Team Second Report

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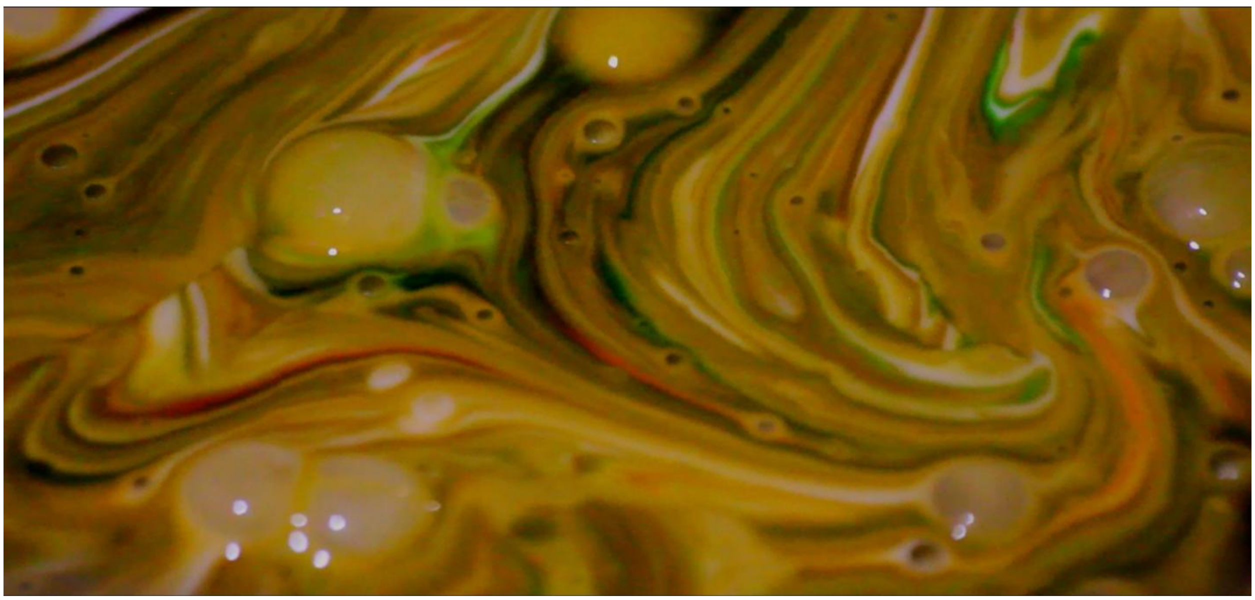


Image 1: Still photo from final video of the Oobleck stir

Background

This is the second team assignment for MCEN 4151: Flow Visualization. Our team decided to observe and experiment with non-Newtonian fluid, Oobleck. The image shown above is a still photo taken from a video that illustrates stirring Oobleck (a mixture of cornstarch and water) with dye on the top of the surface. Initially, Curtis, Cooper and I experimented with Oobleck using petri dishes and various colors of glitter. We attempted to capture the effects of stirring, dropping marbles, and pouring Oobleck into another petri dish. I was unable to capture an interesting photograph or video of this first experimentation. Having left over cornstarch I made another mixture of Oobleck and attempted to get better documentation of stirring the non-Newtonian fluid.

The goal of this experiment was to capture the phenomenon of shear-thickening that is not seen in Newtonian fluids, while also creating a colorful and visually appealing video. Newtonian fluids have constant viscosity, their resistance to flow does not change with applying stress or forces on the fluid. Non-Newtonian fluids do not follow this same principle, the viscosity changes when forces are applied [3].

Set Up

Creating Oobleck requires cornstarch and water. The approximate ratio used in this experiment was two parts cornstarch and one part water. It was mixed into a clear plastic bowl until it acted as a solid when poked but still acted as a fluid if being poured. Red, green and yellow food dye were then poured into a swirling pattern on the top surface. The bowl was then placed on a lower surface, and a tripod was set up on a table to capture the stirring from above. Ambient halogen room lights were used to capture the video, with no additional lighting needed. A figure illustrating the set-up is shown in figure 1.

