Food Coloring at Oil-Water Interface

"Get Wet" Assignment

Ryan Coyle
MCEN 5151: Flow Visualization
Professor Hertzberg
February 4, 2014

The first assignment for flow visualization, entitled “Get Wet”, is intended to allow students to get some first time experience with photographing flow visualization and turning it into art. The requirements for the assignment are to both demonstrate the observed fluid phenomenon as well as create a picture that is artistically sound. This is the only assignment without formal teams, and so I decided to do an experiment without group assistance. The goal of my image was to capture different colored food dyes as they broke through an oil-water interface and spread about the water below, as well as observe how the diffusion of the dye was effected by the cold temperature of the water.

In order to create a good photo, sufficient lighting and a clear glass were needed, along with a good background. A thoroughly cleaned plain tapered glass was used in this case so that maximum transparency could be gained. Cleaning was necessary to eliminate smudges and other artifacts that may have affected the image. To light the photo, 2 large lamps with white lighting umbrellas were used to make the light softer and eliminate shadows. The placement of these lights was slightly behind the subject so as to try and avoid glare off of the glass. For the background, a white sheet was draped over a desk with a soft curve so that wrinkles and shadows would not be present. Once the glass was well lit and the background was set, the camera was positioned a distance of roughly 2 feet from the glass at the same height. The glass was then filled with water about 2/3 of the way, followed by a half inch thick layer of vegetable oil. Blue food dye was then dropped into the oil, which sank through to the oil-water interface where it slowly accumulated before breaking through to the water. Once the blue dye had broken through and sufficiently diffused in the water, red dye was dropped into the oil to create contrast between the colors. Photos were continually taken throughout the process. A simplified side view of the experimental setup can be seen below in **Figure 1**.

