Alexander C. Thompson
University of Colorado Boulder | MCEN 5151
Get Wet Fall 2016

Introduction

Figure 1: "Get Wet" Image of M&M's in a Watered-Down Vanilla Yogurt Medium

As an experimental introduction to Flow Visualization, the first assignment was quite literally to "Get Wet" by finding an inspiration in real life, capture it in an image or video, and report on the fluid mechanics and physics at play. Personally, I found my inspiration relaxing on my couch one evening eating desert. As I had done many times in the last few weeks, I scooped a spoonful of vanilla ice cream into a bowl and poured some trail mix over top. The way the dried fruits get chewy and chocolate candies even crunchier makes adding trail mix to my desert a necessity. And it's healthier too! As I was approaching the bottom of the bowl, I noticed the greens, blues, reds, and yellows that the M&M's bled into the creamy white background, and how they were unintentionally swirled around so artistically. How great would it be to capture an image of M&M's dissolving in the melted ice cream for a class project? At the time I thought it would be so easy, yet creative. And I would not waste any of the materials for I could just eat my project when I was done shooting pictures of it.

As it turns out, in order to get an image I was truly proud of, it took more time and effort than originally expected. Although I was inspired by the color trails that M&M's left in vanilla ice cream, multiple trials (unedited versions shown below in Figure 2) proved that a medium of vanilla yogurt produced more vibrant color trails than ice cream or milk. However, the yogurt did not flow as easily because it has higher viscosity (internal friction) than milk or melted ice cream. Thus, vanilla yogurt was watered down to produce the final image seen in Figure 1.

Figure 2a: Brown M&M Dissolved in Milk

Figure 2b: Brown M&M Dissolved in Vanilla Yogurt

Figure 2c: Brown M&M Dissolved in Vanilla Ice Cream

The Physics and Fluid Mechanics behind the Image

As the flow visualization was composed of items from my kitchen, so too was the flow apparatus used to capture the image in Figure 1. The required ingredients to recreate this image are eight M&M's (only the red ones were used for my representation but that is not a requirement for future experiments), half a cup of tap water, and half a cup of plain vanilla yogurt. By mixing the yogurt and water in a cereal bowl by hand, gently and thoroughly to relieve the production of bubbles, the fluid has the color-absorbance properties of the pearly white yogurt but a reduced viscosity. As previously mentioned, viscosity is the internal friction in a fluid at the molecular level due to inelastic collisions. A fluid with high viscosity is thick like dish soap or honey. Meanwhile a fluid with low viscosity is thinner and "runny," like water out of the tap or chicken broth.

The watered-down yogurt was then poured onto the center of a dinner plate and the red M&M's were placed in a line. It was important to let the M&M's soak in the yogurt for about 5 minutes to allow the colored candy coating to dissolve in the yogurt medium. The plate was then tilted about 30^{o} over the sink, allowing the watered-down yogurt to run off the edge of the plate. The M&M's that were firmly pressed in place did not run when the top layer of yogurt slid down the plate. However, about half of the M&M's were not pressed in as decisively so they slid as far as two centimeters. These steps are shown in the following depictions:

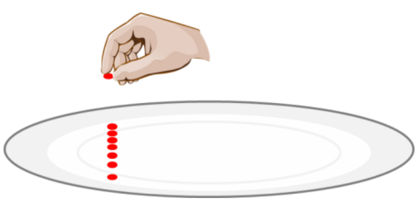

Figure 3a: Pour Yogurt onto the Plate Then Place the M&M's in a Line

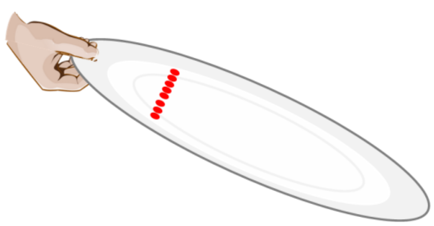

Figure 3b: Tilt the Plate 30^{o} Over the Sink

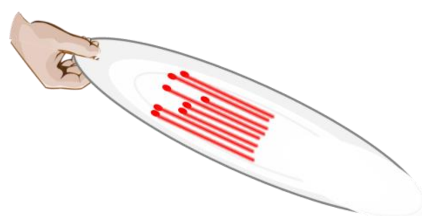

Figure 3c: Hold this position for 5 to 10 Seconds, until the M&M Coloring Runs

In order for this flow visualization to occur, two main physical phenomena must be at play. First, since the M&M's are entirely solid, there is something happening during the 5 minute hold period between Figure 3a and 3b. That phenomena, contrary to common belief, is dissolving. According to the common language people use to describe what they see, the M&M's candy coating would be melting, or changing from a solid to a liquid due to an energy (temperature) increase when placed in the yogurt or ice cream. But the temperature of the M&M is actually decreasing when introduced to the colder environment. Better yet, according to Mary Bellis of About Inventors, the M&M was invented during the Spanish Civil War by Forrest Mars (Son of Frank Mars, Founder of Mars Incorporated, the world-famous confectionery company) in 1941 as a sugar coated chocolate that wouldn't melt on the soldiers in the hot sun. In 1954, M&M candies picked up the slogan, "The milk chocolate melts in your mouth, not in your hand." Thus, rather than melting, the sugar coating on each M&M is designed to dissolve the same way salt dissolves in water.

