Experiments on the Viscosity and Freezing Point of a Starch Water Mixture

Chunyang Ding
Physics Department, Interlake High School, Washington 98008
Alice Huang
Physics Department, Interlake High School, Washington 98008

Non-newtonian fluids have many interesting properties that could be utilized to form more useful, slow-moving liquids. In order to use them effectively, properties such as an ideal concentration as well as the effect of temperature must be investigated. We take into consideration the molecular behavior of cornstarch in order to hypothesize about what sorts of behaviors it tends to exhibit under different circumstances.

I. INTRODUCTION

Oobleck. Although it may sound like a childish word, or simply a creation of Dr. Seuss, this substance, a mixture of starch and water, is not simply a childish toy. The properties of oobleck are non-Newtonian, more complex than water. But how would the concentration of oobleck affect the viscosity? And what would be the freezing point of such a strange liquid?

The effect of temperature and concentration on viscosity are two of the goals for this present work. Another goal is to determine the effect of concentration on freezing point. We have devised multiple apparatuses to investigate these questions in depth.

II. THEORY

In order to understand how oobleck works, we must understand the molecular concepts of fluids as well as what viscous flow means. In all fluids, there is a certain amount of drag between parallel plates within the fluid. This type of sheer forces is characterized by viscosity, so that

$$\frac{F}{A} = \eta \frac{v_0}{d} \qquad (1)$$

in which F is the force, A is the area, and η is the coefficient of viscosity[1]. Viscosity is a drag force, so when a ball is placed into a viscous solution, and reaches terminal velocity, it implies that there is a balance of forces between the net forces from gravity, buoyancy, and drag. This can be represented as

$$F_W - F_D - F_B = 0 \qquad (2)$$

$$\left(\frac{\pi d^3}{6}\right)\gamma_s - \left(\frac{\pi d^3}{6}\right)\gamma_f - 3\pi\mu v_t d = 0 \qquad (3)$$

Therefore, solving for μ, the viscosity of the fluid, is simply

$$\mu = \frac{(\gamma_s - \gamma_f)d^2}{18v_t} \qquad (4)$$

where v_t is the terminal velocity, γ_f is the specific weight of the fluid, γ_s is the specific weight of the sphere, and d is the radius of the ball. This is a specific rearrangement of Stoke's law, which would be effective as long as the Reynold's number is small[2]. Because

Reynold's number is a ratio of the inertial forces to the viscous forces, and we expect large viscous forces to appear, we expect a very small Reynold's number. This guarantee's that Stoke's Law works, as well as that there would be rather smooth laminar flow throughout the fluid[1].

Under these circumstances, we set up a falling ball viscometer, as detailed in our experimental setup, to measure the viscosity of various concentrations of cornstarch.

Cornstarch is a type of non-newtonian liquid, which has unique properties of sheer-thickening due to the polymer forms of starch. It is a large macromolecule, with the formula of $C_{27}H_{48}O_{20}$ and a molecular weight of 692.65802 grams/mole[3]. Therefore, as water is a much smaller molecule, it is possible to visualize the larger molecule bumping into itself throughout the fluid. This kind of random bumping is the cause for the viscosity within the fluid. While the non-newtonian properties of sheer-thickening seem to come arise from particle clustering and Brownian motion, as there seems to be some sort of "traffic jam" as a force is applied[4], the regular fluid properties have a similar cause.

The more particles there are in the solution, the more viscous the fluid should become as each addition results in an additional potential interaction between two particles, and the more difficult it would be for the fluid to flow naturally. Because each particle could in theory interact with each other particle, viscosity should increase exponentially as the concentration is changed.

The effect of temperature on such fluids is thought to be that the colder the temperature, the more viscous the substance. As temperature, or energy, of the fluid is decreased, the macromolecule has less energy to "move" out of the way of the sphere. Therefore, it would resist more change, and cause a greater drag force upon any kind of falling object. One interesting side effect is that the heating of cornstarch is that it would gelatinize as it heats, so that high temperature experiments could not be run.

This portion of the experiment should be able to clarify whether non-newtonian fluids behave the same as regular fluids in this regard. It is possible to consider that a higher temperature results in greater amounts of collisions between particles, so that a lower temperature would actually result in a lower viscosity.

Finally, the freezing of this fluid is interesting to consider, as we although we would be investigating the effect of a solute upon a water mixture, we would see the effect of the macromolecule upon the freezing lattice of the water. Although it is expected that the addition of a solute would lower the freezing temperature[5], it is possible that the impact on the freezing lattice would be greater.

