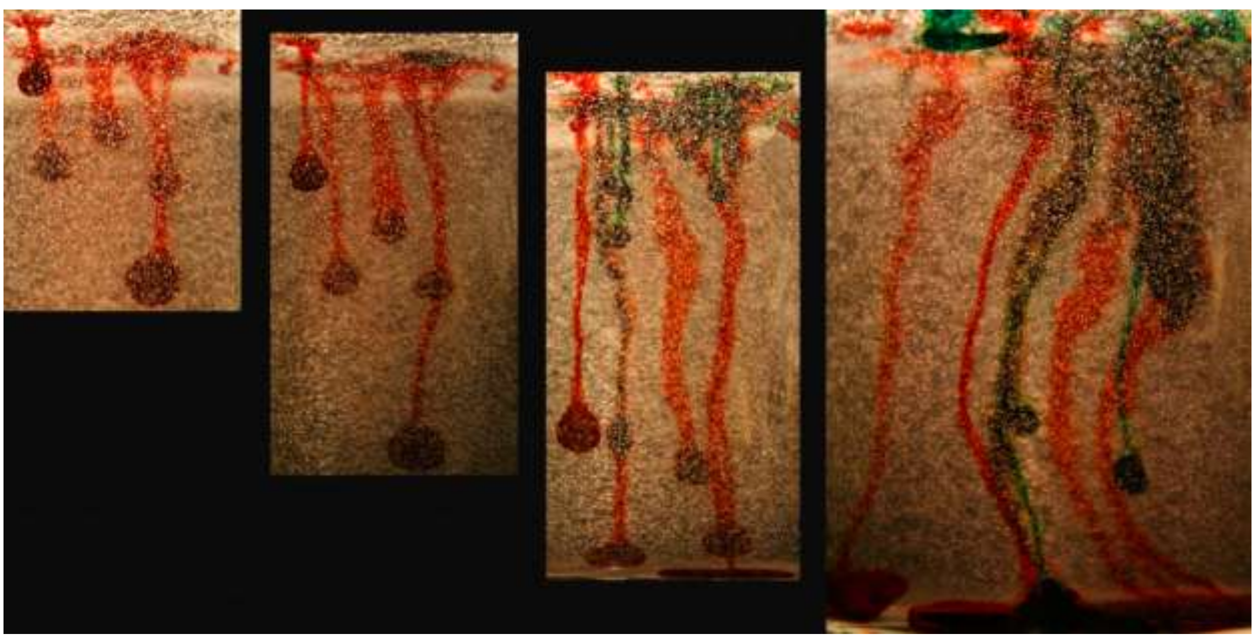
Get Wet:

