MCEN 5151 – Flow Visualization Matt Phee

Team Project 2 Report

This image is my submission to the Team Project 2 assignment. It captures a mixture of cornstarch and water, commonly known as oobleck, which has been placed in the cup of a computer speaker and excited at 45 Hz. Cornstarch/water mixtures are unique in their non-Newtonian response to applied force. Oobleck is a shear-thickening fluid meaning that when shear forces are applied to it or are developed within it, oobleck becomes significantly stiffer and more viscous. If strong enough shear is applied, it may even behave strikingly similar to a solid. Video examples of several oobleck experiments can be found readily on YouTube. The excitement of non-Newtonian mixtures of cornstarch and water by an oscillating speaker face is a common enough set-up, and it yields startlingly life-like fluid behavior. The final submission is a composite of five images taken over several seconds. I felt that the chaotic behavior of the cornstarch mixture was not done justice by a single photo. I wanted to demonstrate how the influence of the speaker signal caused this spire of stiffened fluid to first “grow” from an unassuming pile into an erect column and then to “die” as it keeled over and reentered the pile beneath it. I thought this time-lapse gives the fluid the illusion of life.

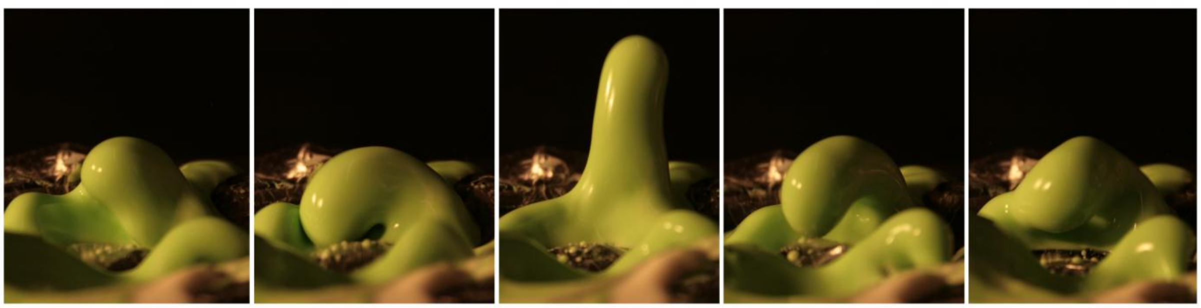

Figure 1: Time lapse compilation of a shear-thickening cornstarch mixture in a speaker cone

The set-up for this experiment includes a typical computer speaker with built-in amplifier, a National Instruments function generator, tripod-mounted painter’s lights, a black backdrop, plastic wrap, cornstarch, water, and food color. The speaker assembly was disassembled and the cone laid flat. The speaker’s built-in amplifier drove the cone using its included 120V AC transformer. A sinusoidal wave function of 10 V peak-peak amplitude and 45 Hz frequency was supplied using the function generator. The lights were positioned to the left of the subject. Figure 2 below shows the apparatus components and their relative positions as viewed by the photographer. To achieve the flow, cornstarch mixture was poured into the speaker cone. Approximately two parts cornstarch was mixed with one part water. Various color combinations of dye were applied to the mixture so that the mixing process could be observed. The mixture in these images had only one drop of green dye in a volume of 2 oz., and the dye was uniformly distributed. Plastic wrap, which was changed often to maintain cleanliness, was used to protect the speaker cone from moisture damage.

