Diffusion of Food Dye and Oobleck in Water

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MCEN 4151: Flow Visualization, Get Wet

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The intent of this image was to capture diffusion of fluids at two very different stages and speeds, with the diffusion of food dye set against a milky background created by the diffusion of oobleck in water. This experiment arose through attempts to play around with numerous different fluids in a relatively free-form manner hoping to capture some interesting fluid phenomena. While perhaps more interesting fluid behavior occurred, due to a mixture of lighting issues and unfamiliarity with camera settings, many pictures taken were ruled out due to a lack of clarity. However, this relatively simple fluid behavior exhibits a stark contrast between the color of the food dye and the milky, white water & oobleck mixture that is visually interesting. Special acknowledgement to Michael Becerra for providing his lighting box and kitchen as a space to perform the experiment and for dropping the food dye into the water so I could focus on capturing the image.

The flow apparatus used was a simple mason jar placed inside of a lighting box, with a light at the top of the box and internal faces of reflective material designed to create a relatively uniform lighting effect within the box. Oobleck was placed in the jar first as it is the densest fluid and would sink to the bottom regardless, however, we did not want premature mixing. Next clear water was placed above the oobleck, which began the slow diffusion of the oobleck into the water, eventually creating the milky appearance. Next, canola oil was layered above the water. Finally, a droplet of water-based food dye was dropped into the jar and due to its similar density to water and the hydrophobic behavior of oil, passed unperturbed down through the oil layer into the layer of water. A sketch of the experimental setup can be seen below in Fig 1.

