Final Report

EFFECT OF TEMPERATURE AND AGITATION SPEED IN MIXING AND HEAT TRANSFER SYSTEMS

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***Summary***

It is very common in industries to use the technique of agitation to mix a fluid. In this work, the effect of agitation speed and the heat transfer coefficient on a system mixing a 0.5% xanthan gum solution was analyzed. For the purpose of this experiment, a Hamilton-kettle agitated vessel was used as the mixing equipment. Ten gallons of the xanthan gum solution was poured into the vessel, and the agitation speed was set using a tachometer, and the power consumption was measured with a power meter. This experiment was composed of five trials at different agitation speeds (19.2 rpm, 33.3 rpm, 44.2 rpm, 56 rpm, and 61.2 rpm). At a pressure of 20 psi, a flow of steam was opened into the system, which increased the temperature of the solution being mixed. The times required for the system to reach 40°C, 50°C, 60°C, 70°C, and 80°C was recorded and afterward the steam valve was closed. The steam was then purged out of the system in order for the solution to cool below 80°C so it could be drained safely. The vessel was filled with room-temperature water and agitated, so the kettle could cool to below 30°C for the next trial. Multiple batches of the 0.5% xanthan gum solution were rotated throughout the trials in this experiment to save time, and while one batch was being used, the other was being cooled in a warm-water bath and occasionally stirred. After the vessel cooled to a temperature below 30°C, the water was drained, and the next experimental trial was run. Using the experimental data collected, it was found that the 0.5% xanthan gum solution was a shear thinning non-Newtonian fluid because the apparent viscosity of the fluid decreased as the agitation speed and temperature increased. As agitation speed and temperature increased, the mixing time of the xanthan gum solution decreased. This information helped calculate the heat transfer coefficient for the different trial situations of the experiment.

**\*Don’t know what else to put in the for the results/analysis**

**\*just need that and the conclusions/recommendations summarized.**

***Introduction***

Processing industries, such as chemical and biological industries, use the technique of agitation to process fluids. Agitation is used to force a fluid in a circular motion to ensure that it is effectively mixed (Geankoplis, 2010). There are multiple equipment variations that can be used for agitation, and the one selected in this study was a Hamilton-kettle agitated vessel. An important part of an agitation vessel is the jacket, which can aid in heating or cooling the product being mixed with the use of steam or a cooling agent. Heating or cooling a fluid while it is agitated is very common in producing a product, making the jacket a valuable resource. In this study a solution of 0.5% xanthan gum, which is a non-Newtonian fluid, was the fluid that was mixed using agitation. How the agitation speed and the heat transfer coefficient of the jacket correlate when mixing the fluid was the focus of this experiment. To successfully analyze the relationship between agitation speed and the heat transfer coefficient, the effects of the power consumption, mixing time, and rheology of the fluid were also considered in this study. It is important to study these factors to ensure that the agitation process is running efficiently, to maximize the production and output of the system.

***Theory/Basic Principles***

Shear stress is external force acting on an object or surface parallel to the slope or plane in which it lies. It is usually measured with force applied to the object divided by unit area. In this experiment, force was applied by the rotating agitator. Shear rate is the rate of change of velocity at which one layer of fluid passes over an adjacent layer. In this case, the inner layer of the xanthan gum solution was rotating with the agitator while the outer layer of the solution near the wall of the fixed kettle was relatively stable. Newtonian fluids have shear stress values proportional to shear rate and are unrealistic in biological and food products. The xanthan gum solution was a non-Newtonian fluid with a shear thinning behavior. The relationship between shear rate and shear stress of the xanthan gum solution follows a power law equation below:

𝝉 = K(𝜸)n [1]

The value of n will be less than one for a shear thinning fluid, equal to one for a Newtonian fluid and more than one for a shear thickening fluid. Because the viscosity of the xanthan gum solution decreases while the shear rate increases, the average apparent viscosity can be calculated using the equation:

μapp = K(𝜸ave)n-1 [2]

A shear rate coefficient is a proportional relationship between shear rate and rotational speed of an impeller or agitator.This experiment uses Ks = 11 in the equation below:

𝜸ave = 11N [3]

For determining the apparent viscosity of a non-Newtonian fluid, the equation relating average shear rate to impeller speed is applied to shear thinning fluids with a shear rate coefficient.

