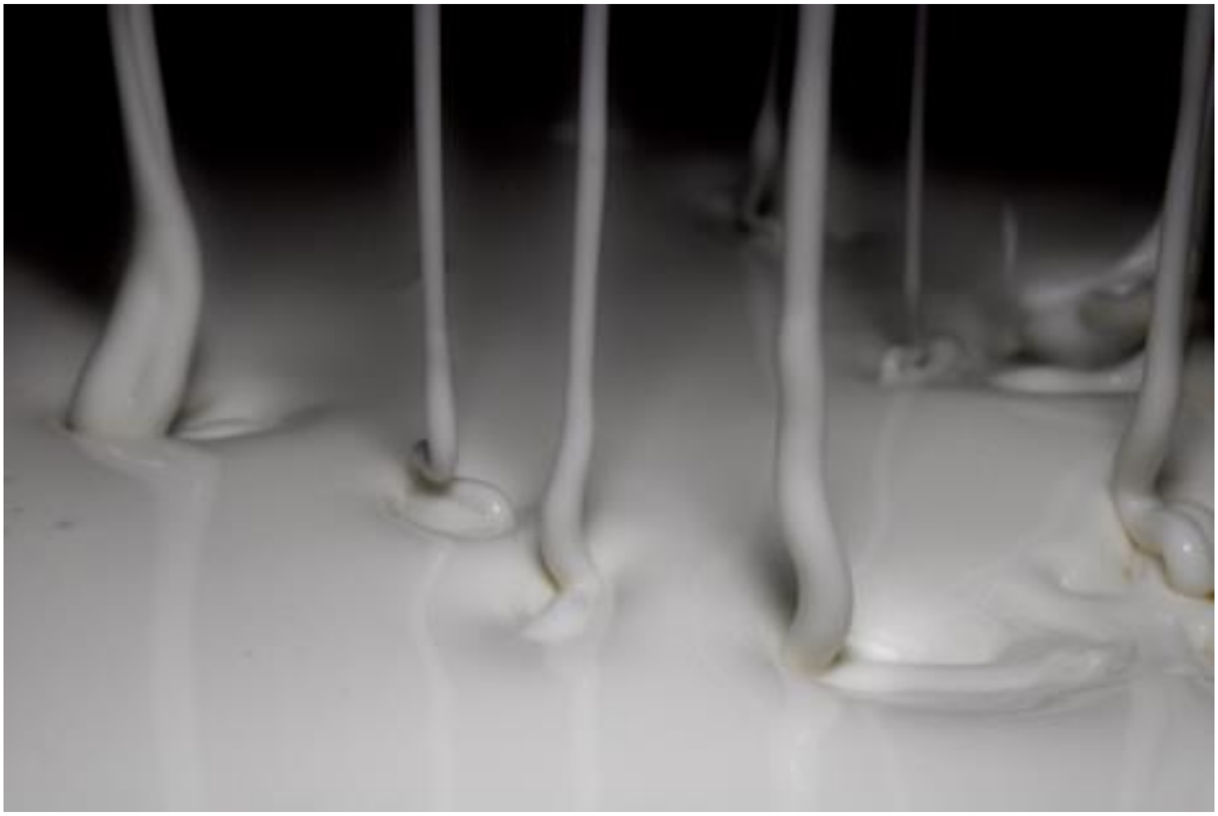
Shear-Thickening Fluid

Team Second 2019, Group 5, MCEN 5151
11-11-2019
Matt Knickerbocker



Introduction

The purpose of this paper is to document and describe the experimental process that was followed to produce a flow visualization photo that was captured as a requirement for the second team assignment of MCEN 5151 - Flow Visualization called Team Second. The original post can be found at http://www.flowvis.org/2019/10/20/team-second-matt-knickerbocker/. The task of the assignment was to capture a photo of fluids that both (1) clearly demonstrate the phenomenon being observed and (2) is a good photo. The intent of the photo for this assignment was to observe the flow physics of a non-Newtonian shear-thickening fluid. Those who collaborated on the idea of the photo included Faisal Alsumairi, Blake Chin, Robert Drevno, and Abhishek Kumar who are all members of group 5. The experiment for this photo itself was performed by myself alone, however I assisted some of the other group members with the setup for their photo.