After allowing the M&M's sugar coating to dissolve for about 5 minutes, releasing the red food coloring from vegetable dye into the white yogurt, the plate is tipped at a 30° angle. This is to provide the flow part of the flow visualization. According to Newton's Law of Friction, the yogurt shears under the gravitational forces, and begins to flow down the plate. The shear stress from gravitational forces can be found using the following equation:

$$\tau = \mu \frac{d\vec{v}}{dy}$$

Where τ is the shear stress for a fluid with given viscosity μ, acted on causing the fluid to flow with velocity $\vec{v}$. Back to Figure 3b, if that position (the plate at a 30° tilt) is held, it allows the very top layer of yogurt to flow on average 4.5 cm in 5 seconds. That equates to an average velocity of 0.9 cm/s (or 0.009 m/s). Before this is applied to Newton's Law of Friction, there are a few assumptions that can be made to simplify the mathematics. The M&M's that were firmly planted to the bottom of the yogurt layer did not drift when the plate was tilted. This means the yogurt in contact with the plate did not move. If at the boundary between a viscous fluid and a solid, the fluid does not move relative to the boundary, then the no-slip condition is met, according to Richardson of the University of Edinburgh (1972). The other assumption would imply that the velocity is a linear relationship with thickness of the viscous fluid. In that assumption, the velocity $\vec{v}$ is a function of height, measured in y. The derivative $d\vec{v}/dy$ is hence the slope of the line $\vec{v}(y) = \frac{v}{h}y$. Thus:

$$\frac{d\vec{v}}{dy} = \frac{d}{dy}\left(\frac{v}{h}y\right) = \frac{v}{h}$$

Where v is the average velocity of the fluid at height h. The diagram in Figure 4 is used to determine the amount of shear that the yogurt experiences due to the gravitational force.

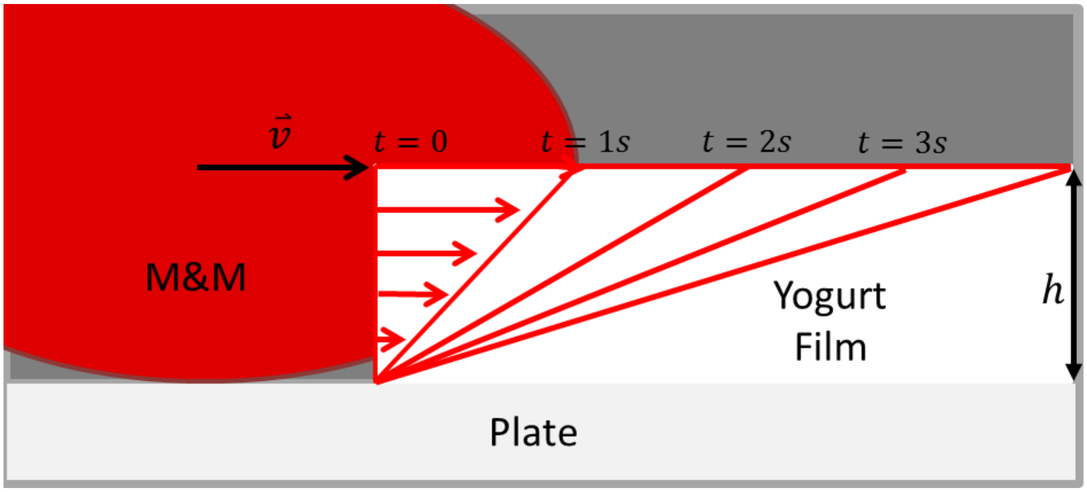

Figure 4: Classic Shear Diagram of the Yogurt Film

The watered-down yogurt is assumed to have a viscosity $\mu = 0.01\ Ns/m^2$(greater than the viscosity of milk or blood), and with a velocity of $v = 0.009\ m/s$ and a height of $h = 0.0025m$, the shear stress on the yogurt is calculated: $\tau = 0.036N/m^2$. This is a fairly small shear stress, but one large enough to spread the red dye down the plate in a matter of seconds.

When capturing the image, place the plate back down on a flat, level surface. Since the watered-down yogurt is a fluid (it reacts continuously to a shear and down not return to its previous shape, as a solid would) the flow will "freeze in time" for the photography.

Visualization and Photography Techniques

The visualization technique was a simple one, utilizing common materials in my kitchen to capture the red dye dissolve in yogurt flowing down a tilted plate. As previously mentioned, the only ingredients were Lucerne Vanilla Yogurt and Mars' famous M&M's. However, I did not need to go out and purchase them for this experiment for I had them in my kitchen already. The yogurt was mixed 1:1 with water from the tap to decrease the viscosity. The watered-down yogurt was poured on a dinner plate and set in a large piece of black poster board on the floor of my kitchen when ready to take the picture. For lighting, the overhead fluorescent bulb was left on along with a point source of white light from an LED camping headlamp. The LED was held about 45^o behind my left shoulder by my brother, Zack Thompson. I did not use the camera's built in flash.