μapp = K(11N)n-1 [4]

For non-Newtonian fluids, such as the xanthan gum solution, viscosity of the fluid varies with shear rate. The impeller Reynold’s number of this experiment can be found by using the diameter of the agitator impeller, density of the fluid and the average apparent viscosity of the fluid.

N’Re,n = Da2N𝛒 / μapp  [5]

Another important factor to be considered is the power number. Because the impeller was run by electricity, had different fluid properties, impeller rotational speed, and geometry, it affected the power number. The relationship between different rotational speeds and power consumptions were measured and analyzed in this experiment. Power number is a dimensionless number relating the resistance force to the inertia force. It can be calculated by dividing power with the product of fluid density, rotational speed and diameter of the impeller.

NP = P / (𝛒N3Da5) [6]

Mixing time is the time for a heterogeneous material to transform into homogenous in the mixing process. It is an important parameter when evaluating the mixing efficiency of the mixing device. In this experiment, the dimensionless mixing factor was determined by the Reynold’s number for non-Newtonian fluids using the chart, the correlation of mixing time for miscible liquids using a turbine in a baffled tank (Geankoplis, 2010). Mixing time can be calculated by the dimensionless mixing factor, rotational speed, diameter of the impeller, diameter of the vessel, standard gravity, and height of the solution contained in the vessel.

Ft = tT \*(NDa)2/3g1/6Da1/2/(H1/2 Dt3/2) [7]

In the experiment, the kettle heated the xanthan gum solution by releasing steam into the vessel. Temperature of the steam can be found from the steam table with known pressure values. The convective heat transfer from steam to the xanthan gum solution by temperature differences was equal to the heat generated in the solution. The convective heat transfer can be calculated by the overall heat transfer and area of the vessel. The heat generated of the xanthan gum solution was figured by the mass, heat capacity and temperature change. To simplify the calculation, the vessel area was assumed to be a perfect half sphere. The relationship between ln[(Ts-To)/(Ts-Tf)] and time can be found by equating and integrating Equation 8 and Equation 9. After plotting ln[(Ts-To)/(Ts-Tf)] and time, the overall heat transfer is  
obtained from the slope.

Qin = UA(Tsteam- Tf) [8]

Qgen = mCP ∂T/∂t [9]

m = V𝛒 [10]

Heat transfer in this experiment was separated into the convection of steam, conduction of wall and the convection of the xanthan gum solution as Equation 11 showing below. Since the stainless-steel agitator was thin and had high heat transfer efficiency, the thickness of the agitator wall was assumed to be zero. The area of steam and the xanthan gum solution was assumed to be equal. Therefore, the heat transfer coefficient of the xanthan gum solution could be calculated.

1/ (UA) = R1+R2+R3= 1/(h0A0) + Δx / (KAw) + 1 / (hiAi) [11]

In the equations listed below, c and d are assumed to be ⅓ and 0.21. After plotting the data of heat transfer coefficient and rotational speed, a power law relationship between heat transfer coefficient and rotational speed was found. The value of coefficients a and b could be calculated from the power law equation.

Nu = a \* Reb\* Prc \* Vid [12]

Nu = h\*D / k [13]

Re = D2N𝛒 / μ [14]

Pr = Cpμ / k [15]

Vi = μ / μ0  [16]

***Experimental***

A ten gallon pre-made 0.5% xanthan gum solution was first poured into a Hamilton-kettle agitated vessel. A tachometer was used to measure the agitation speed and set the agitator as close as possible to the desired value (19.2 rpm, 33.3 rpm, 44.2 rpm, 56 rpm, and 61.2 rpm) and the actual value was recorded. The system steam valve was then opened such that steam flowed into the system at a pressure of 20 psi. The power consumption of the agitated vessel was measured with a power meter and the value recorded. As the steam increased the temperature of the solution, the vessel’s built-in thermometer was monitored. Once the temperature of the xanthan gum solution reached 30°C, a timer was started and the time it took for the system to reach 40°C, 50°C, 60°C, 70°C, and 80°C was recorded. At 80°C, the steam valve was closed and the built-up steam was purged from the system. The xanthan gum solution was continually stirred to cool it down below 80°C so that it could be drained from the kettle into a holding bucket. The kettle was then filled halfway with room-temperature water which was also continually stirred to cool the vessel down below 30°C. Meanwhile, the hot xanthan gum solution was cooled in a water bath and manually stirred with a whisk to also cool it down below 30°C so that it could be used in a future trial. Once the vessel was cooled, the water was released and allowed to flow down the floor drain. For trials 2 and 3, a fresh batch of xanthan gum solution was used and in the following trials, half of a fresh batch was mixed with half of a batch used in an earlier trial in order to more quickly cool the old batches for use.

