Agricultural & Biological Engineering

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Subject: Rheology of Various Fluids

Rheology is the study of the movement of fluids which is significant in biological and food processes. One of the key factors to analyze is viscosity which is a fluid's resistance to motion. It is important to biological engineering applications because it has a noted effect on pumping, mixing, mass transfer, heat transfer, and aeration of fluids (Doran, 2013). When a fluid has a constant viscosity at different shear stresses, it is classified as Newtonian. Non-Newtonian fluids have a viscosity that changes when different shear stresses are applied. Rheological parameters like the flow behavior index, n, and consistency index, k, describe the behavior of fluids. As mentioned before, different pumps may need to be used based on the type of fluid and the viscosity as well as pipe sizes.

Viscosity and percentage of torque can be measured by a Brookfield digital viscometer. The apparatus used can be seen in Figure 2. Six solutions were analyzed including hair conditioner, yogurt, corn starch 55% w/w in 35% w/w glycerol, 85% glycerol, xanthan gum with and without cells. A beaker containing 200 mL of each solution was placed under the viscometer and the spindle was lowered into the material without touching the beaker. The viscometer manual was consulted to select the proper spindle size and to ensure correct operating procedure (Brookfield). These viscosity ranges can be seen in Table 3. Measurements were recorded at 18 speeds while they ascend and again while they descend. By taking results both while increasing and decreasing, it allows for statistically analyzing the results. This process was intended to be repeated for 3 runs for each fluid.

Rotational speed (rpm) was collected and converted to shear rate, Υ, using Equation 1.

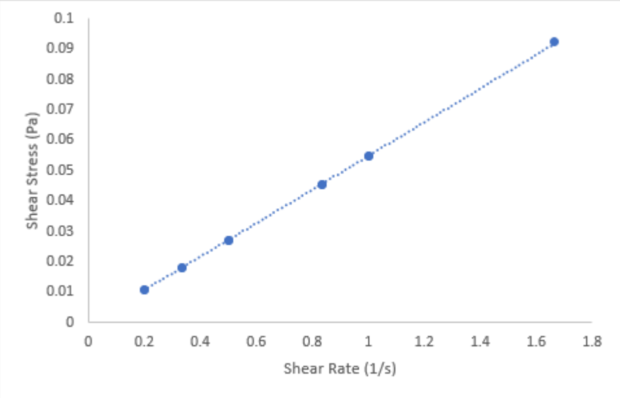
$$\gamma = \left(\frac{rpm}{60}\right) \cdot 2\pi \tag{1}$$

The outputted viscosity was converted from cP to Pa. Then shear stress, τ, was calculated using Equation 2.

$$\tau = \mu \cdot \gamma \tag{2}$$

Both the calculation of shear rate and shear stress can be seen in the sample calculations in the appendix. Analysis of each fluid can be done by plotting viscosity versus shear rate and shear stress versus shear rate and observing the trends. Table 2 in the appendix was used in comparison to help classify each fluid.

Figure 1 displays both shear stress as a function of shear rate and viscosity as a function of shear rate for the 85% glycerol solution. In comparing to Table 2, this fluid follows a Newtonian model. The correlation coefficient is 1 which proves the trendline fits the data perfectly. The exponent of x, n, is almost 1 which suggests a Newtonian fluid. Additionally, the left graph in Figure 1 of viscosity as a function of shear rate supports this conclusion. Newtonian fluids have a flat slope when it comes to their change in viscosity. If the n value is above 1, it would indicate shear thickening while a value less than 1 would suggest shear thinning.