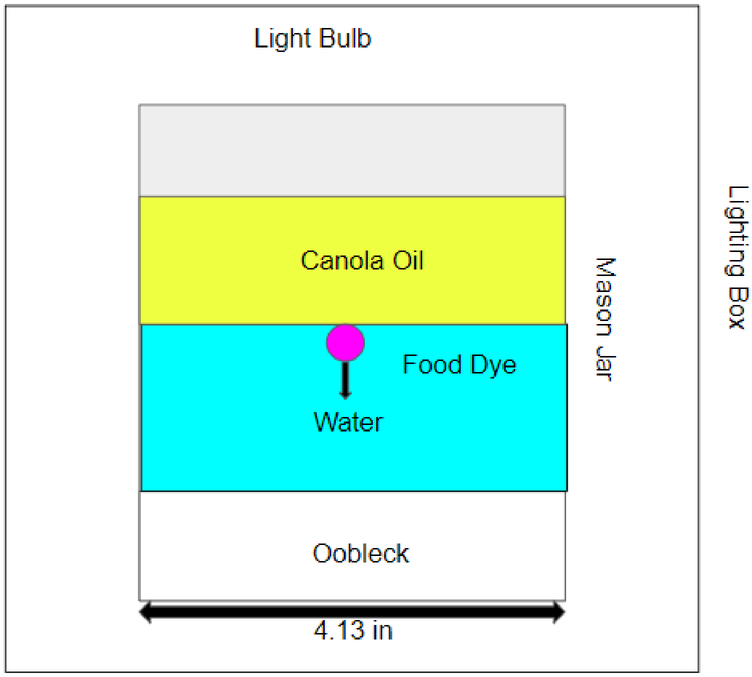

Fig 1: Experimental Setup

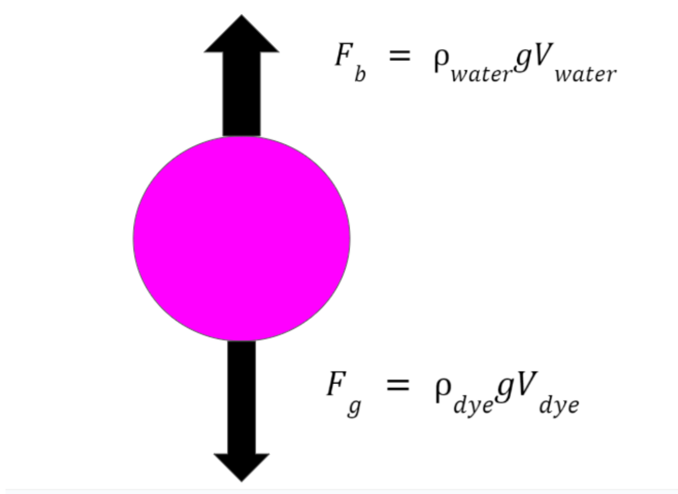

Fig 2: FBD of Dye Droplet in Water

The free-body diagram in Fig 2 shows the forces acting on the droplet of dye as it descends through the layer of water, namely the force of gravity acting on the droplet and the buoyant force from the surrounding water. Because $V_{dye} = V_{water}$, the net force on the droplet can be simplified to $\sum F = gV(\rho_{water} - \rho_{dye})$. Assuming the standard density of water of 997 kg/m^3 and the water-based food dye has a slightly higher density of 1000 kg/m^3 (National Library of Medicine) and that a single droplet of water has a volume of approximately 0.05 mL (Pearson), we can calculate the force acting on the drop to be $-1.47 * 10^{-6}\ N$. With a mass of $5 * 10^{-5}\ kg$, the acceleration of the drop is found to be $0.029\ \frac{m}{s^2}$. The buoyant force in the oil layer above the water would be lower, meaning the droplet would accelerate faster. Assuming the droplet enters the oil with no velocity and spends about 3 seconds traveling through the oil with a density of 920 kg/m^3 and 5 seconds traveling through the water, we can calculate a rough velocity of 2.5 m/s. Approximating the Reynolds number as that of a spherical object in a fluid, using the diameter of the droplet as the characteristic length, the calculation becomes

$$Re = \frac{\rho u D}{\mu} = \frac{(997\frac{kg}{m^3})(2.5\frac{m}{s})(0.00621*2\ m)}{10^{-3}\ Pa*s} = 30900.$$

This results in a highly turbulent flow which may be what initially breaks the surface tension of the droplet and begins the diffusion process. This Reynolds number is a very rough calculation due to the nature of the flow phenomenon not having a clear-cut calculation and the time spent sinking being estimated. It seems very high but regardless, the flow of the dye exhibited in the photograph is clearly turbulent. As the dye diffuses, the ribbon like patterns exhibited show the fluid following convective heating patterns in the water, likely caused by the lights in the box warming the outer regions of the water layer. It can be seen that the dye quickly spreads outwards before spreading much upwards.

The techniques used to capture the image were quite easy as the main effect was simply watching the dye diffuse. The oobleck diffusing into the water was very helpful as it provided a white background to contrast with the color of the dye. In terms of lighting, a light box was used in order to light the experiment in a relatively uniform method and more importantly, to provide enough light that a high shutter speed could be used on the camera to accurately capture a particular moment of the diffusion effect without any blurring that would be caused by a longer exposure. No flash was used from the camera because the curvature of the mason jar distorted the light and severely obscured the fluid within.

A DSLR camera (Canon Rebel EOS 1500D) was used to capture this image, taken roughly 6-9 inches from the jar. This distance allowed for easily getting the entire jar in frame and in focus without having to zoom so much that focusing would be quite difficult. The exposure specs included a 1/640 sec. exposure time, ISO-1000, and an f-stop of f/5.6. The exposure time was chosen in order to capture the diffusion phenomenon in motion without any blurring while the rest of the camera settings were used in order to provide a proper amount of light into the camera for the image to come out bright enough. After capturing the photograph, the RAW file was loaded into darktable to boost the contrast and sharpness of the image while also altering the color profile to manipulate the color of the dye from a pale purple into a bright pink. This color manipulation also made the oil more vibrant which added another layer of color contrast to the image. However, these edits also led to some visual noise and “burned pixels” in the darker areas of the image. The before and after images are displayed below.