Food Coloring in Dish Soap

Hamed Yazdi

MCEN 5151: Flow Visualization

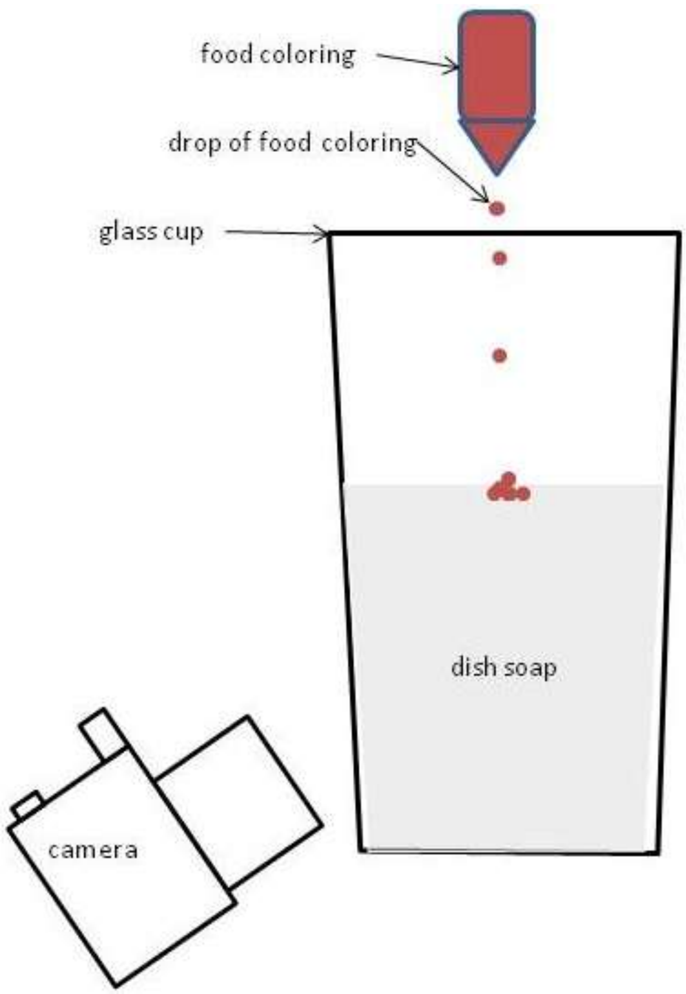


Purpose:

The purpose of this image is to capture the physics of how a low-viscosity (thin), yet more dense fluid behaves over time as it is dropped into a higher-viscosity (thicker), lower dense fluid. The effects of a centripetal force on the fluids are also examined. The low-viscosity fluid in this image is food coloring, and the high-viscosity fluid is dish soap. Two different colors of food coloring were used for an artistic purpose.

Apparatus:

The equipment used for this setup included a glass cup, dish soap, and red and green food coloring. The dish soap filled the cup about 3 1/4 inches high (8.3 cm), had an average diameter of 2 3/8 inches (6.0 cm), and a volume of about 30 in^3 (490 ml).



I first dropped a few drops of red food coloring and took pictures as the food coloring started to sink in the dish soap. After about 40 seconds, I added some drops of green food coloring. I dropped the food coloring at a height of about 3 inches (7.6 cm) above the dish soap.

The camera was held about 8 inches (approximately 20 cm) away from the glass cup. I took a series of pictures of the flow of the food coloring in the dish soap over a time period of time. The time elapsed between the first image in the collage to the last image is 6 minutes and 10 seconds. Sometime between the third and fourth picture of the collage, I twirled the cup a few rotations on the counter for a different artistic effect.

Flow Phenomena Observed:

The force that is causing the movement of the food coloring through the dish soap is gravity. The slow movement of the food coloring is a result of the high viscosity of the dish soap. The reason the food coloring sinks is that it has a higher density than the dish soap.

The main ingredients of food coloring are propylparaben, propylene glycol, and water, whose densities at room temperature are 1.063[1], 1.036[2], and 0.998[3] g/ml, respectively. Using Stoke's Law, I was able to

[1] http://www.chemicalbook.com

estimate the density of the food coloring to be 1.003 g/ml (see appendix). Using a beaker and scale, I measured the density of the dish soap to be 0.98 g/mL, which is less than the density of the food coloring. Thus, the higher-density food coloring sinks in the lower-density dish soap.

Viscosity is a measure of a fluid's resistance to flow.[4] Essentially, what we have in this image is a low-viscosity, high-density fluid slowly penetrating a high-viscosity, low-density fluid (relative to each other). The fact that the dye leaves behind a trail in the dish soap suggests that it is miscible in the dish soap (i.e. that it dissolves in the dish soap). Normally, a miscible fluid would disperse in its surrounding fluid. Furthermore, a density-induced settling of a fluid usually results in an instability, which will cause the fluid to disperse, as can be seen in the event that food coloring is dropped in water[5]. However, in this case, the high viscosity of the dish soap suppresses the dispersion of the food coloring, and keeps the food coloring quite compact[6]. This effect, along with the surface tension of the food coloring, allows the food coloring to remain as a "conglomerated blob" as it sinks, until it finally disperses due to shear forces created by the normal force of the bottom of the cup opposing gravity as the blob reaches the bottom of the cup.