The fluid phenomenon under scrutiny in this experiment is fluid growth and motion that results from the shear-thickening attributes of non-Newtonian cornstarch water mixture. Cornstarch mixed with water results in what is called a cornstarch suspension. The vast majority of liquids are shear thinning meaning that increased shear stress leads to decrease in the viscosity of the fluid. According to the British Standard Rheological Nomenclature, “shear thickening is defined

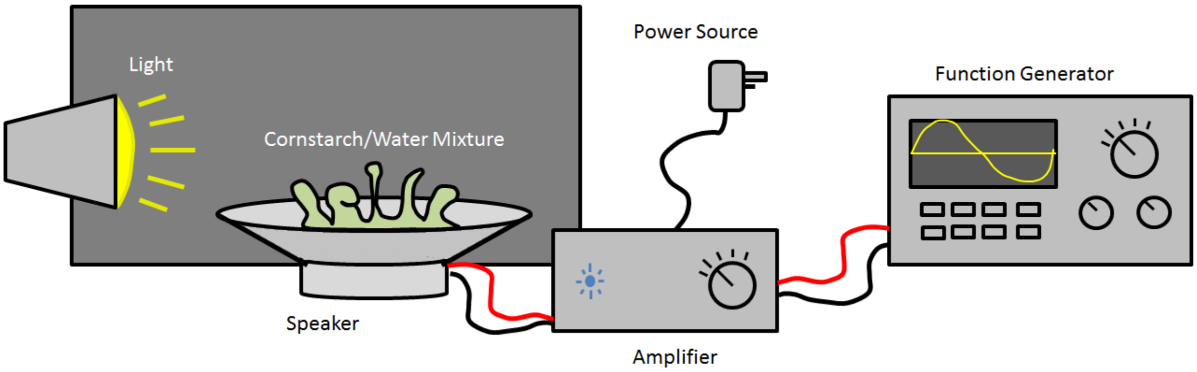

Figure 2: Diagram of experimental apparatus

[…] as the increase of viscosity with increase in shear rate" [1]. Simply put, if the faster a fluid is sheared, the more difficult to shear (stiffer) it becomes, it is shear thickening. Cornstarch suspensions exhibit such a property.

In 2008, a group led by Abdoulaye Fall sought to explain the mechanism for shear thickening behavior. By performing various experiments with cornstarch suspensions, the group compared vane-in-cup Coulette and plate-to-plate apparatus. Using the plate-to-plate apparatus and a rheometer, the group observed shear stress τ of the fluid is a function of torque C and plate radius R and shear rate $\dot{\gamma}$ is a function of R, rotation rate ω, and plate spacing b [2].

$$\tau = 3C/2\pi R^3 \qquad \dot{\gamma} = 2\pi R\omega/b \qquad (1)$$

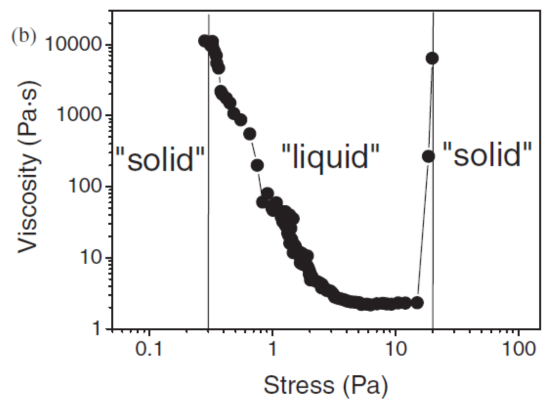

Figure 3: Apparent fluid viscosity vs. applies shear stress [1]

This modeling led to an analysis of the relationship between shear stress and apparent fluid viscosity shown in Figure 3. Fall asserts that shear thickening fluids experience three distinct states as shear stress is applied. Under no shear, the fluid with particulate suspension behaves as a solid. As shear is applied, the suspension is forced to flow, or is "fluidized". This continues as shear is added until a critical point at which the suspension suddenly locks up and becomes very stiff. The critical stress is a function of suspension concentration (wt % cornstarch in this case). The group concludes that shear thickening is caused by reentrant jamming transition of the suspended cornstarch. Simply put, under enough shear stress, the particles impede each other to such a degree that the fluid can no longer flow. The paper likens the application of shear to the increase in a fluid temperature. Glassy, shear thinning fluids become less viscous as either temperature is increased or shear is applied. In the opposite fashion, shear thickening fluids, which may have a solid phase at elevated temperatures, can be mad solid by applied shear [2].