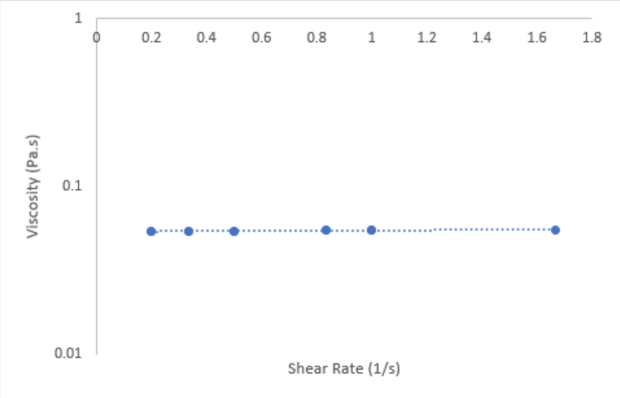


Figure 1. Shear stress versus shear rate and viscosity versus shear rate for the 85% glycerol solution. A logarithmic y axis is used to show the flat line confirming Newtonian fluid.

The remaining fluids were analyzed in the same way with analysis of the plots of viscosity and shear stress against shear rate. The rheological properties that were found for each are displayed in Table 1. This is a combination of results from Figures 1, 3, 4, 5, 6, and 7 in the appendix.

Sample	Behavior Index (n)	Consistency Index (k)	Classification
Glycerol Solution	1.0106±0.0024	0.0548±0.0002	Newtonian
Yogurt	0.2388 (Increasing)	4.749 (Increasing)	Shear Thinning (Time Dependent)
	0.6262 (Decreasing)	6.135 (Decreasing)	
Corn Starch Solution	1.006	0.7176	Newtonian
Hair Conditioner	0.3956	2.4753	Shear Thinning
Xanthan w/ Cells	0.1577	2.5174	Shear Thinning
Xanthan w/o Cells	0.1753	12.551	Shear Thinning

Table 1. Rheological properties observed and calculated for all analyzed solutions.

The decreasing viscosity graphs suggest that the yogurt, hair conditioner, xanthan solution with cells, and xanthan solution without cells could be time dependent. The plot of the yogurt shows a significant difference between the increasing and decreasing points which proves that this fluid is time dependent. The hair conditioner was a very close call to determine if it was time dependent but the data points were close enough to one another suggesting that it is not time dependent as seen in Figure 4.

Due to time constraints, multiple trials weren't completed for every fluid which explains why there aren't standard deviations for each sample seen in Table 1. For the yogurt and the hair conditioner, two trials were done for each fluid but that is still an insufficient number in order to obtain meaningful standard deviations. Several irregularities occurred during data collection which caused several missing data points. Some fluids were not analyzed multiple times for 100 RPM, some points were out of range for one trial but not outside of range for others. Lack of data hinders the result heavily in terms of the corn starch solution. Corn starch is a very common shear thickening fluid (White, 2009). Our data, due to human error and lack of data leads us to determine Newtonian while other experiments prove it is a shear thickening fluid. The xanthan solutions should have had a thixotropic or time dependent shear thinning effect but this was not what the data supported (Doran, 2013). Further trials could lead to showing time dependency but the one trial that we did for each resulted in a fluid independent of time.

The hair conditioner and yogurt both seem consistent with previous research. The apparent viscosity of the yogurt does change with time as the fluid is sheared based on Figure 3 showing dependence on time. As time continues, the yogurt thins and flows far more easily. In a flow apparatus, shear thinning fluid, like the yogurt, hair conditioner, and xanthan solutions result in less friction and therefore faster heat transfer when compared to Newtonian fluids (Graham, 2004). When using Table 1,

Figure 6, and Figure 7 to compare the xanthan solutions, the presence of cells resulted in a decreased viscosity and shear stress.