In order to describe the flow characteristics of the food coloring, we can calculate the Reynolds number, which is a dimensionless number that that gives a measure of the ration of inertial forces to viscous forces[7]. For the sake of simplicity, I will assume that the food coloring blob is a rigid, spherical object sinking in the dish soap. The Reynolds number is defined by the following equation:

$$Re = \frac{\rho V L}{\mu} \qquad \text{eq. (1)}$$

Where ρ is the density of the object (food coloring), V is the velocity of the object, L is a characteristic linear dimension, in this case, the diameter of a blob, and μ is the dynamic viscosity of the fluid (dish soap). All of the above values are known except for the viscosity of the fluid. As we can assume from the slow movement of the food coloring that the flow is a laminar flow, we can use Stoke's Law to calculate the viscosity of the dish soap, which is:

$$\mu = \frac{2}{9}\frac{(\rho_o - \rho_f)}{v} g R^2 \qquad \text{eq. (2)}$$

Where μ is the dynamic viscosity of the fluid (dish soap), ρ_o is the density of the spherical object (food coloring blob), ρ_f is the density of the fluid (dish soap), v is the terminal velocity of the object (food coloring blob), g is the gravitational acceleration (9.81 m/s^2), and R is the radius of the spherical object (food coloring blob).

Although the drops are dropped from above the glass, the impact on the dish soap slows down the drops to have an effective velocity of zero, and then the force of gravity pulls down the high-density

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[2] www.engineeringtoolbox.com,
[3] http://van.physics.illinois.edu
[4] http://www.princeton.edu/~gasdyn/Research/T-C_Research_Folder/Viscosity_def.html
[5] http://www.colorado.edu/MCEN/flowvis/galleries/2011/Get-Wet/Reports/Vallejo_Michael.pdf
[6] Harihar Rajaram, Ph.D. Professor at CU, Boulder, personal communication on 2/22/12
[7] http://www.grc.nasa.gov

food coloring until it quickly reaches its terminal velocity somewhere between the first and second photograph (see appendix). Thus, to calculate the constant velocity of the food coloring, the velocity calculated between the second and third photograph must be used. By observing the photographs, I was able to evaluate the velocities of three food coloring blobs. I then took an average and used that value for the velocity in my calculations, which turned out to be about 0.0009 mph (0.001 km/h).

Now the only value that is left to calculate the dynamic viscosity of the dish soap is the density of the food coloring, which I did not have, was not able to calculate because I ran out of food coloring and was not able to find that particular type again. Therefore, I set up a simple experiment to avoid this problem. In the lab, I dropped a small steel ball of known diameter and density into a beaker of dish soap and recorded the time it took for the steel ball to fall to the bottom of the beaker. Knowing the time it took and the distance that the ball fell, I was able to calculate the velocity of the ball. Thus, I was able to use eq. (2) to calculate the dynamic viscosity of the dish soap, which was determined to be about 0.85 Pa-s.

Now that I had calculated the dynamic viscosity of the dish soap, I could use Stoke's Law (eq. 2) again to calculate the density of the food coloring by using the known properties of the food coloring instead of the steel ball. For this calculation, I took an average radius of the same three food coloring blobs I observed for calculating the average velocity. The resulting density of food coloring is 1.003 g/ml. Finally, I have all the values necessary to calculate the Reynold's number using eq. (1):

$$Re = \frac{\rho V L}{\mu} = \frac{1003\,\frac{kg}{m^3} * 0.004\,\frac{m}{s} * 0.0026\,m}{0.85\,Pa - s} = \ 0.12$$

Thus, the Reynolds number is 0.12, which confirms the previous assumption that we have a laminar flow. In fact, this Reynolds number gives reason to believe that this flow is purely laminar.[8]

In the last photo, I introduced a forced vortex by twirling the cup on the countertop. Because it was a forced vortex and not a free vortex, the speed of the vortex was zero in the center and greatest at the inner surface of the cup. Hence, any food coloring streams that were closer to the inner surface of the cup experienced a greater circular displacement than the streams closer to the center.

