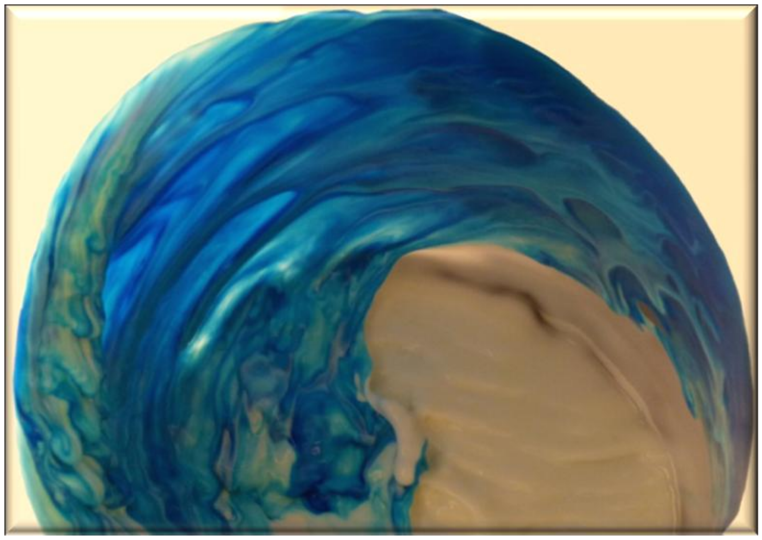
First Team Project Report



Michael J. Vallejo

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Group Members - Team 6:

Daniel Anson

Matthew Feddersen

Bradley Samuels

Kryztopher Tung

I. INTRODUCTION

This reports documents the visualization techniques and physics of a non-Newtonian fluid for the first of three team projects of the Flow Visualization course at the University of Colorado at Boulder (CU). The goal of this document is to describe the image of rotating non-Newtonian fluid presented on the cover page (p. 1) and photographic techniques used to capture the image. The non-linear shear versus strain and shear thickening characteristics of a non-Newtonian "oobleck" will be described in some detail.

II. EXPERIMENTAL PROCESS

The goal of Team 6 was to photograph and visualize interesting phenomena of a non-Newtonian oobleck mixture made of one part water and two parts corn starch. A variety of experiments using oobleck were run in the CU Durning lab in order to discover the most visually and physically interesting aspects of the fluid. Some examples of experiments run include folding-in food coloring into the oobleck, tossing a golf ball into a cup of thinned oobleck, and spinning a sample of oobleck in a Spin Art-type toy. Another interesting experiment run involved heating a beaker half filled with oobleck on a hot plate with a goal of boiling the fluid; though boiling did not occur, the oobleck hardened and acted like a displacing piston in the beaker as the air below the semi-solid fluid was heated. The figure below shows a sampling of the experiments run.

Figure 1. Experimental photos of oobleck with folded-in food dye (left), a golf ball tossed into thinned oobleck (center) and dyed fluid rotating in a Spin Art toy (right).

While the experiments described above were visually interesting they did not demonstrate the complicated shear thickening phenomena that was the goal of the team. Ultimately it was decided that pouring the oobleck from a certain height, rotating the fluid in a cylinder and deforming the mixture with fingers resulted in both visually stunning images and complex fluid mechanics. Spinning a sample of dyed oobleck in a graduated cylinder will be the focus for the remainder of this report.

III. FLOW APPARATUS

Figure 2 depicts the experimental setup used to capture the image of rotating dyed oobleck. Setup begins by preparing a mixture of one part water with two parts cornstarch in a bucket-like cylindrical container of around 12 inches in diameter (6 inch or 0.15 m radius) and 15 inches deep. Two cups water and four cups cornstarch were used for the image. For best results, the cornstarch was gradually added to the water and stirred with a metal spoon until thick. Neon blue food coloring was then added to the surface of the oobleck as shown in Figure 3. One member of the team held the bucket of oobleck while standing 1 foot from the camera. For lighting, the black and yellow dual studio lights available in the Durning lab (unknown model and wattage) were placed two feet to the left of the bucket. Once the lighting and camera were set, the team member holding the bucket began to rotate the bucket by hand at approximately 1 revolution every 14 seconds (four revolutions per minute). The gradual stretching of the oobleck inside the bucket highlighted by the food coloring was then photographed.