Appendix A: Figures and Tables

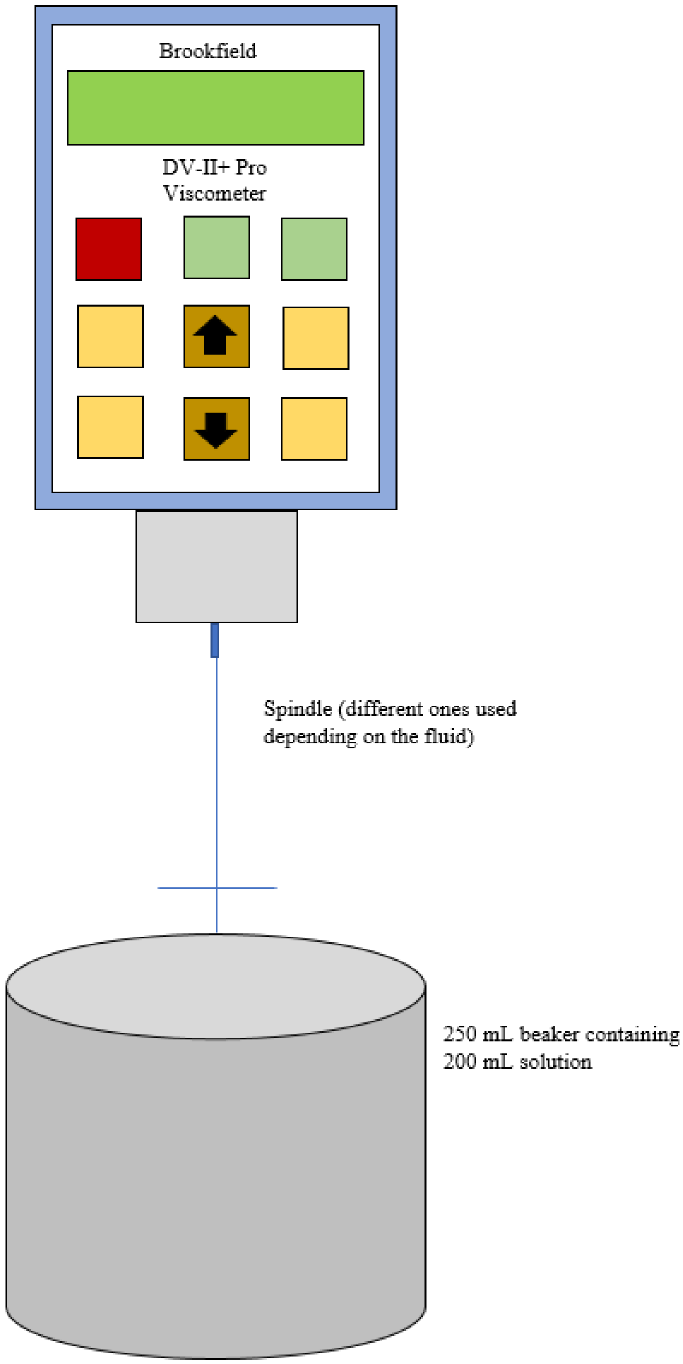


Figure 2. Schematic of the experiment. The spindle attaches to the bottom of the viscometer and then is lowered into the beaker of solution without touching. Different spindles were required for each fluid to obtain an accurate reading.

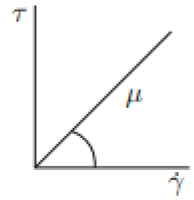
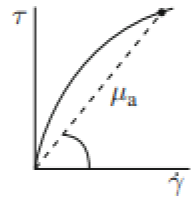
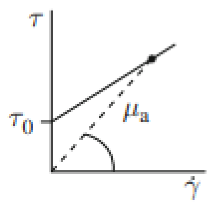
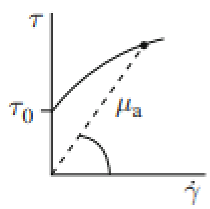
Fluid	Flow curve	Equation	Apparent viscosity μ_a
Newtonian		$\tau = \mu\dot{\gamma}$	Constant $\mu_a = \mu$
Pseudoplastic (power law)		$\tau = K\dot{\gamma}^n$ $n < 1$	Decreases with increasing shear rate $\mu_a = K\dot{\gamma}^{n-1}$
Bingham plastic		$\tau = \tau_0 + K_p\dot{\gamma}$	Decreases with increasing shear rate when yield stress τ_0 is exceeded $\mu_a = \frac{\tau_0}{\dot{\gamma}} + K_p$
Casson plastic		$\tau^{1/2} = \tau_0^{1/2} + K_p\dot{\gamma}^{1/2}$	Decreases with increasing shear rate when yield stress τ_0 is exceeded $\mu_a = \left[\left(\frac{\tau_0}{\dot{\gamma}}\right)^{1/2} + K_p\right]^2$

Table 2. Rheological behavior and classifications of various fluids (Doran, 2013). Used to analyze the graphs of shear stress versus shear rate for the fluids tested.