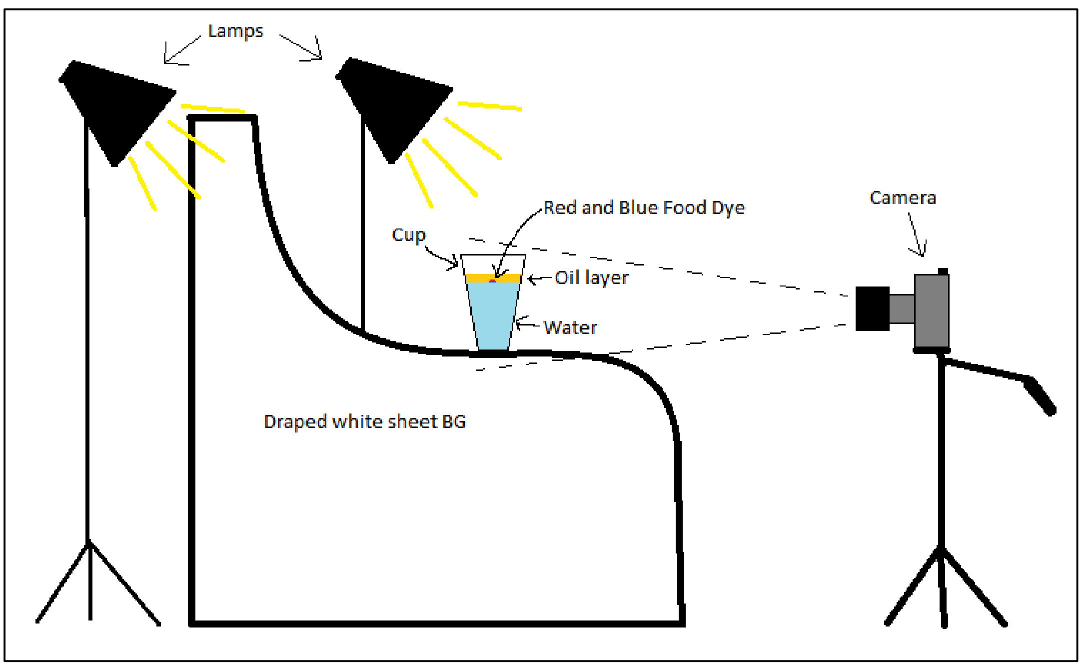

Figure 1: Side view of experimental setup

There are several important fluid phenomena that are occurring in the photo (seen on title page). All of these fluid phenomena played an important role in shaping the fluid flow observed in the photo. First, we can see that the vegetable oil is floating on top of the water, creating an oil-water interface. The reasons for the existence of this interface are twofold; oil is hydrophobic and is also less dense than water.[1][2][5] Both of these properties of oil gave rise to the situation we see in the photo. Oil does not mix with water because it is hydrophobic due to the unsaturated fatty acids that form the oil's molecular structure. These unsaturated fatty acids are not soluble in water, and so when vegetable oil is dropped in water, there is a tendency for them to separate. Because it cannot fully separate, the oil limits the area of contact between interfaces. The reason the oil floats to the top and does not stay in the middle or sink is because it has a density of around 800 to 900 kg/m^3 compared to 1000 kg/m^3 for water. This difference in density causes a net upwards buoyancy force on the oil generated by pressure differences at the top and bottom of the individual oil droplets (**Figure 2**). A shown in the figure below, the pressure acts perpendicular to the surface of the oil droplet at all points. The forces in the horizontal direction cancel out, but because the pressure force on the bottom is greater than on top (due to the depth difference from top to bottom), the net force in the vertical direction is upwards. This is known as the buoyancy force, and because oil is less dense than water, it is able to overcome gravitational forces and causes the oil to float.

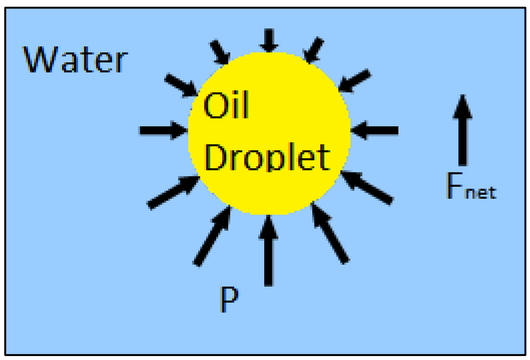

Figure 2: Depiction of pressure forces on the surface of an oil droplet.

Looking back at the image, we also can see a pool of dye appearing at the oil-water interface. This occurred for a couple reasons. Firstly, the oil does not want to break the interface and increase the area of contact between water and dye.[2][5] Because of this, the dye has to push its way through the surface, which takes time (around 3 minutes for the photo shown). The time taken to break through the interface is increased significantly if less dye is used, which is why there is a lot of dye in the photo. It is also caused because food dye has a lot of water in it, which causes the same hydrophobic interaction between the oil and food dye. This is the reason the food dye sinks in oil rather than float, and it is why the both the dye and oil molecules are working towards breaking through the interface rather than staying in contact.

Another fluid phenomena that occurred between the dye and water is diffusion. Diffusion is the process by which the dye spreads throughout the water. In the photo, we can see that the blue dye has sufficiently diffused, whereas the red dye has not yet started to diffuse significantly. For this experiment, cold water was used, which in turn cooled the temperature of the dye. What this means, in terms of the diffusion rate, is that the dye will spread throughout the water slower. This is because the water molecules in cold water are moving much slower than they would be in lukewarm or hot water, for example. Because the molecules in both the water and dye were moving slower, they could not move about the fluid as quickly, which lead to slower diffusion rates.[3][4] This diffusion rate dependence on the fluid temperature can be seen in **eq. (1)** below:

$$J = -D\frac{de}{dz} - eD_T\frac{dT}{dz} \tag{1}$$

In the equation, J is the mass flow (diffusion), D represents the Brownian diffusion coefficient, e is the particle concentration in mass per unit volume, and D_T is the coefficient of thermal diffusion.[4] Because we are looking at this on a macroscopic scale, the diffusion due to Brownian motion can be ignored, leaving only the second term in the equation. As is shown from the equation, the mass flow, J, has a linear dependence on T. From this, we can deduce that if the temperature decreases, so will the magnitude of J. What this means in the photo is we get long periods of no diffusion. This can be seen in the stream of red die, which shows very little diffusion, and it is also why the blue dye made it all the way to the bottom of the glass before starting to diffuse, at which time it did so because of convection (cold fluid sinks, warm fluid rises) and contact with the side of the glass.