As for the shot itself, the photograph was taken with an Olympus point-and-shoot digital camera. The camera was held about half a foot above the plate, and a foot to the side of the plate. The camera was zoomed in slightly, then the boundaries cropped out in Photoshop. The aperture was set to a larger f-number of f/4.3 to allow more light to enter the camera since the sources of light were not bright compared to natural sunlight. The shutter speed was set to 1/320 sec to try to reduce the amount of blur from my hands moving while holding the camera. I did not have a tripod for capturing this image. And lastly, the sensitivity was set to High ISO. At the time, I did not realize that the high sensitivity would result in the addition of noise (as seen in the top left corner of Figure 1). Once the picture was taken, it was edited in Photoshop. As previously mentioned, the borders were cropped to center the fluid flow while limiting the distractions in the image. The color contrast was then edited using the curve adjustment tool. Each end of the RGB color spectrum, the whites and the blacks, were brought in to fully utilize the entire range of contrasts. Then each end of the red curve was adjusted to enhance the coloring of the red M&M's on the white and shadow-black background. Last, the sharpen tool was used to highlight the edges just slightly. The original image snapped by the camera on the morning of September 11th, 2016 is shown in Figure 5a. The Photoshop color curve of the RGB color scale is shown in Figure 5b, and the color curve of the Red color scale is in Figure 5c. All of these edits result in the final image, again shown in Figure 1 on the first page.

Figure 5a: Original Image

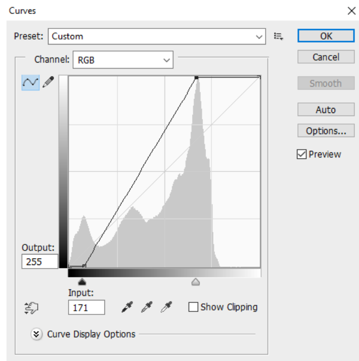

Figure 5b: RGB Color Curve Adjustment

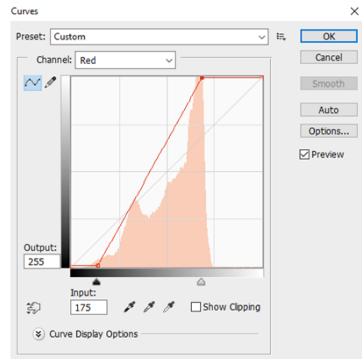

Figure 5c: Red Color Curve Adjustment

Conclusion

In the end, the image reveals the true visual beauty in food that gets overlooked while we are mindlessly eating it. The inspiration for this image came from my desert. Specifically, when I poured a handful of trail mix with M&M's on top of my vanilla ice cream one evening. The M&M's began to bleed colors all over the bowl. When stirred together with a spoon, the colors mixed, swirled, and ran. I like the fact that this image was composed with food. I also like the uniformity of the image. Using only red M&M's was not part of the initial design. However, the final image turned out great with the high contrast of black on white, with just red representing the remainder of the color spectrum. I also like the fact that the paths are mostly parallel and very simple. However, if I were to take this image again or try capturing a slightly different appearance, I would lower the ISO with the fast shutter speed and large iris diameter to reduce the noise in the image. The noise is very subtle right now, but as the artist, I see it every time I look at the image. The idea could be taken a number of directions from here. For example, if a mere five red M&M's were added inline, and blue M&M's added at a later time, a flow visualization similar to this one could become patriotically symbolic as the American Flag. Overall, the intent of this image was fulfilled. Meanwhile, many lessons have been learned from the initial idea stage; specifically, in taking the picture, editing it, and then receiving critiques.

References

Bellis, Mary. *History of M&M's Chocolate: Forrest Mars.* About Inventors. (2016). http://inventors.about.com/od/mstartinventors/a/ForrestMars.htm

Munson, Bruce. Okiishi, Theodore. Rothmayer, Alric. Iowa State University Department of Mechanical Engineering. Huebsch, Wade. West Virginia University Department of Mechanical and Aerospace Engineering. *"Flow Over Immersed Bodies." Fundamentals of Fluid Mechanics*. Seventh Edition. John Wiley & Sons Inc. (2013).

Richardson, S. *On the No-Slip Boundary Condition.* Article. University of Edinburgh, Applied Mathematics. *Fluid Mechanics* (1973) vol 59, Part 4. (1973). http://www.che.rochester.edu/~dafoster/ChE%20441/ChE441%202009/Project/RichardsonArticle.pdf

Zhu, Yingxi. Granick, Steve. *Limits of the Hydrodynamic No-Slip Boundary Condition.* University of Illinois Department of Material Science and Engineering. American Physical Society. (2001). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.88.106102