Possible Sources of Error:

Please note that my assumption of treating the blob of food coloring as a solid object is not entirely accurate. In reality, the food coloring within the blob will have internal circulation inside itself because its outer surface is in contact with the dish soap as it sinks. Basically, the movement will create two side-by-side hemispheres within the blob. Considering the orientation of the blobs in the photograph, the hemisphere on the left will have clockwise internal circulation while the hemisphere on the right will have counter-clockwise internal circulation.[9] The internal circulation will most likely change the values I calculated while treating the food coloring blobs as rigid objects. Furthermore, the blobs are not perfectly spherical, so again, the actual properties of the flow will be different from the properties that I

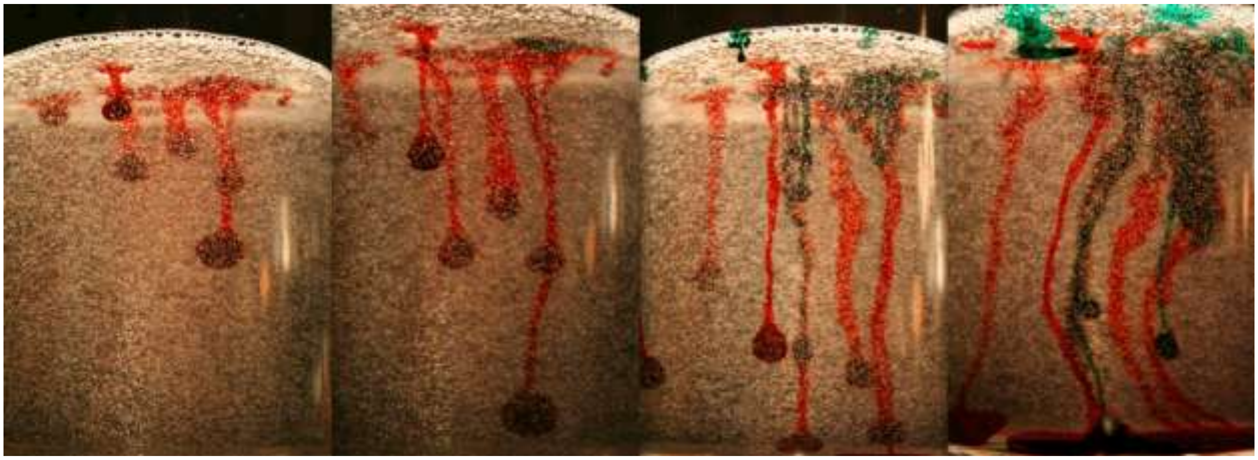
[8] P. Kulkarni, P. A. Baron, K. Willeke, "Aerosol Measurement: Principles, Techniques, and Applications," 2011
[9] http://www.bubbleology.com/BubbleologyFrame.html

used in my calculations. Also, my measurements for the apparent velocities and diameters of each of the blobs I considered were not very precise, as I was estimating the distances traveled by observing the photographs. This would have been much more precise if I had a ruler next to the glass cup as I was taking photos of the fluid motion. Finally, I ignored the effect that the existing bubbles within the dish soap might have had on the flow of the food coloring as it sinks.