III. EXPERIMENTAL SETUP

The apparatus for our first investigation is shown in Fig. X. In order to change the concentration of starch to water, we measured out a certain amount of grams on the balance and added it to the water, measured out by the graduated cylinder. However, for easier mixing, we stirred the substance first in a wider beaker and then transferred this liquid entirely to the graduated cylinder. In order to measure the velocity of the ball, we measured out a certain distance on the graduated cylinder with tape and then used a timer to

measure the time it took for the bottom of the ball to travel from one dotted line to the other dotted line on Fig. X.

In order to retrieve the metal ball, we simply poured the substance back into the larger beaker and cleaned it off with a paper towel.

The apparatus in Fig. X was used again to investigate the effect of temperature on viscosity, except with the addition of a freezer in order to decrease the temperature of the liquid. After the substance was thoroughly stirred in the large beaker, it was transferred to the graduated cylinder, with the appropriate markings. Then, a thermometer was placed in the substance to measure the temperature. The substance was then placed in a freezer to decrease the temperature, and then removed when the testing temperature was achieved.

The same ball procedure was used for this investigation. However, after each trial, the graduated cylinder was put back into the freezer to make sure the temperature was accurately at the testing temperature.

In order to investigate the effect of the concentration of starch on the freezing point, we utilized containers that had the same dimensions as Fig. Y. We utilized five of the same sized containers to do five trials are the same time with corresponding timers. However, unlike Fig. Y, the lids were not kept on the containers while they were in the freezer. In addition, the container was not filled up all the way with the liquid. The container was filled up only 0.8 cm for each container.

The temperature of the freezers used in these experiments was at 4° C. In addition, the containers were all placed on the second shelf away from the sides of the freezer.
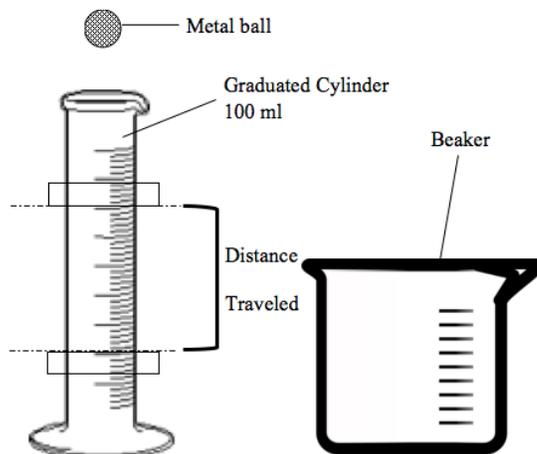

Fig. X. Experimental arrangement. The dotted lines indicate the start and end point for the bottom of the ball through the liquid.

Fig. Y. Dimensions of the containers used for the freezing experiment.

IV. RESULTS AND DATA ANALYSIS

The following figures verify several of our previous conjectures as well as validate assumptions made in the theory portion.

The initial, and perhaps most important, concentration experiment resulted in a clear trend of exponential growth as the concentration increases. Fig. a shows the exponential growth of viscosity, which leads to the conclusion that additional concentration leads to more and more collisions. This supports our collision theory as it pertains to the viscosity of a fluid.

Concentration of Cornstarch vs Viscosity of Fluid
Fig. a

$y = 0.8305e^{4.7798x}$
$R^2 = 0.9778$

Temperature vs Time
Fig. b

$y = 30623x^{-2.714}$
$R^2 = 0.9913$

Concentration of Cornstarch vs Freezing Time
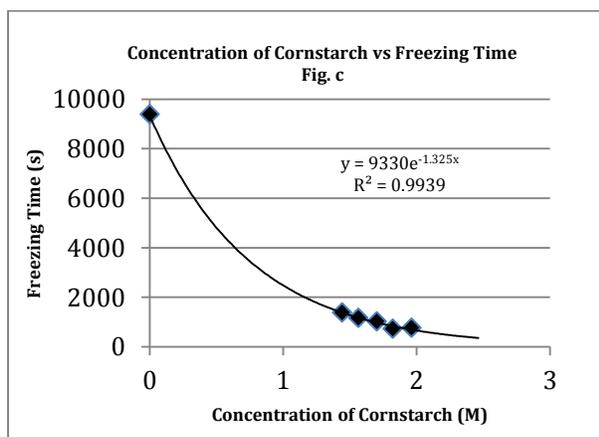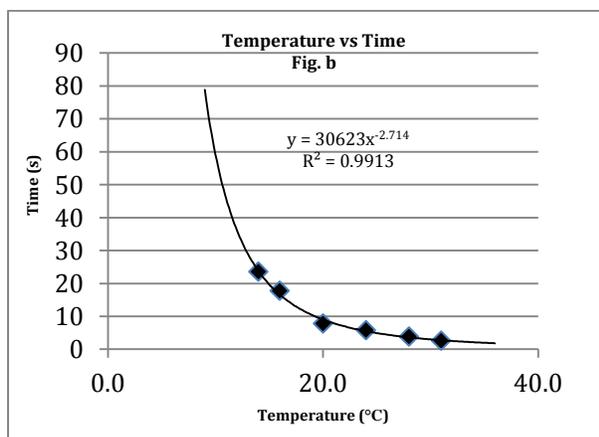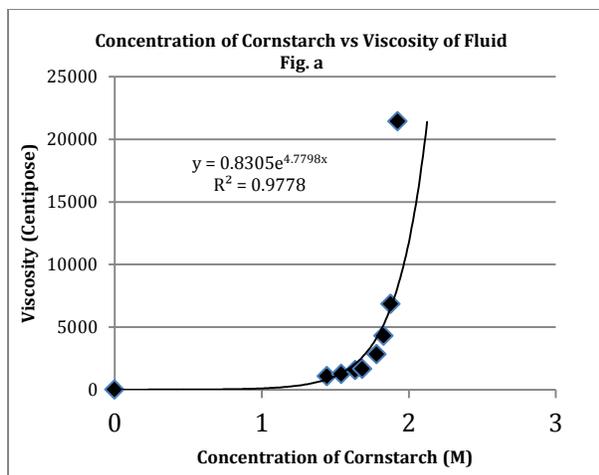**Fig. c**