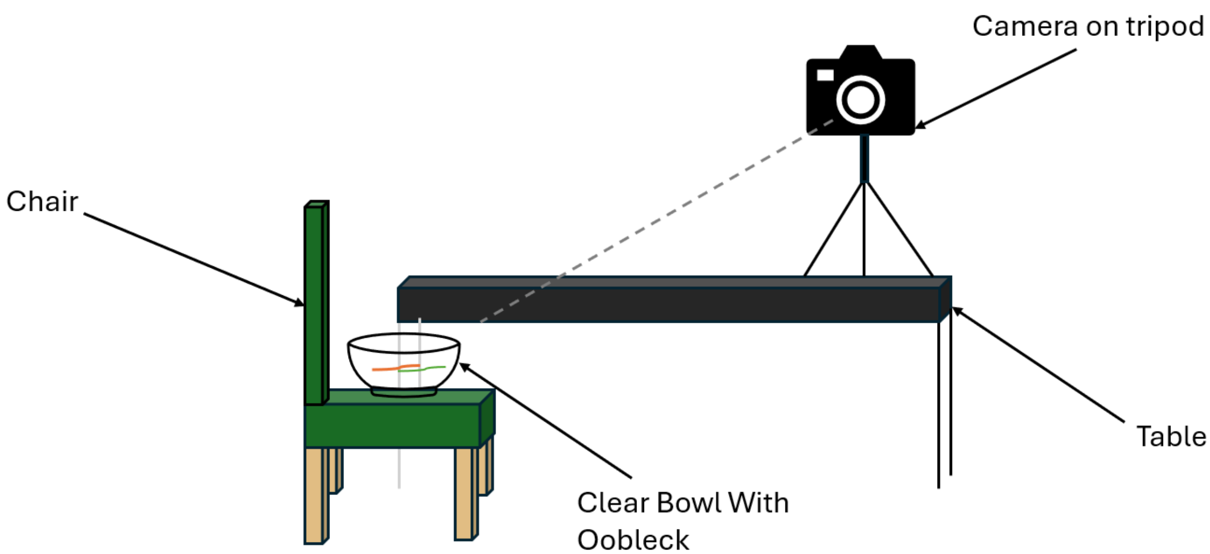


Figure 1: Illustration of set-up for video capture

A long ¼" thick metal straw was used to stir the Oobleck in the bowl. The plastic bowl had a 10" diameter and a height of 6". While stirring the mixture the dyes created boundary layers for streamlines of the Oobleck flow. These streamlines helped illustrate how the mixture of cornstarch and water resisted the stirring nonlinearly.

Fluid Physics

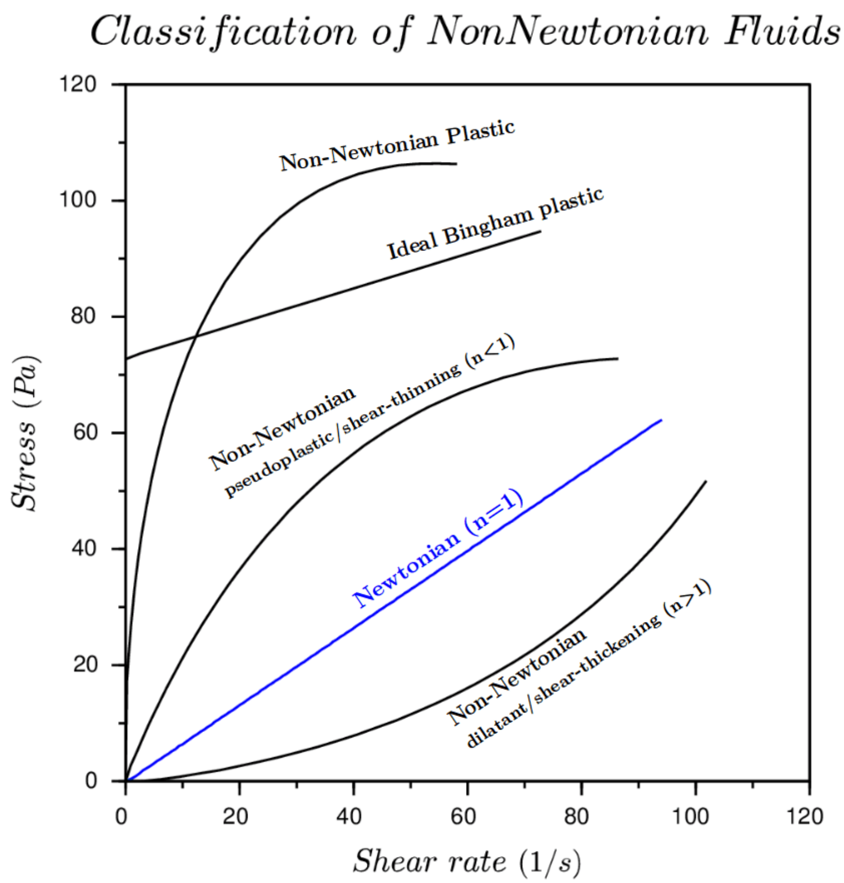
Viscosity is the measure of a fluid's resistance to flow; a higher viscosity fluid is a 'thicker' fluid that is more resistant to flowing. Oobleck is a non-Newtonian fluid, it does not have a linear viscosity relationship like classic Newtonian fluids. A nonlinear viscosity relationship causes a fluid to either act as a solid when force is applied or become more fluid-like with higher stresses [3]. Oobleck is the former, as force is applied to the fluid it acts more solid-like, this is known as shear-thickening.