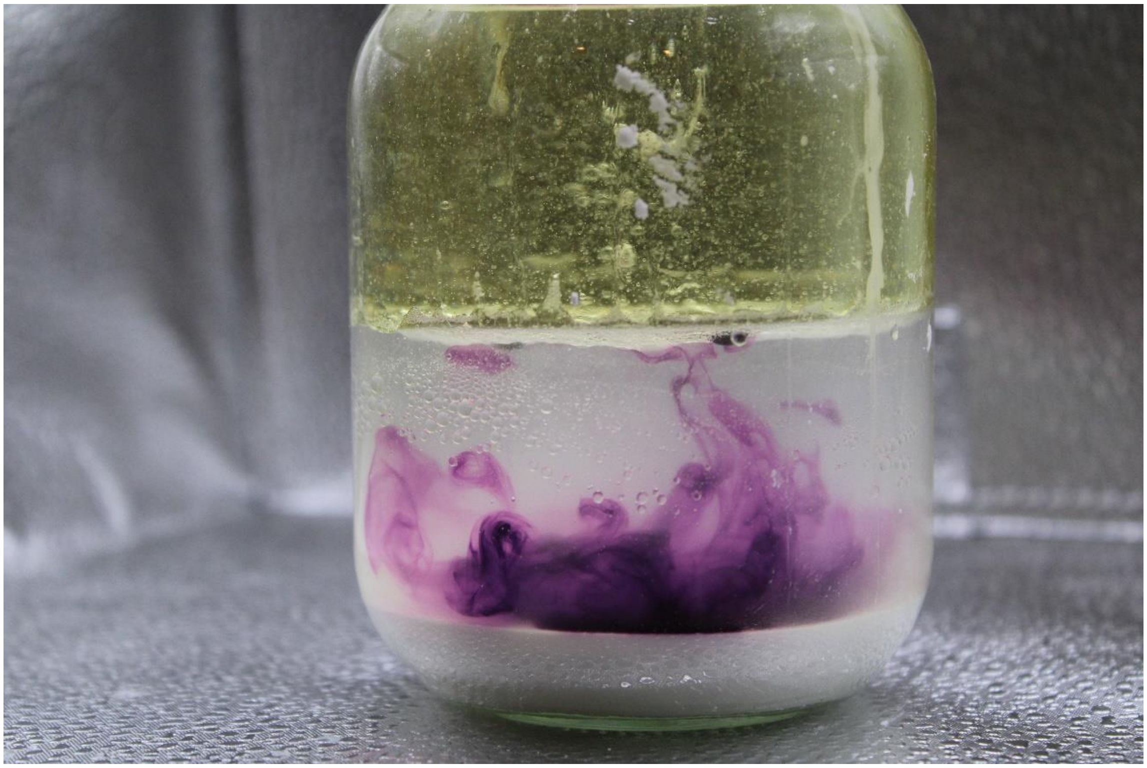

Fig 3: Original Image (Unedited)

Fig 4: Final Image (Edited)

This image reveals information about the mechanism behind diffusion and convective currents due to uneven heating of a fluid. The diffusion is semi-random due to Brownian motion of individual molecules, however, uneven heating leads to pockets of increased temperature in the water. Higher temperatures also mean more molecular motion and faster diffusion. On a macro scale, this causes the dye to diffuse in the direction of higher temperatures, which is visualized by the ribbons of dye emanating radially and upwards from the point of highest concentration near the center axis of the jar at the bottom of the water layer. Personally, I like the contrast of color in this image, specifically the pink dye against the milky white background. I cropped the image to include some of the oil to add another layer of color to the image. I also like that due to the colder temperature of the water, the droplet of dye sank to the bottom before beginning to diffuse, creating an almost sinister looking dark region of high concentration near the bottom of the image. My main problem with the image is the condensation buildup on the outside of the jar due to the temperature difference between the water and the ambient air as I believe it acts as a distraction from the main focus of the image. In future pictures, I would also like to avoid the level of graininess present in the darker regions of the image. My main intent with this experiment was to get experience composing images, learning camera settings, and exploring some of the basics of fluid dynamics to build skills that are transferable to future experiments. In this regard, I think the experiment and the image were fairly successful; however, I wish I had been more ambitious for this first project. To take this basic concept of multiple fluids diffusing, in the future I could add droplets of different colored dye to different locations in the water and capture the interactions as the different dyes approach each other.

References

Lehmkuhler, Arlie L, et al. "Dataset of FD&C Certified Food Dyes in Foods Commonly Consumed by Children." *Data in Brief*, U.S. National Library of Medicine, 7 Dec. 2022, www.ncbi.nlm.nih.gov/pmc/articles/PMC9803911/.

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