Sample	Viscosity range	Spindle
Glycerol 85% w/w	15-20000	2
Xanthan with Cells	15-20000	5
Xanthan without Cells	15-20000	5
Corn Starch Solution	50-100000	2
Hair Conditioner	200-400000	4
Yogurt	50-100000	6

Table 3. Spindle selection for fluids. Each fluid has a specific range of viscosity which requires use of different spindles to best model those fluids. Data came from the Brookfield Manual (Brookfield).

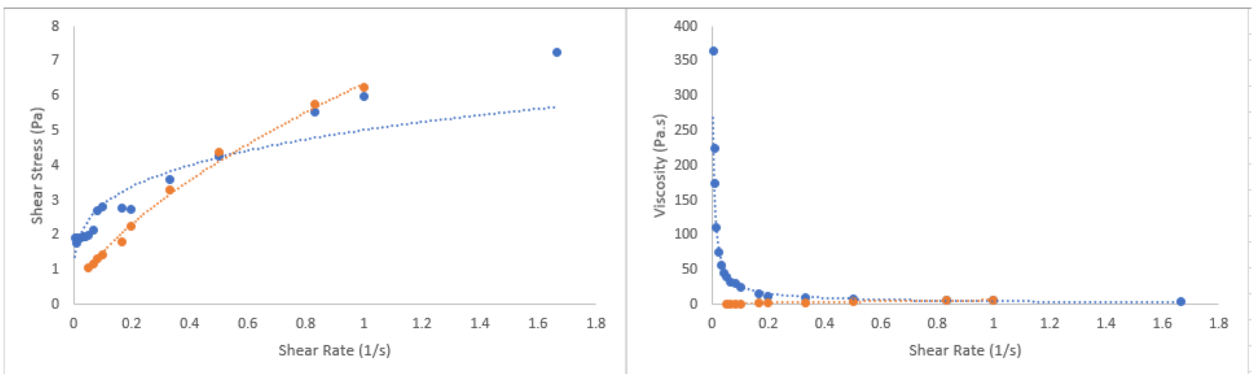


Figure 3. Shear stress versus shear rate (left) and viscosity versus viscosity (right) for the liquid yogurt. As seen in the left graph, the increasing points (blue) and the decreasing (orange) follow different paths suggesting time dependency.