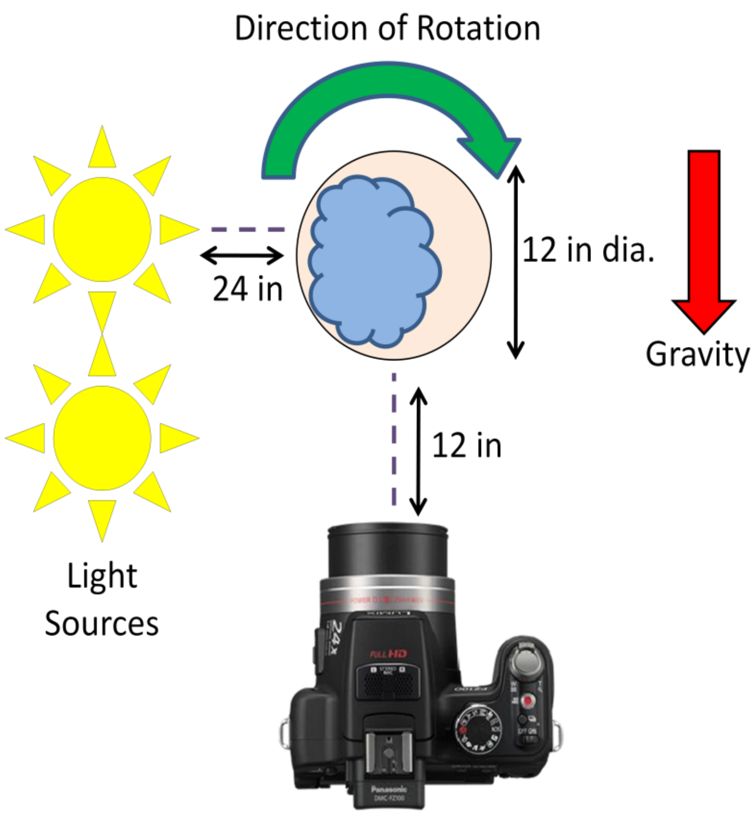

Figure 2. Flow apparatus including camera location, fluid container, light sources and directions of forces (FZ100 camera image courtesy of Panasonic[1]).

Figure 3. Food coloring on oobleck prior to rotation.

IV. DESCRIPTION OF FLOW

Shear thickening fluids such as oobleck are a subset of non-Newtonian fluids that do not show a linear relationship between shear stress and strain. Consequently, an inherent viscosity cannot be specified. Instead an apparent viscosity μ_{ap} is used to describe the flow of the oobleck. The figure below compares the shear stress versus strain rate for a shear thickening fluid along with other fluid types and is used for reference.

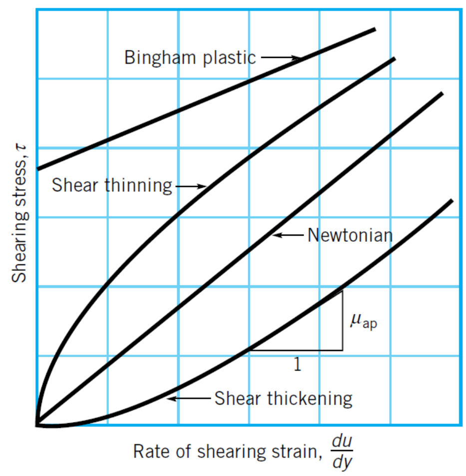

Figure 4. Comparison of Newtonian and non-Newtonian shearing (courtesy of Munson, Young and Okiishi[2]).

The figure depicts that the harder a shear thickening fluid is pulled or deformed, the more viscous it becomes (the slope of the stress-strain curve increases). As an example of this, when covering one's hand with the oobleck solution, the faster one pulls the harder it is to remove the hand. This is due to small amounts of liquid between the starch particles acting as a lubricant that reacts in relation to velocity. Complicated equations have been derived to compute the apparent viscosity of a non-Newtonian with great accuracy[3]. Here, more simplified methods will be used here to describe μ_{ap}.

Sanders, Joseph and Beavers characterize a fluid coating the inside of a rotating cylinder as "rimming" flow[4] and attempt to describe the apparent viscosity as a function of angular velocity of the cylinder and gravity. A rough approximation of the apparent viscosity can be made using the equation

$$\mu_{ap} = \frac{gD^2\rho}{3\Omega R} \quad \textbf{[1]}$$

where g is acceleration due to gravity (9.81 m/s²), D is the average film thickness of fluid on the walls of the container, ρ is the density of the fluid, Ω is the angular velocity of the container and R is the radius of the cylinder. For the approximation of this captured non-Newtonian flow, the average film thickness judging by the photograph is 1 cm (0.01 m) and the density of the cornstarch/water mixture is 1500 kg/m³[5]. Inserting these values along with the angular velocity and radius defined in Section III into Equation 1 reveals

$$\mu_{ap} = \frac{(9.81 m/s^2)(0.01\ m)^2(1500\ kg/m^3)}{3(1/14\ \mathrm{s}^{-1})(0.15\ \mathrm{m})} = 45.8\ kg/s\ m\ = 458\ poise$$

The calculated viscosity suggests the non-Newtonian fluid at any point is several orders of magnitude higher than water at room temperature (0.01 poise).

