Imaging Falling Streams of Oobleck using Highlighter Fluid as a Tracer and Black Lighting

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1. Introduction

The goal of the experiment was to try and capture an image demonstrating some of the interesting qualities and properties of the non–Newtonian, shear thickening (or *dilatant*) fluid that is Oobleck (1:1 mixture of cornstarch and water). Team 5 as a whole came up with the idea to use Oobleck and multiple tests were conducted. The image provided as the submission for this assignment, however, this experiment was also conducted separately. The image was taken with a more artistic approach in mind for this assignment.

2. Flow Phenomena

Oobleck is a fluid that acts as a solid when a force/ pressure (aka *shear stress*) is applied to it (usually in a short period of time). The solidity of the fluid depends on the magnitude of stress over time. A slow, soft movement results in the fluid remaining in liquid form whereas a fast, hard movement results in increase in viscosity, hence thickening to the point that the oobleck acts as a solid (Bahr & Lemmer, 2016). To understand oobleck, we need to first understand non–Newtonian fluids. To do so, we need to know the characteristics of Newtonian fluids. Given below is an equation that mathematically defines Newtonian fluids (Munshi & Prabhakar, 2012).

$$\tau = \mu \times du/dy$$

Where, du/dy is the strain rate (velocity gradient perpendicular to the direction of shear) in sec^{-1},

τ is the shear stress exerted by the fluid (drag) in Pascals, and μ is the viscosity of the fluid in Pascal-second.

Another useful equation is the power law equation, which is,

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

Where, γ is the shear rate in sec^{-1}, K is a constant (consistency), η is the viscosity of the fluid in Pascal-second, and n is flow index. For dilatants, $n > 1$ and for Newtonian fluids, $n = 1$.

A non–Newtonian fluid's viscosity is not independent of shear rate, and hence, the plot of shear rate over shear stress is not a straight line, as seen in Newtonian fluids, as it varies, due to not having a constant viscosity (see Figure 1 (top)). Now that we know how non–Newtonian fluids behave, let's take a deep dive into reveal some physico–chemical interactions in the molecular level. A phenomenon called *hydroclustering* (or *hydrodynamic clustering*) occurs in dilatants (Farr et al., 1997). This is when the molecules of a suspension (like cornstarch in oobleck, which is solid cornstarch particles in water)

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conglomerate or flocculate in little lumps when a force is applied, and are comprised of particles that compressed together until the force remains, hence increasing the viscosity. Initially, the suspension is stable and immobile (see Figure 1 (bottom)).

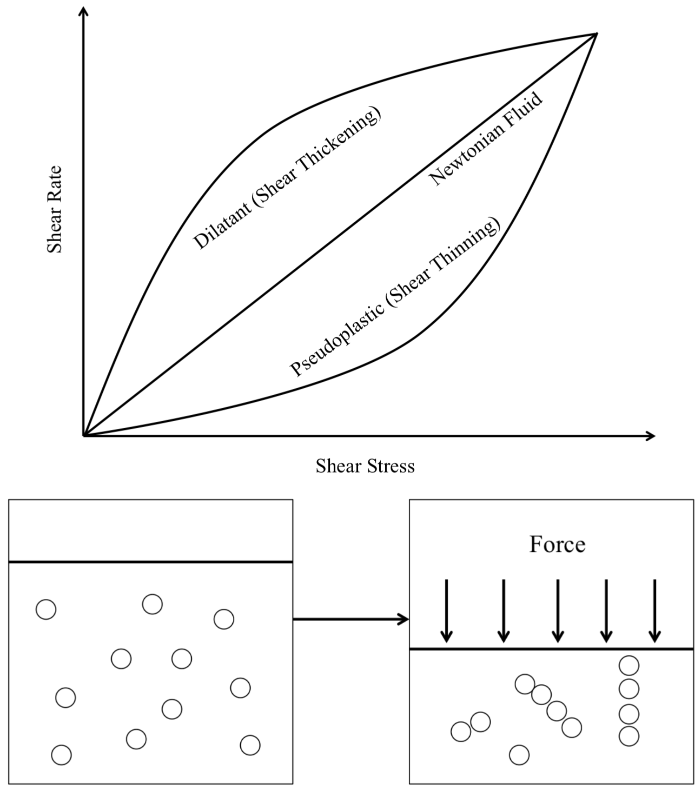

Figure 1: Differences between common types of non–Newtonian fluids (Top) and Hydrodynamic clustering (bottom)

A Reynold's number can be estimated using the formula given below, by approximating the density to be 800 Kg/m^3, the velocity of flow to be 0.4 inches per second (see Section 4), and the length of flow is known, but the only issue is the changing viscosity. The flow in Figure 4 seems to be fairly straight, with some degree of ambiguity due to the time–averaging. If we assume that the streams have not broken apart into solid clumps/ chunks that have been time averaged to look like a stream, we can assume an average Re and calculate viscosity at the time of flow. Unfortunately, the ability to accurately measure Re was lacking in the experiment, and the Re for this particular flow cannot be determined.