Flow Description

The apparatus used in this flow experiment involved a shear-thickening fluid, a potato masher, a glass container, and an LED light source. A Canon EOS T7 Rebel DSLR camera was tripod mounted to capture the photo as shown in the experimental setup below (Figure 1). The shear-thickening fluid was produced by mixing a one-to-one ratio of cornstarch and water together in order to form a total volume of 8 fluid ounces. The glass container was filled with the shear-thickening fluid and the potato masher was then placed into the fluid such that it became submerged. The photo was then taken as the potato masher was pull upwards and out of the fluid such that several streams of fluid ran off from different locations of the potato masher. The photo captures the separate streams running back downwards and impacting the surface of the fluid in the container. This interaction displayed the shear-thickening characteristics of the fluid.

A shear-thickening fluid, also known as a dilatant, is a type of non-Newtonian fluid in which the viscosity increases non-linearly with the shear-strain rate [1]. Thus, when a shear stress is applied to the fluid, a rapid increase in viscosity can be observed where the fluid becomes thicker and behaves more like a solid. In general, a non-Newtonian fluid is one that does not follow Newton’s law of viscosity that states viscosity will be constant and independent of stress. Many common fluids do follow this law (e.g. water, air) such that it is used for most fluid mechanics calculations. The viscosity of a shear-thickening fluid instead follows a Power law as a function of shear rate as shown in Equation 1 below where η is the viscosity, K is a material based constant, and γ is the applied shear rate.

$$\eta = K\dot{\gamma}^{n-1}$$

Equation (1)

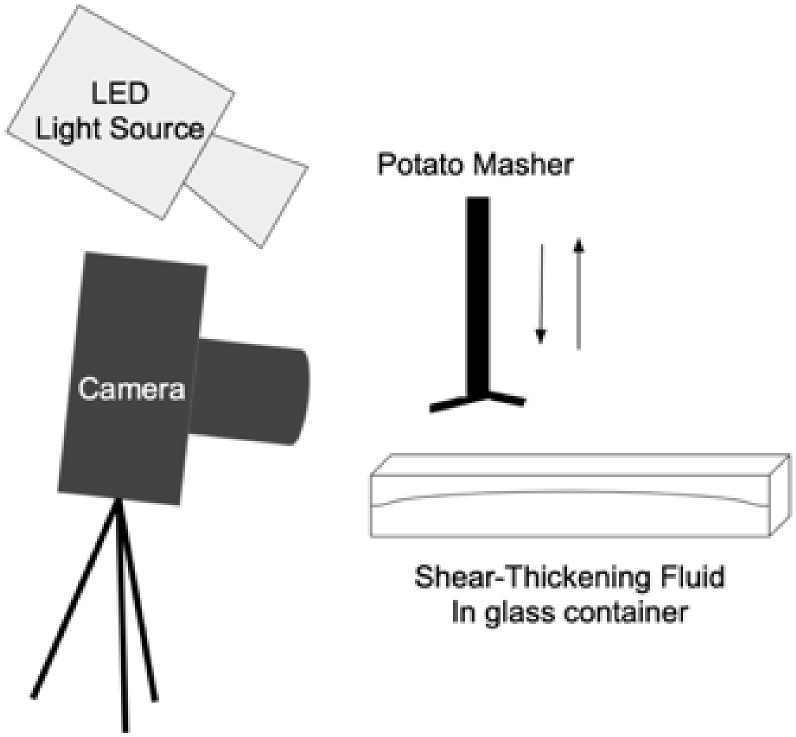


Figure 1: Experimental Setup

With small amounts of applied shear, the fluid flows easily like a liquid which can be observed when slowly stirring the fluid. If the rate of stirring is increased past a certain point however, a large resistance to the motion develops as the fluid increasingly thickens. This phenomenon can be seen in the photo where the streams of fluid are thin enough to run smoothly off the ends of the potato masher until they impact the surface and experience a rapid increase in shear rate. This in turn rapidly increases the viscosity, causing the fluid to thicken and pile upon itself. Since the viscosity of the fluid is not constant, it is difficult to estimate at one point, especially since it also depends on the specific mixture of cornstarch and water. Based on a one-to-one mixture, a density of 300 kg/m^3 can be estimated. Also, based on the distance traveled and the shutter speed, a flow speed of 1 m/s can be approximated. If a viscosity could be defined at one point, a Reynolds number could be calculated using Equation 2 below where ρ is the density, *u* is the flow velocity, *L* is a characteristic length scale, and μ is the viscosity.