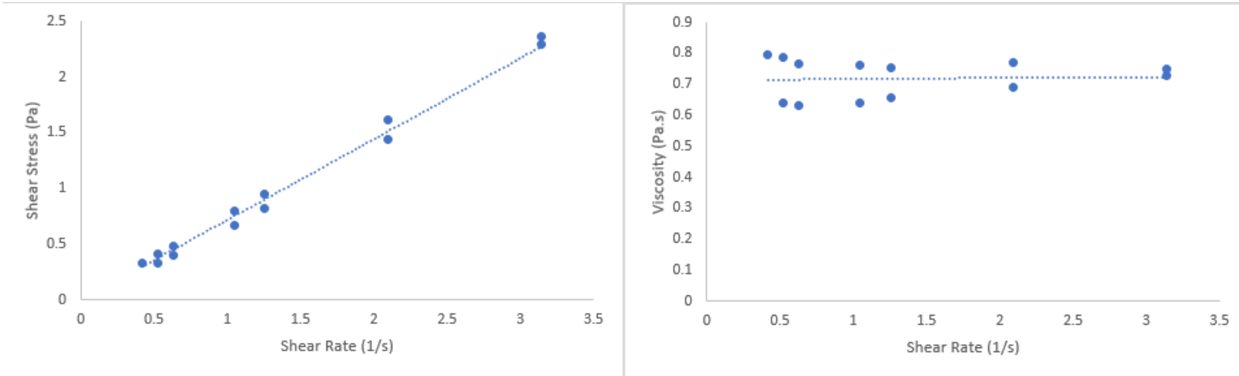


Figure 4. Shear stress versus shear rate (left) and viscosity versus viscosity (right) for the corn starch 55% w/w in 335% w/w glycerol. There is a linear correlation between shear rate and shear stress indicating Newtonian fluid.

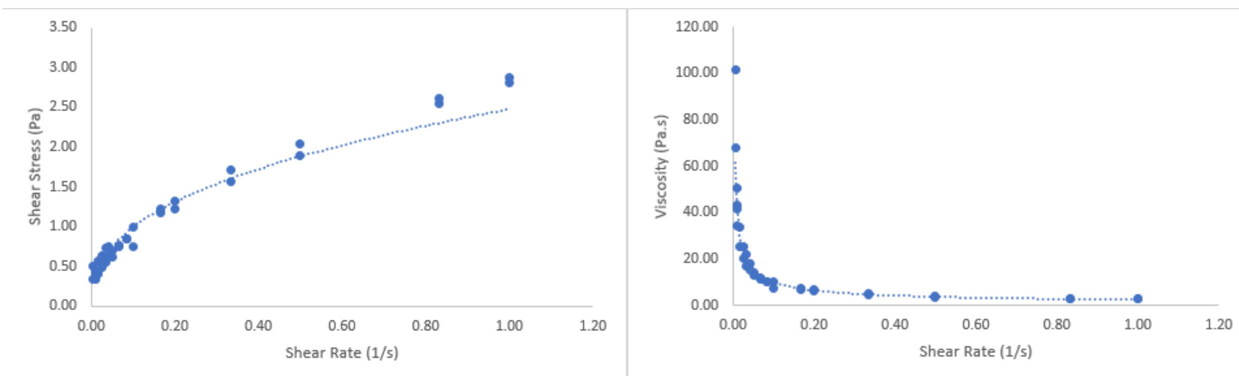


Figure 5. Shear stress versus shear rate (left) and viscosity versus viscosity (right) for the hair conditioner. The small n and the negative relationship between viscosity and shear rate suggests shear thinning.

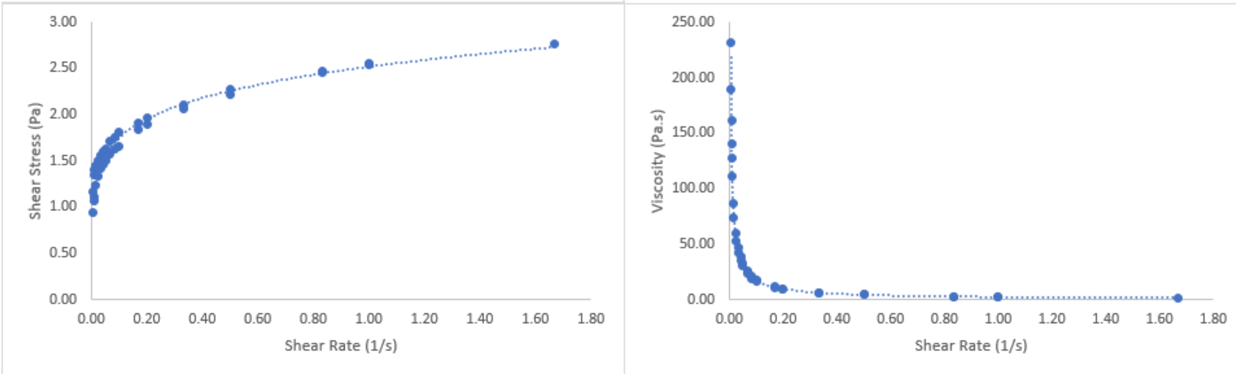


Figure 6. Shear stress versus shear rate (left) and viscosity versus viscosity (right) for the xanthan solution with cells. The small n and the negative relationship between viscosity and shear rate suggests shear thinning.