Stirring Oobleck introduces shear stress to the fluid. The force of the metal straw is being applied parallel to the layers of the liquid. This causes molecules of the liquid to collide with each other and deform the liquid (causes movement liquid) [1]. These collisions of molecules result in internal frictional forces that impede the flow of a fluid, this results in the measurable characteristic: viscosity. The dynamic viscosity is the ratio of shear stresses (force applied over an area) over the shear rate (velocity gradient).

$$\tau = \mu * \frac{du}{dy}^{*}$$

*Shear stress equation: τ is the shear stress, μ is the dynamic viscosity and $\frac{du}{dy}$ is the velocity gradient

As the shear rate increases for Oobleck the shear stress increases significantly faster than Newtonian fluids and shear thinning fluids. The resistance to flow (viscosity) increases as more force is applied to the fluid. This shear thickening property is due to intermolecular forces within the fluid. At low shear rates repulsive forces of particles prevent frictional contact and the fluid acts as a frictionless suspension. However, as the stress increases, these repulsive forces can be overcome and allow friction between particles. At this critical stress, molecules collide and pile up, increasing the friction between them and the fluid takes on a solid-like appearance [1].



Graph of Shear Stresses vs Shear rate for different fluid classifications [2]

Dimensionless numbers cannot be accurately estimated for non-Newtonian fluids using classical methods. The Reynolds number is used to characterize fluid flow, as either laminar or turbulent, however it also relies on a constant viscosity.

$$Re = \frac{\rho V l^*}{\mu}$$

Reynolds number for a Newtonian fluid, where ρ is the density, V is the velocity, μ is constant viscosity, and l is the characteristic length

To account for this viscosity relationship other mathematical models have been developed, such as the power law model. The power law model estimates an effective viscosity, that can be used with the generalized form of the Reynolds number equation to calculate the Reynolds number for non-Newtonian fluids.

$$\mu_{eff} = K * \dot{\gamma}^{(n-1)}$$

Power law model: Where μ_{eff} is the effective viscosity, $\dot{\gamma}$ is the shear rate, n is the flow behavior index, and K is the consistency index

The effective viscosity is then used in the Reynold number equation. Constants K and n are obtained from the fluid experimentally [4]. K is the consistency index of the fluid and n is the flow behavior index of the fluid, in this case $n>1$ since it is a shear thickening fluid. Unfortunately, these values could not be obtained for the fluid used in this experiment. They cannot be estimated as it could drastically change the Reynolds number to an already unpredictable fluid.

Visualization

To capture the fluid flow of the Oobleck mixture, red, yellow and green dye were used to portray a boundary layer on the top surface, this allowed individual streamlines to be visualized. The original video was recorded with a resolution of 1920 x 1088 and 29.97 fps. In post-processing, the video was slowed down to half the speed to capture how the mixture resistance increased when stirring. Additionally, the saturation of yellows, and contrast of the video increased slightly to have a more vivid color scheme. A DSLR canon rebel t3i camera was used to capture the stirring.

Conclusion

The Oobleck stir video illustrates, how Oobleck interacts with shear forces. The initial force of the straw is impeded by viscous forces of the shear thickening fluid and once the shear force exerted on the fluid decreases it is allowed to flow through the fluid smoothly. This initial impediment of flow allows air bubbles to form on the top surface of the fluid. The dye boundary layers show motion of the fluids streamlines while also creating an aesthetically pleasing image. Dimensionless numbers could not accurately describe the motion of the fluid, due to its shear thickening behavior. This shear thickening is due to the intermolecular forces in the mixture. If this experiment was recreated, the video quality should be taken into consideration more. The video appears grainy at times. Additionally, multiple stirs captured on the video could better illustrate the shear thickening behavior of Oobleck.

References

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[3] V. Boonfahpratan, R. Chokdeepanich, P. A. Durão Rodrigues, R. Goyal, & K. Terdprisant. (2023). On the Mechanical Properties of Oobleck. *International Scholastic Journal of Science*, *17*(1), 6.

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