperature compact fluorescent light approximately five feet from the glass, at an angle so that the shadow of the glass would be projected on the wall behind it. An image of the setup is provided in Figure 3.

Figure 3. Relevant Setup Images

The video was captured using a Canon Vixia HF G20 digital camcorder, shooting a 1920 x 1080 pixel image at 24 frames per second. The camera has a fixed lens with a variable 4.25-42.5 mm focal length and a maximum aperture of f/1.8. The camera lens was placed three feet from the glass and the horizontal field of view was approximately ten inches for the first shot and five inches for the second. The reason that the camera was a large distance away from the glass was so that the zoom lens could be utilized to increase focal length used and achieve a shallower depth of field so that the background of the image would be slightly blurred. The camera's auto-exposure feature was used to create this video, as the results it created were satisfactory, but the individual aperture, shutter speed, and ISO settings were subsequently located buried in the camera's menu and will be manipulated for future images. The video was edited and post-processed using the Hitfilm 3 Pro software. The contrast of videos was increased slightly to make the difference between the colors more striking, but no changes to the colors were made. A royalty-free music track, "icy feeling cold ambient scary," retrieved from Pond5.com was included in the video.

The end result is a video which clearly demonstrates the Rayleigh-Taylor instability and also visualizes convection currents while evoking a calming, ethereal mood. I chose to film against an orange background and use blue food coloring, and really like the complementary warm and cool aesthetic that this creates. I also like the blurred background that I was able to achieve, especially in the close-up shots of the glass. While I like the shadow that was projected against the wall and think that it adds interest to the image, I would have liked to see a more detailed reproduction of the flow visible in that shadow. I could achieve this by using a flat white background rather than the textured orange background that I used here. Additionally, I did not discover that I could individually control my camera's aperture, shutter speed, and ISO gain until recently, and I would perhaps like to revisit this video and experiment with changing those settings.

References

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