***Presentation and Discussion of Results***

From the given rheological data set, the shear stress was plotted against the shear rate to find the rheological coefficients at each temperature, 25°C, 30°C, 40°C, 50°C, 60°C, 70°C, and 80°C (see Appendix A, Figures 1 - 7). The flow consistency index is determined by the constant that the shear rate is multiplied by in the power regression equation and the power law index is determined by the exponent of the shear rate. The arcing, concave down shapes of the data trends show that the 0.5% xanthan gum solution is a non-Newtonian, shear-thinning fluid.

With the rheological constants found, the average apparent viscosity at each temperature was calculated using Equation 2 (Geankoplis, 2010).

By graphing apparent viscosity vs. temperature at each agitation speed, it is obvious that the apparent viscosity of the xanthan gum solution decreases as temperature and agitation speed increase, which is consistent with the finding that the solution is a shear-thinning fluid (see Appendix A, Figure 8).

Using the apparent viscosity found at 30°C, the impeller Reynolds number was calculated with Equation 5 at each agitation speed (See Appendix A, Table 1) (Geankoplis, 2010). The average power consumption was then used to calculate the power number with Equation 6 (Geankoplis, 2010). The power number was plotted against the Reynolds number (Appendix A, Figure 9). Comparing the experimental curve with those from literature, it appears most similar to that of a propeller-type agitator (Rushton et. al., 1950). The actual agitator type is an anchor paddle; when comparing the experimental curve with an anchor paddle curve from literature, the curve shapes do appear similar, so it is reasonable to say that the experimental data makes sense (Furukawa et. al, 2012).

Approximate mixing factors were obtained from a graph of mixing factor against Reynolds number from literature at 30°C and 80°C for each agitation speed (Geankoplis, 2010). These values were used to calculate mixing time from Equation 7. By graphing the mixing time against the agitation speed for both temperatures, it can be seen that as agitation speed and temperature increase, the mixing time decreases (Appendix A, Figure 10).

Using Equations 8 and 9, the relationship between temperature, time and the overall heat transfer coefficient was derived and the experimental temperature and time data was plotted for each agitation speed. The slope of Figures 11-X (Appendix A) was used to determine the overall heat transfer coefficient in each situation using Equation 17. Assuming that the areas of the steam film and xanthan film was equal, the thickness of the agitated vessel is negligible, and the heat transfer coefficient of the steam is 1000 W/m2°C, the heat transfer coefficient of the xanthan solution was calculated for each agitation speed with Equation 11 (Overall Heat Transfer Coefficient, n.d.).

U = dln[(Ts-To)/(Ts-Tf)]/dt \* 𝛒VCp/A [17]

A dimensionless analysis was then performed with the Nusselt number, the Reynolds number, the Prandtl number, and the viscosity index. The Nusselt number was plotted against the product of the other three dimensionless numbers to obtain the a and b coefficients for Equation 12; a was determined to be 0.370 and b was determined to be 8.826 (Figure X, Appendix A). The value of a came from the slope of Figure X (Appendix A) and the value of b was calculated by dividing the intercept of Figure X by the Prandtl number raised to 0.33 and the viscosity index, which was interpolated at 75°C, raised to 0.21. Values from literature indicate that coefficient a is typically around 0.36 for heating inside a vessel with an anchor-type impeller and coefficient b is typically 0.67 for heating inside the vessel (Pietranski, 2012). One possible reason for this error is the use of fresh batches of solution between different agitation speed trials, leading to different volumes and xanthan gum concentrations and thus different heat transfer responses.