Imaging Techniques:

For these photos, I used very simple photographing techniques. The lighting was supplied by six 50-Watt halogen ceiling lights spaced evenly about 6 feet above the cup in the kitchen, with no other lighting sources (the photos were taken at night). The images were taken with a Canon EOS Digital Rebel XT. I took all photos on the manual program. The shutter speeds for the first and second images were 1/125 s and for the third and fourth, 1/60 s and the ISO for all images was 1600. I used a relatively high ISO and high shutter speed due to the fact that I was taking photos of a moving object and the lighting wasn't very good. The high shutter speed helped get clear images of the moving flow and the high ISO allowed ample light sensitivity for the images with the high shutter speed. The focal length and aperture for the first image was 42 mm and f/5.0, respectively, and for the other three images, they were 55 mm and f/5.6. The original photos were all 2304 pixels wide and 3456 pixels high, except for the last one which was 1152 x 1728. After cropping the images, the final images were, in chronological order, 1352 x 1380, 1748 x 3120, 1492 x 2980, and 1152 x 1576 pixels. There was no particular reason for changing the settings other than experimenting to see what images would turn out better, but due to the simple nature of the setup, there are no noticeable changes between images.

For the final collage, I made some simple manipulations using Photoshop. The first thing I did was crop the images to contain the part of the flow I wanted the user to focus on. I basically made sure to keep the same streams and blobs of food coloring in all images, without superfluous dish soap on the sides, the edges of the cup, and kept the height of the image at the top of the dish soap. Secondly, I took away any glare that was from the lights reflecting off the glass walls of the cup by using the clone stamp tool. Finally, I increased the hue and saturation of the reds and greens in the image to make them stand out better from the bubbles in the dish soap. The following is a side-by-side shot of all the images before any Photoshop manipulations:



Analysis and Conclusions:

As mentioned earlier, this image reveals the motion of a low-viscosity, high-density fluid slowly penetrating a high-viscosity, low-density fluid (relative to each other). I believe the image communicates the flow very clearly, although the bubbles in the dish soap are a bit distracting. Overall, I am satisfied with the main concepts that were captured, but there are a few things I wish I had thought of before taking the photos. First of all, I would have liked all the images to be the same size and taken from a fixed position, perhaps from a tripod. This way, it would have been easier to see exactly how the movement of one image translates to the next. Also, I think I could have dropped the green food coloring more strategically to get more artistic images. Something I didn't think of at the time was to wait long enough for the bubbles to clear, so I could get more vivid images of the food coloring. I wonder what effects the bubbles had on the flow and if there is a way to measure that. I also wonder how far a blob could keep sinking in an infinitely deep fluid due to loss of mass from the trail it leaves behind as it sinks. The most interesting part of this project was that I had to analyze the fluid phenomena that were taking place, which really made me think a lot about something I hadn't thought about at all while taking the image. It was a challenging, yet insightful thought process for me.

Appendix

The following chart summarizes my measurements of three different food coloring blobs:

blob	t_1 (s)	y_1 (in)	t_2 (s)	y_2 (in)	t_3 (s)	y_3 (in)	V_1,2 (in/s)	V_2,3 (in/s)	V_2,3 (m/s)
1	0	0.5	36	1.1	131	2.7	0.0178	0.0168	0.0004
2	0	0.3	36	0.9	131	2.0	0.0169	0.0118	0.0003
3	0	1.0	36	1.7	131	3.3	0.0206	0.0164	0.0004
						avg:	0.02	0.0150	0.0004

V_1,2_avg (mph)	0.0010
v_2,3_avg (mph)	0.0009

Calculating viscosity of dish soap using steel ball

ro_soap	980	kg/m^3	Viscosity:	0.85	Pa-s
ro_steel	7800	kg/m^3			
v_terminal	0.16	m/s			
g	9.81	m/s^2			
R	0.003	m			

Calculating density of food coloring

blob	diam (in)	radius (m)
1	0.2	0.0025
2	0.24	0.0030
3	0.18	0.0023
avg	0.21	0.0026

Calculating density of food coloring

viscosity	0.85	pa-s	ro_coloring	1003	kg/m^3
ro_soap	980	kg/m^3			
v_terminal	0.0004	m/s			
g	9.81	m/s^2			
R	0.0026	m			