$$Re = \frac{\rho u L}{\mu}$$

Equation (2)

This shear-thickening behavior is due to the fact that the fluid is composed of cornstarch particles suspended in water. At rest or low shear rates, these particles remain ordered in an equal distribution throughout the fluid, allowing it to maintain a fairly constant viscosity. Past a critical shear rate, the particles begin to clump together which thickens the fluid and causes it to resist further motion (shear) [2]. These types of fluids have been considered for use in several real-world applications like car traction control or ballistic body armor. Studies have been performed that investigated the effectiveness of a Kevlar fabric that was impregnated with a shear-thickening fluid which allowed for a flexible but penetration resistant composite. The results showed significant improvements in energy dissipation as well as penetration depth [3].

Flow Visualization Technique

As mentioned above, the flow visualization technique used in this experiment was performed through the use of a shear-thickening fluid which was allowed to flow off the ends of a potato masher. The fluid was composed of a mixture of equal parts water and cornstarch which were mixed together with a spoon until a consistent mixture was achieved. The correct consistency was found when significant resistance to stirring occurred, indicating that the fluid was thickening when a shear stress was applied. The cornstarch was of generic brand and the potato masher was a Cuisinart purchased from Safeway. The lighting used for the photo was a single bulb 100-Watt LED lamp that was used to illuminate the entire subject area. The light was oriented in line with the camera lens which caused a shadow to form over the back of the frame due to the potato masher blocking the light there. This direct lighting also caused reflections of the individual streams to appear on the surface of the fluid pool left in the container.

Photographic Technique

The camera used to produce the photo was a tri-pod mounted Canon EOS T7 Rebel DSLR. The photo was shot with a resolution of 6012 x 4008 pixels at a lens focal length of 55 mm. The field of view was roughly 3 inches by 2 inches with the camera lens positioned about 6 inches from the fluid. The lens used was a Canon 18-55 mm zoom lens with an aperture range of 1:3.5-5.6. The exposure was produced using an aperture value of f/14, an ISO of 800, and a shutter speed of 1/800 of a second. The desire for a larger depth of field drove the choice of a higher aperture value and the velocity of the fluid required a shorter shutter speed to avoid motion blur.

Fairly minimal post-processing of the photo was performed, and screenshots of the original and final photo can be seen below in Figures 2 and 3, respectively. The photo white balance along with the contrast and saturation were adjusted in order to darken the upper background and enhance the visibility of the fluid details and reflections. All of these edits were performed through the use of the GNU Image Manipulation Program (GIMP).

Figure 2: Original Image.

Figure 3: Final Image.

Conclusion

The photo produced in this experiment reveals the nature of shear-thickening fluids and how their viscosity can rapidly change under an applied shear stress. This effect can clearly be seen in the region where the fluid is impacting the surface of the pool in the container. Instead of smoothly flowing into itself or causing a splash like a Newtonian fluid, the dilatant thickens and piles upon itself in reaction to the sudden change in shear stress. As the stress relaxes with time, the fluid slowly flows back together in a smooth nature, returning to a lower viscosity with a corresponding flat surface in equilibrium. Aesthetically, this image has a spooky feel to it, especially with the black background. It is counterintuitive to observe a fluid rapidly change from a flowing stream into a nearly solid body deforming over itself. I personally enjoy the simplicity of the photo and the lack of color. I think that the light glaring off the fluid, the reflections from the pool, and the out of focus streams in the background make this photo well rounded and intriguing. I definitely fulfilled my intent with this photo and am very happy with the result. My biggest regret is that I had to choose only one to present as I had hundreds of equal quality.

References

[1] Wagner, N. J., & Brady, J. F. (2009). Shear thickening in colloidal dispersions. Physics Today, 62(10), 27-32.

[2] Barnes, H. A. (1989). Shear-thickening (“Dilatancy”) in suspensions of nonaggregating solid particles dispersed in Newtonian liquids. Journal of Rheology, 33(2), 329-366.

[3] Young S. Lee, E. D. Wetzel, N. J. Wagner. (2003). The ballistic impact characteristics of Kevlar® woven fabrics impregnated with a colloidal shear thickening fluid. Journal of Materials Science 38: 2825. https://doi.org/10.1023/A:1024424200221