***Conclusions and Recommendations***

Blah blah blah

***Nomenclature***

Symbol Meaning Units

A area [m2]

Cp specific heat capacity [J/K]

Da impeller diameter [m]

Dt vessel diameter [m]

Ft dimensionless mixing factor dimensionless

g specific gravity [kg/m3]

H height of the solution [m]

h heat transfer coefficient [W/m2K]

K consistency index [Pa.sn]

Ks shear rate coefficient dimensionless

m mass [kg]

n flow behavior index dimensionless

N rotational speed [rps]

Np power number dimensionless

N’Re,n Reynold’s number dimensionless

P power [W]

Pr Prandtl number dimensionless

Qgen heat generated [J]

Qin convective heat transfer [J]

Ri radius [m]

T0 initial temperature [K]

Tf final temperature [K]

Tsteam steam temperature [K]

tT mixing time [s]

U overall heat transfer [W/K·m2]

V volume [m3]

ΔT temperature change dimensionless

Δx thickness of agitator wall [m]

𝜸 shear rate [s-1]

𝜸ave average shear rate [s-1]

μapp average apparent viscosity [kg/m·s]

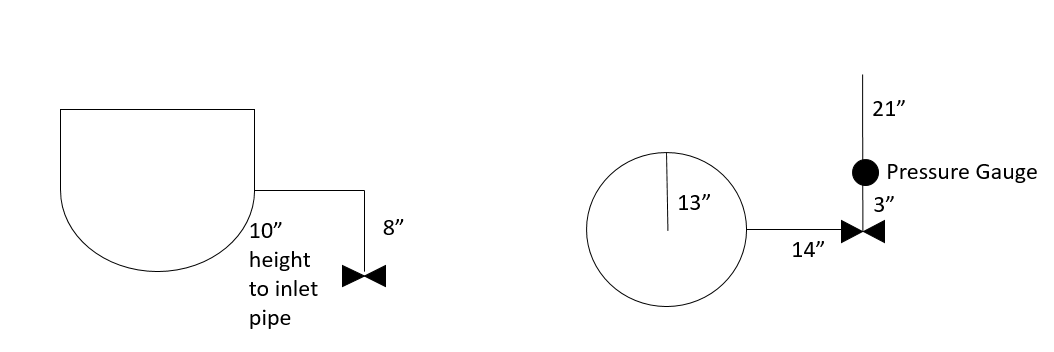
𝛒 density [mg/mL]

𝝉 shear stress [Pa]