More recently, a group led by F.J. Galindo-Rosales sought to model the viscosity of shear thickening fluids in three zones. The group divides the continuum of viscosity response to shear into zone I where slight shear thinning behavior exists up to a critical shear rate $\dot{\gamma}$, zone II in which shear thickening occurs between $\dot{\gamma}$ and a higher $\dot{\gamma}_{max}$ (where viscosity maximizes), and zone III in which a steep shear thinning occurs at shear rates above $\dot{\gamma}_{max}$ [1]. Empirical data supports the piecewise model (2), reproduced from the group's 2011 paper [1].

$$\eta(\dot{\gamma}) = \begin{cases} \eta_I(\dot{\gamma}) = \eta_c + \dfrac{\eta_0 - \eta_c}{1 + [K_I(\dot{\gamma}^2/(\dot{\gamma} - \dot{\gamma}_c))]^{n_I}} & \text{for } \dot{\gamma} \le \dot{\gamma}_c, \\ \eta_{II}(\dot{\gamma}) = \eta_{\max} + \dfrac{\eta_c - \eta_{\max}}{1 + [K_{II}((\dot{\gamma} - \dot{\gamma}_c)/(\dot{\gamma} - \dot{\gamma}_{\max}))\dot{\gamma}]^{n_{II}}} & \text{for } \dot{\gamma}_c < \dot{\gamma} \le \dot{\gamma}_{\max}, \\ \eta_{III}(\dot{\gamma}) = \dfrac{\eta_{\max}}{1 + [K_{III}(\dot{\gamma} - \dot{\gamma}_{\max})]^{n_{III}}} & \text{for } \dot{\gamma}_{\max} < \dot{\gamma}. \end{cases} \tag{2}$$

The paper goes no further into explaining the mechanism behind shear thickening phenomena other than to reaffirm the work of other groups by identifying the formation of jamming clusters bound together by hydrodynamic lubrication forces, or "hydroclusters" [1]. Rather, this paper is focused on demonstrating an acceptable correlation between the proposed model and the experimental data obtained.

These papers provide a solid explanation for the observed viscosity increase in non-Newtonian oobleck as a result of applied *shear* stress. The set-up for this experiment did not apply direct shear to the cornstarch mixture. Rather it applied transient, oscillating *normal* stress to the body of fluid. It is therefore assumed that internal shear stress at some point developed within the fluid. As the speaker vibrated, a two-dimensional wave pattern presented on the surface of the fluid. The peaks and troughs of this wave pattern inverted at a rate proportional to the frequency of the speaker. Over time, the peaks and troughs of the wave grew more defined until spires like that pictured developed. Once developed, the spires flailed around in unpredictable directions and quickly fell. Though the chaotic behavior of the spires is the subject of photography, it is the ordered and consistent manner in which the spires originated that is of importance in identifying the mechanism of growth. Indeed, alternating wave patterns like those observed would induce the assumed internal shear stress needed to thicken the mixture and cause larger wave peaks to eventually become spires. Furthermore, increase in shear rate may not be the only means of increasing viscosity here. Cornstarch suspensions display characteristics of rheopectic non-Newtonian fluids meaning that exposure to shear over time, even constant shear, will result in an increase in fluid viscosity [3]. The shear thinning counterpart to rheopectic fluids are thixotropic fluids which thin over time at constant shear.

The cornstarch/water mixture was mixed with green food color dye in order to make flow visualization more apparent. One drop of dye was mixed uniformly through 2 oz. of the cornstarch/water mixture. Over the course of each experimental run, the dye diffused through the fluid until a uniform mint green developed throughout. Because of the extremely high frequency of speaker oscillation, fast shutter speed was used to ensure tine resolution of the image. As such, bright light was required for decent exposure. Two large, tripod-mounted painter's lights were used to adequately illuminate the subject.