$y = 9330e^{-1.325x}$
$R^2 = 0.9939$

Fig. b shows how the viscosity seems to follow an inverse square trend with the temperature of the fluid. All of these values were measured with a constant concentration of 1.877 M. This experiment makes sense, as it implies that a 0 degree (frozen) fluid would

have infinite viscosity, and that the warmer the liquid, the more viscous it would be. This shows that our original hypothesis of how increased collisions resulting in increased viscosity is incorrect.

Fig. c is a particularly interesting graph as it shows how an increase in concentration seems to decrease the freezing time, even though the freezing point should have been lowered. There is a possibility that as the concentration was increased, it got to a point where it resulted in less water being in the container, but it is more likely that the trend is a result of how the macromolecules seem to interact with the freezing of the water. Given the chemical structure of cornstarch[3], it seems that the cornstarch could serve as some sort of binding substance that the water could form IMFs with, resulting in a faster freezing time for a solid structure.

Our measurements inherently had errors, as we used the falling ball viscometer and did not have access to a real viscometer. This results in the human error of timing the ball. A more difficult error was the homogeneity of the mixture. Although we stirred the mixture as frequently as possible to distribute the particles, there still seemed to be sections where the ball would either accelerate or slow down, pointing to various pockets within the fluid.

V. DISCUSSION

Although there is room for improvement, via using more accurate viscometers and having a better mixing device, our graphs show the clear general trend for this starch-water mixture.

The use of exponential regressions through fig. a and fig. c show that the presence of the particles point to a more vigorous interaction as compared to other substances. It seems that the reason these are exponential and not some sort of power regression is found through calculus. The differential equation, $\frac{dV}{dC}$, is dependent on x, the number of particles. As concentration is directly linked to the number of particles, it is clear that the differential equation is $\frac{dV}{dX} = kx$. When integrating, this results in some form of exponential equation in the form of

$$V = C_k e^x$$

which matches the empirical formula.

While the temperature/viscosity graph is less clear, there is an interesting relationship, as it seems to vary on a x^e function. While it is unclear if this was a coincidence or some sort of constant of nature, it does warrant further investigation. Chiefly, using different concentrations of cornstarch, or to use different fluids and see if the same general trend persists. Although there has been research regarding this relationship, it would be interesting to continue on the basis of different non-newtonian fluids.

Through these experiments, information about the properties of a starch-water mixture has been gleamed. Although not enough is known to usefully utilize such a mixture, the analysis of different non-newtonian fluids, such as oils, liquid polymers, and other fluids is encouraged. Such experiments, while out of reach of these experimenters, would result in a better understanding of the fundamental properties of such non-newtonian liquids and aid to the understanding of their differences.

[1] Richard P. Feynman, *The Feynman Lectures on Physics, Book 2*. (Basic Books, New York, 2010), Sec. 41.

[2] P. Yuan and B. Y. Lin, *Measurement of Viscosity in a Vertical Falling Ball Viscometer*, (American Laboratory, Lee Ming Institute of Technology, 2008)

[3] PubChem Compound, *NCBI NLM NIH* Cornstarch Compound Summary

[4] X. Cheng, J. H. McCoy, J. N. Israelachvili, I. Cohen. "Imaging the Microscopic Structure of Shear Thinning and Thickening Colloidal Suspensions," Science. Mag. **333.6047** 1279-1279 (2011)

[5] S. S. Zumdahl, *Chemistry* 3rd. ed. (D. C. Heath and Co. Lexington, MA, 1993) Ch. 11.5