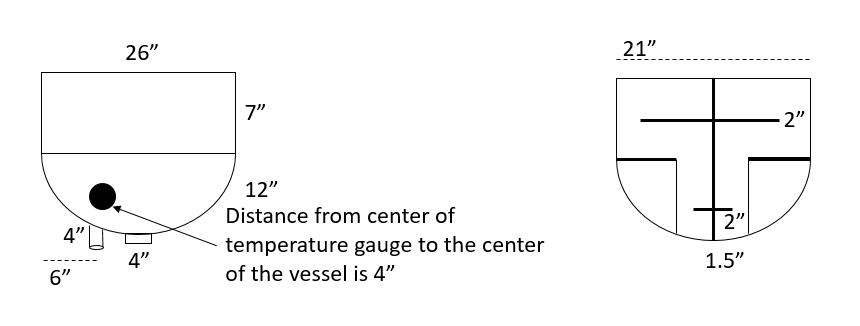
***Appendices***

**Appendix A: Figures and Tables**

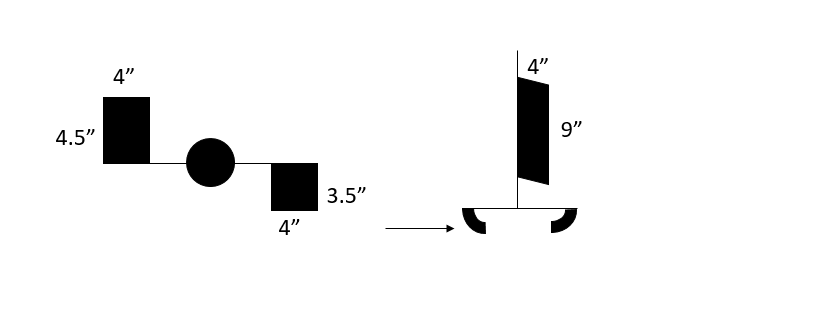
**A**



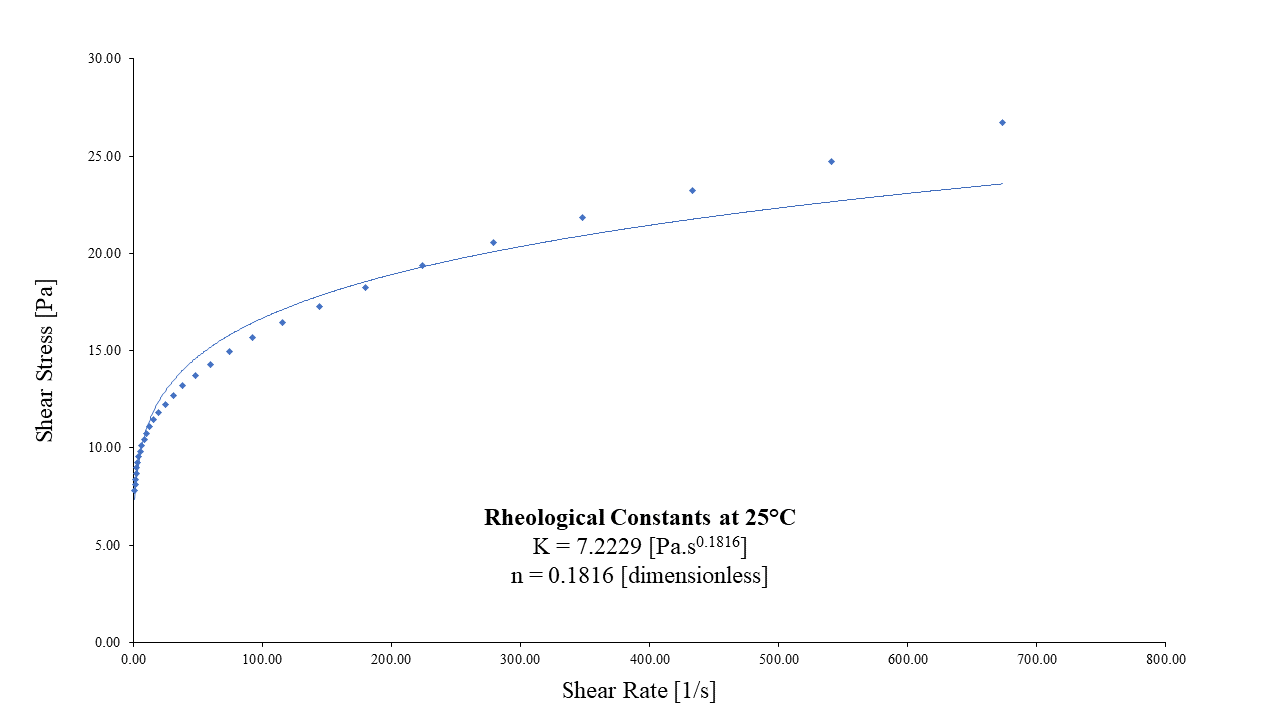
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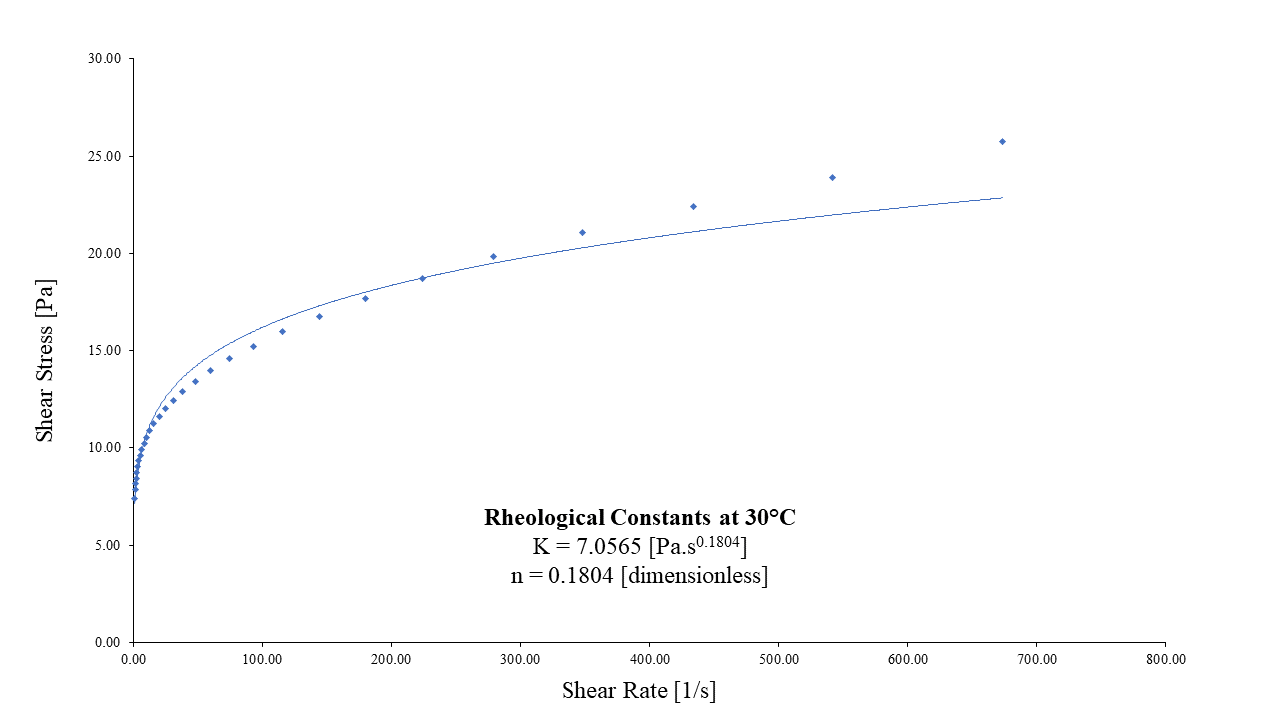