$$\mathrm{Re} = (\rho \times V \times L)/\mu$$

3. Flow Visualization Technique

Highlighter fluid was used as the tracer for this image, accompanied by blacklit conditions (UV lighting). The base fluid used was a Oobleck, a non–Newtonian shear thickening fluid. A 1:1 mixture of water and cornstarch was used to make the fluid, and the fluid was poured over a vegetable steamer that was held steadily, 15" from the horizontal (as shown in Figure 2). The lighting had to be placed above to activate the highlighter fluid's fluorescence that would make the streams visible. This was the chosen lighting method, due to the Oobleck being bright yellow, runs the risk of oversaturating the image in the areas of interest. The object (as seen in Figure 4) itself was about 4.5 inches in length vertically. The vegetable steamer was about 8 inches in length horizontally when fully extended. Flow was through 4 inches in the middle.

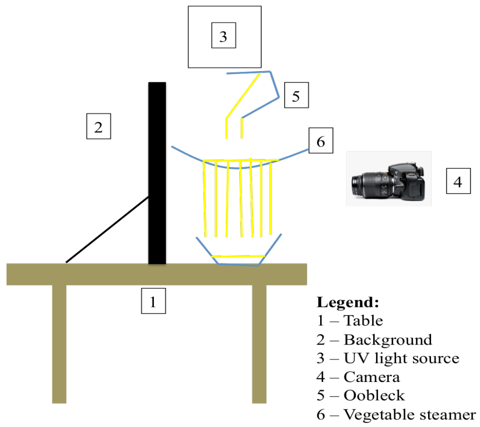

Figure 2: Setup used for imaging flow

4. Photography Technique

The Camera used was a Nikon D3200 with an 18–55 lens (DSLR digital camera). As shown in Figure 2, the camera was hand–held, and kept orthogonal to the lighting source. The required parameters are listed and calculated as follows:

1. *Lens Specs* – Focal length: 52 mm, F number (f/): 5.6
2. *Exposure specifications* – Shutter Speed: 1/5 sec, ISO: 8064, Aperture size = 9.285 mm(1)
3. *Camera and Image* – Nikon 3200 DSLR (digital), Original (w x h) = 6016 x 4000 pixels, Final (w x h) = 5457 × 4000 pixels
4. *Distance of object (to lens)*: 15 in(2)
5. *Field of View*: 66 in^2(3).
6. *Time Resolution*: 0.4 in/sec (4).
7. *Final cut processing (Photoshop)*: The self-explanatory Figure 3 summarizes the adjustments made in Photoshop of the original image, and Figure 4 shows the image before and after processing. The grainy-ness of the image was used to an advantage, as turning the image black and white gives a "60's conspiracy newspaper article" feel. The grains add to the newspaper–like texture.

   Reasons for choosing the mentioned settings: Higher ISO for better image saturation in the dark, low F#/ high aperture size to allow more light. Time averaging (1/5 sec) happened as a result of changing F# and ISO.

Calculations:

[1]**Aperture size:** $D = F / f\# = 52 \text{ mm} / 5.6 = 9.285 \text{ mm}$

[2]**Distance to lens:** a non-conventional formula was used:

$$Ob = \frac{F(\text{mm}) \times \text{Real Height (mm)} \times \text{Image Height (Pixels)}}{\text{Object Height (Pixels)} \times \text{Sensor Height (mm)}} = \frac{52 \times 114.3 \times 6016}{4092 \times 15.4} = 567.4 \text{ mm} = 22.34 \text{ in}$$

Angle of view (degrees) for length:

$$= 2\times\left(\arctan\left[\text{Sensor Width (mm)}/(2\times F(\text{mm}))\right]\right) = 2\times\left(\arctan\left[23.2/(2\times 52)\right]\right) = 12.575^{\circ}$$

Angle of view (degrees) for height:

$$= 2\times\left(\arctan\left[\text{Sensor Height (mm)}/(2\times F(\text{mm}))\right]\right) = 2\times\left(\arctan\left[15.4/(2\times 52)\right]\right) = 8.42^{\circ}$$

Angle of view (degrees) for diagonal:

$$= 2\times\left(\arctan\left[\text{Sensor Diagonal (mm)}/(2\times F(\text{mm}))\right]\right) = 2\times\left(\arctan\left[27.85/(2\times 52)\right]\right) = 15^{\circ}$$

[3]**Hence Field of View for length:**

$$= 2\times(\tan(\text{Angle of View})\times\text{Object Distance}) = 2\times(\tan(12.575)\times 567.4) = 253.14\text{ mm} = \underline{10\text{ in}}$$

[3]**Hence Field of View for height:**

$$= 2\times(\tan(\text{Angle of View})\times\text{Object Distance}) = 2\times(\tan(8.42)\times 567.4) = 168\text{ mm} = \underline{6.6\text{ in}}$$

Hence, the covered area was about ***10 in x 6.6 in = 66 in***^{2}, which is the field of view.