The resolution of the photo is 2435x2973 pixels, which means it contains 3 decades of information and is highly resolved. For visualizing fluid flow in the laminar regime, 3 decades of information are required, which means that the photo is spatially resolved. Because the photo is spatially resolved, we know that we are able to visualize all of the fluid phenomena that are happening in the photo (disregarding the areas that are too dark to see). The size of the photo is roughly 10cm by 7.5cm, and some of the smaller features in the photo include the oil-water interface and the chute of red dye poking through it. The width of the chute is on the order of 0.25 to 0.5 cm depending on the specific point being visualized. If we compare this value to the 10cm height of the photo, we see that there are 2 decades of separation.

Because the photo was taken indoors at night, significant lighting was used so that no flash would be required and the ISO could be kept low to avoid grain. A standard zoom lens was used with a low f number so that the depth of field would be kept relatively low. This allowed me to keep the glass in focus but not the white sheet in the background. A fast shutter speed was used to freeze the fluid motion in place, but was not so fast that the image would appear unlit. All of these camera specifications in combination (seen in **Table 1** below) led to a well-lit image with low grain, good focus and high resolution. The photo was edited in Adobe Lightroom where it was cropped, saturated, brightened, sharpened and given more contrast. Because a large amount of dye was used in order to break through the interface, the information in the plume of red dye could not be recovered in editing.

Table 1: Camera settings

Camera Body	Canon EOS Rebel T2i
Camera Lens	Canon EF 28-135mm IS USM standard zoom
Shutter Speed	1/125
ISO	400
Aperture (f-stop)	4.0
Focal Length	41mm
Pupil Diameter	10.35mm

After conducting the experiment and editing the image, I feel as though it is a good demonstration of several fluid dynamics principles including buoyancy force, diffusion and the interaction of insoluble fluids. Looking back, there are a few things I would change. I was unable to deal with the glare on the glass during editing, so I would place the lights in a way that glare would not be visible. I would also move the camera closer to the glass so as to limit the amount of background appearing in the photo, and I would crop out any of the glass and/or negative space during editing. Lastly, I would use different colors of ink (and less of it) to get brighter colors and better contrast.

References

[1] Bassam, Shakhashiri. "Chemical of the Week: Fats & Oils." *Scifun.org*. N.p., 30 Jan. 2008. Web. 4 Feb. 2014. <http://scifun.chem.wisc.edu/chemweek/pdf/

[2] Beverung, C.j., C.j. Radke, and H.w. Blanch. "Protein Adsorption At The Oil/water Interface: Characterization Of Adsorption Kinetics By Dynamic Interfacial Tension Measurements."*Biophysical Chemistry* 81.1 (1999): 59-80. Print.

[3] Debenedetti, P. G., and R. C. Reid. "Diffusion And Mass Transfer In Supercritical Fluids." *AIChE Journal* 32.12 (1986): 2034-2046. Print.

[4] Iacopini, S., R. Rusconi, and R. Piazza. "The “macromolecular Tourist": Universal Temperature Dependence Of Thermal Diffusion In Aqueous Colloidal Suspensions." *THE EUROPEAN PHYSICAL JOURNAL E* 19.1 (2006): 59-67. Print.

[5] Moore, F. G., and G. L. Richmond. "Integration Or Segregation: How Do Molecules Behave At Oil/Water Interfaces?." *Accounts of chemical research* 41.6 (2008): 739-748. Print.