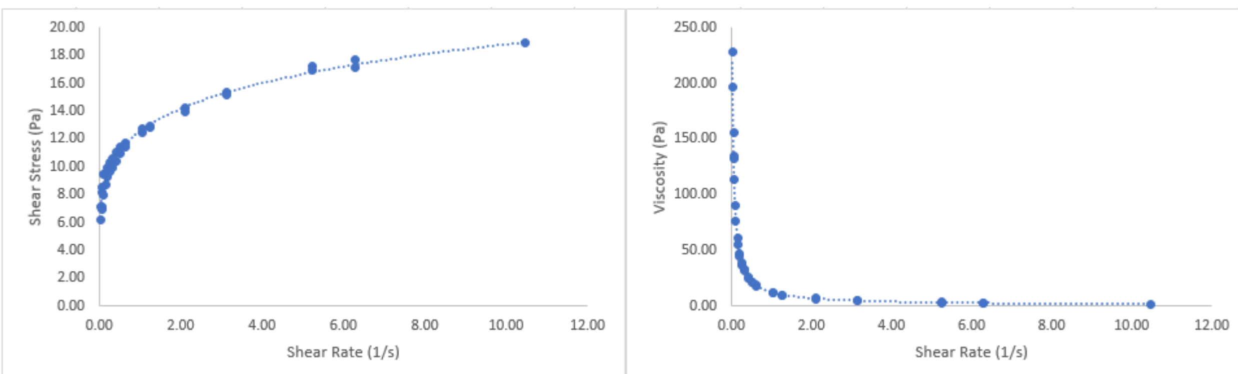


Figure 7. Shear stress versus shear rate (left) and viscosity versus viscosity (right) for the xanthan solution without cells. The small n and the negative relationship between viscosity and shear rate suggests shear thinning.

Sample	Yield Stress	
Yogurt	1.7174 (Increasing)	0.6316 (Decreasing)
Hair Conditioner	0.3514	
Xanthan with Cells	1.1288	
Xanthan without Cells	7.0385	

Figure 8. Yield stress for all shear thinning fluids. Yield stress was determined by used polynomial plots of each fluid and finding the highest order shear stress intercept. Shows initial amount of stress for each of the fluids.

Appendix B: Nomenclature

Symbol	Meaning	Units
k	Consistency index	Dimensionless
n	Flow behavior index	Dimensionless
ϒ	Shear rate	1/s
µ	Viscosity	Pa.s
τ	Shear stress	Pa

Appendix C: References

Brookfiled Digital Viscometer. Operating instructions. Brookfield Engineering Technologies. Manual No. M03-165-F0612

Doran, P.M. (2013). *Bioprocess Engineering Principles*. Academic Press.

Graham, L.J.W. & Pullum, L. (2004). Turbulent Pipe Flow of Shear-Thinning Fluids. *Biotechnology and Bioengineering*. 118, 33-48.

White, Erica E. Bischoff, Manoj Chellanuthu, Jonathan P. Rothstein (2009). Extensional rheology of a shear-thickening cornstarch and water suspension. Rheologica Acta.

Appendix D: Sample Calculations

Sample Calculations

<u>Shear Rate</u>

rpm = 12 $\quad \dot{\gamma} = \frac{RPM}{60} = 0.2\ ^1/_s$

<u>Viscosity</u>

$\mu_{cp} \cdot 10^{-3} = \mu_{Pa.s} \quad 54.6 \cdot 10^{-3} = 0.0546\ Pa.s$

<u>Shear Stress</u>

$\tau = \mu \dot{\gamma} = (0.0546\ Pa.s)(0.2\ ^1/_s) = 0.01092\ Pa$