V. VISUALIZATION TECHNIQUES

The materials and apparatus described in Section III were used to visualize the shearing effects of the non-Newtonian oobleck fluid. The choice of using blue food coloring on the natural cream color of the oobleck not only highlights the long strings of fluid against the boundary walls but also creates an ocean wave effect inside the rotating cylinder, mimicking a shape typical of a standard Newtonian fluid. The choice and proximity of lighting creates a soft coloring effect for this particular image. The fluid is created using tap water and materials readily available at any supermarket.

VI. PHOTOGRAPHIC TECHNIQUES

a). Camera Settings

A 14.1 megapixel Panasonic Lumix DMC-FZ100 digital camera was used for the image. The photograph of the fluid flow was taken with the camera lens 12 inches from the front of the rotating bucket as depicted in Figure 2. A focal length *f* of 15 mm was used in order to zoom in on the oobleck while holding the camera at a reasonable distance away from the bucket. The field of view was approximately the same size as the bucket diameter of 12 inches. For the exposure, a shutter speed of 1/60 s and an f-stop (relating to aperture size) of *f*/4 was used. The shutter speed and aperture diameters were chosen to balance the incoming light into the camera lens with a relatively quick exposure time in order to capture the rapidly changing dynamics of the fluid flow. The ISO was set to 200 due to strong lighting available in the apparatus. The 11 frames per second burst shooting feature of the camera was used to snap several images of the rotating oobleck quickly.

b). Image Post Processing

Adobe Photoshop CS5 was used for post processing of the image. The original 4320 x 2432 pixel JPEG image was imported into Photoshop to begin post processing. The image was then cropped to 3400 x 2392 pixels in order to remove as much of the bucket as possible. The background was created by deleting the existing background in the photo with Photoshop's magic wand tool. The eyedropper tool was then used to match the cream color of the oobleck in order to fill in the blank background with the paint bucket tool. Finally, the smudge tool was used to smooth out rough pixels at the oobleck/bucket interface. The original image and post processed image are shown side-by-side in the figure below.

Figure 5. Original image (left) and image following post processing (right).

VII. IMAGE ANALYSIS AND CONCLUSIONS

The image clearly captures the shear thickening effect of a non-Newtonian fluid. The physics of the strands of stretched oobleck highlighted with dye are shown well. The wave-like shape of the fluid makes for interesting mimicry of a Newtonian fluid. Homemade oobleck is fascinating to play with one's hands and many of the fluid's properties cannot be captured with single photographs alone. Overall, the goals of describing the physics of rotating non-Newtonian fluid with an aesthetically pleasing image were achieved. The visualization could be improved by combing the frames from burst shooting into a slow-motion video. The use of specially-design rotating device similar to a cement mixer in addition to the use of a tripod would improve the quality and control of the image capturing process as well as the mixing speed of the oobleck and dye. More research into the interactions between the Newtonian food coloring and the oobleck could also be investigated.

VIII. REFERENCES

[1]Panasonic. "DMC-FZ100K - Lumix Digital Cameras." Panasonic Digital Cameras. 2009. Accessed 9 February, 2011. <http://www2.panasonic.com/consumer-electronics/shop/Cameras-Camcorders/Digital-Cameras/Lumix- Digital-Cameras/model.DMC-FZ100K.S_11002_7000000000000005702#tabsection>.

[2]Munson, Bruce, Donald F. Young and Theodore H. Okiishi. Fundamentals of Fluid Mechanics. New York: Wiley and Sons, 2002.

[3]Galido-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): 321-325.

[4]Sanders, J., D. D. Joseph and G. S. Beavers. "Rimming Flow of a Viscoelastic Liquid Inside a Rotating Horizontal Cylinder." Journal of Non-Newtonian Fluid Mechanics 9 (1981): 269-300.

[5]Wikipedia article on starch, accessed 20 March, 2011. <http://en.wikipedia.org/wiki/Starch>.

APPENDIX

Link to Team 6 video for first group project

http://vimeo.com/20743439