The photographic technique used to capture this flow was digital color photography using a Canon EOS Digital Rebel XTi DSLR camera with an EF-S18-55mm, f/3.5-5.6 lens. The field of view was 3 in. x 2 in. The camera lens was positioned 1.5 feet from the subject and full zoom capability was utilized to fill the frame with the subject. The original images were captured at

10.1 Megapixel (3888 x 2592 pixels) resolution. The high frequency vibration of the subject required a very fast exposure time of 1/400 seconds. This quick exposure did not allow light to reach the receiver for very long, so f/6.3 was used to maximize the percentage of available light received. The downside of using this f-stop is the depth of field was only about 1 in. Close examination of the images reveals poor focus in the foreground and background. ISO-400 sensitivity was used. A higher ISO may have allowed for a brighter image, but due to undesirable graininess, the team decided against this.

The images were saved initially as JPEGs by the camera, but I converted them to TIFFs at soon as possible. I chose the five consecutive .tiff images I wanted to showcase and imported them into Adobe Photoshop Elements 8©. I cropped the images considerably and performed very minor color curve manipulation to achieve the lighting, color, and contrast I wanted. I then stitched the images together into a single file leaving thin white borders between and around each image to provide easier viewer distinction between them. The final composite image is a .tiff file with dimensions 7968 x 2044 pixels.

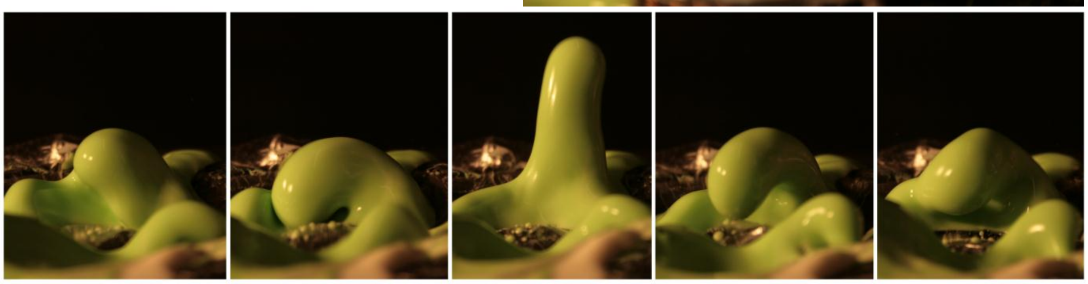

Figure 2: Before and after comparison of image post-processing

Overall I am pleased with the outcome of this project. I believe the sequence of images I chose reveals an intriguing phenomenon unique to shear-thickening fluids and also enables viewers to impart a sense of life to what is no more than water, starch, and dye. During an in-class critique session, some of my classmates joked that this flow looks like “flubber” and that I should have drawn a face on it. I am glad my images were able to inspire the imaginations of the viewers; in this regard I view my work a success. From and experimental and photographic angle, I recognize several areas of potential improvement. I am not particularly thrilled about some of the more distracting elements in the images. In particular, the plastic wrap used to protect the speaker cone unnecessarily reflects light and the white smears in the foreground, remnants of previous trials, are likewise distracting to the eye. For future iterations, I would take more time to develop an apparatus that is both functional for achieving the flow and provides a better artistic backdrop than I achieved here.

References

[1] Galindo-Rosales, F.J., F.J. Rubio-Hernandez, and A. Sevilla. "An Apparent Viscosity Function for Shear Thickening Fluids." *Journal of Non-Newtonian Fluid Mechanics* 166 (2011): 321-25. Print.

[2] Fall, Abdoulaye, N. Huang, F. Bertrand, G. Ovarlez, and Daniel Bonn. "Shear Thickening of Cornstarch Suspensions as a Reentrant Jamming Transition." *Physical Review Letters*100 (2008).

[3] “Non-Newtonian Challenges.” *Process Engineering* (2010): 34. Print.