[4]**Time Resolution:** Object streams moved 4 inches in 2 seconds => 2 in/sec.

Exposure time: 1/5 seconds = 0.2 seconds. Hence the object is moving at, $2\times 0.2 = \underline{0.4\text{ in/sec}}$.

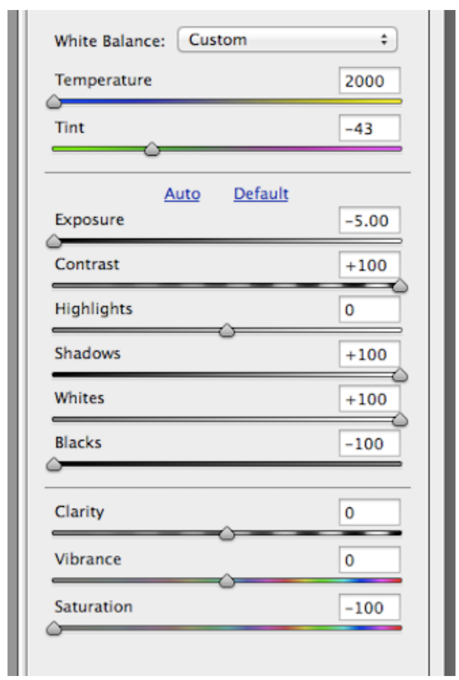

Figure 3: Basic menu on Photoshop was used to edit the image

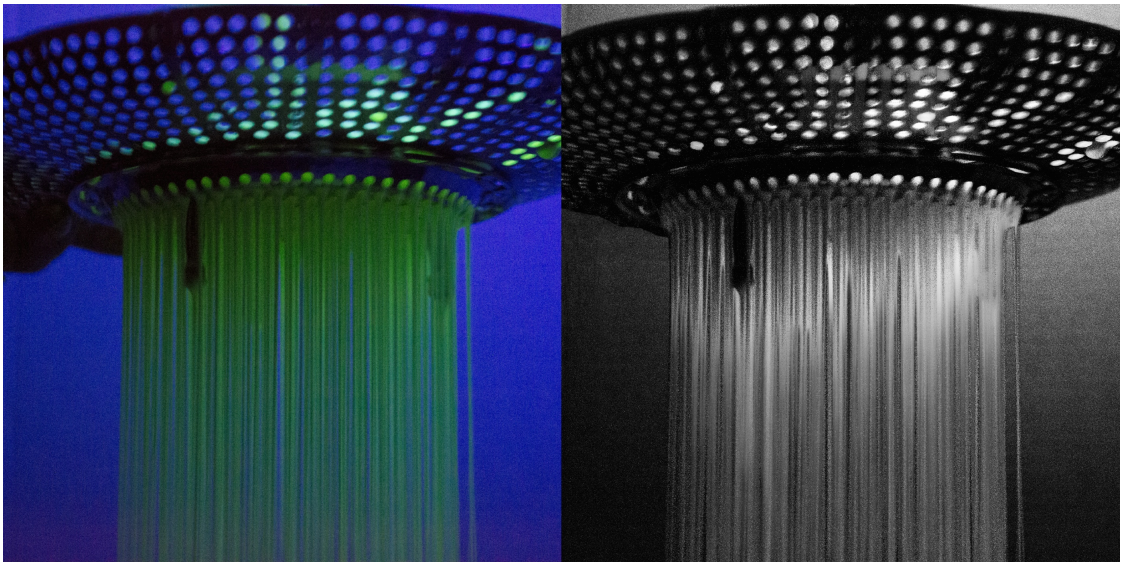

Figure 4: Unedited (left) and Edited (right) versions of Image

5. Image Characteristics

As seen in Figure 4, we can clearly see the streamlined flow of the non–Newtonian fluid. From an artistic point of view, the original image itself looks like an alien spacecraft beaming up/ dropping fluidic organic alien matter. However, the grain in the image is noticeable, hence editing out the color as shown in Figure 3 helps incorporate the grain into the desired texture, which is a newspaper article feel. The post–processing does not impede the visualization of flow, and the high–lit areas are clearly visible in the edited image. If this experiment were to be repeated again, the shutter speed used to take the image would be smaller, and a flash would be used to freeze flow, to mitigate the ambiguity of tension–breaking.

References:

Bahr B., Lemmer B., Rina P. (2016), "Non–Newtonian Fluid", *Quirky Quarks A Cartoon Guide to the Fascinating Realm of Physics* (2016), 10: p38 – 41.

Munshi B., Prabhakar R. (2012), "CFD Analysis of Newtionian Fluid Flow over a Rotating Cylinder".

Farr R., S., Melrose J., R., Ball R,. C. (1997), "Kinetic Theory of Jamming in Hard–Sphere Startup Flows", *Physical Review E* (1997), v. 55: #6.