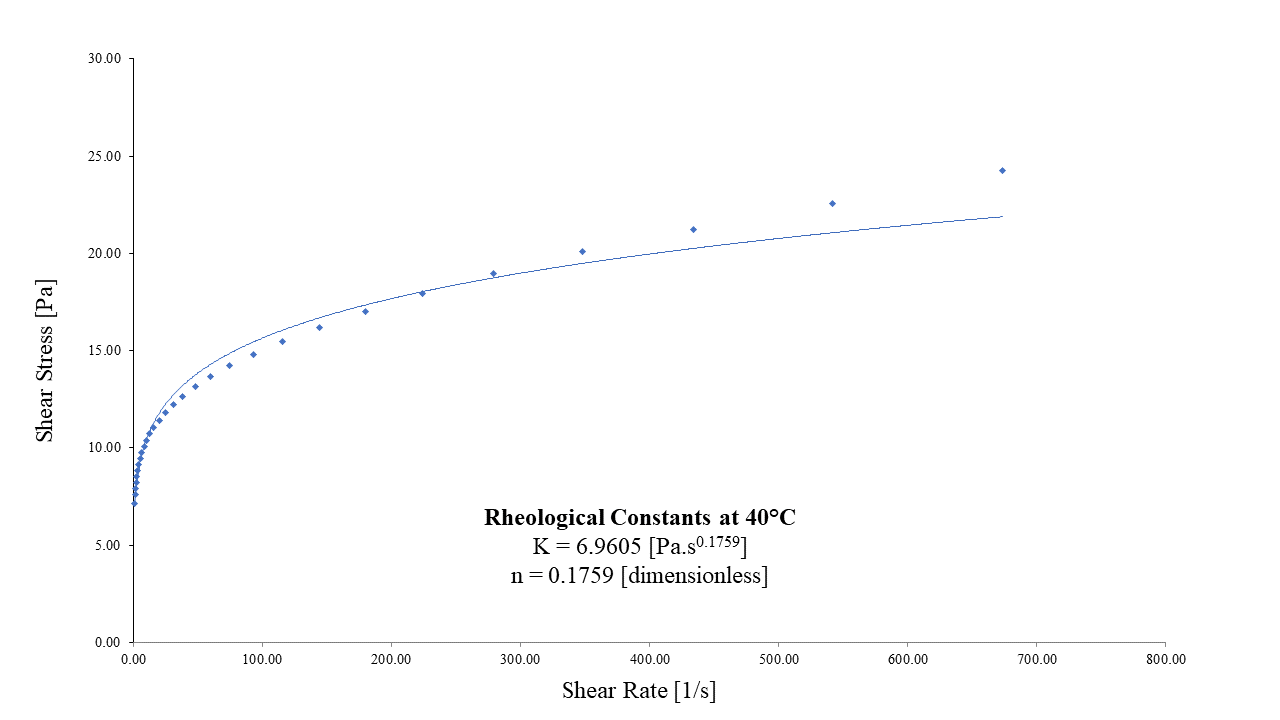
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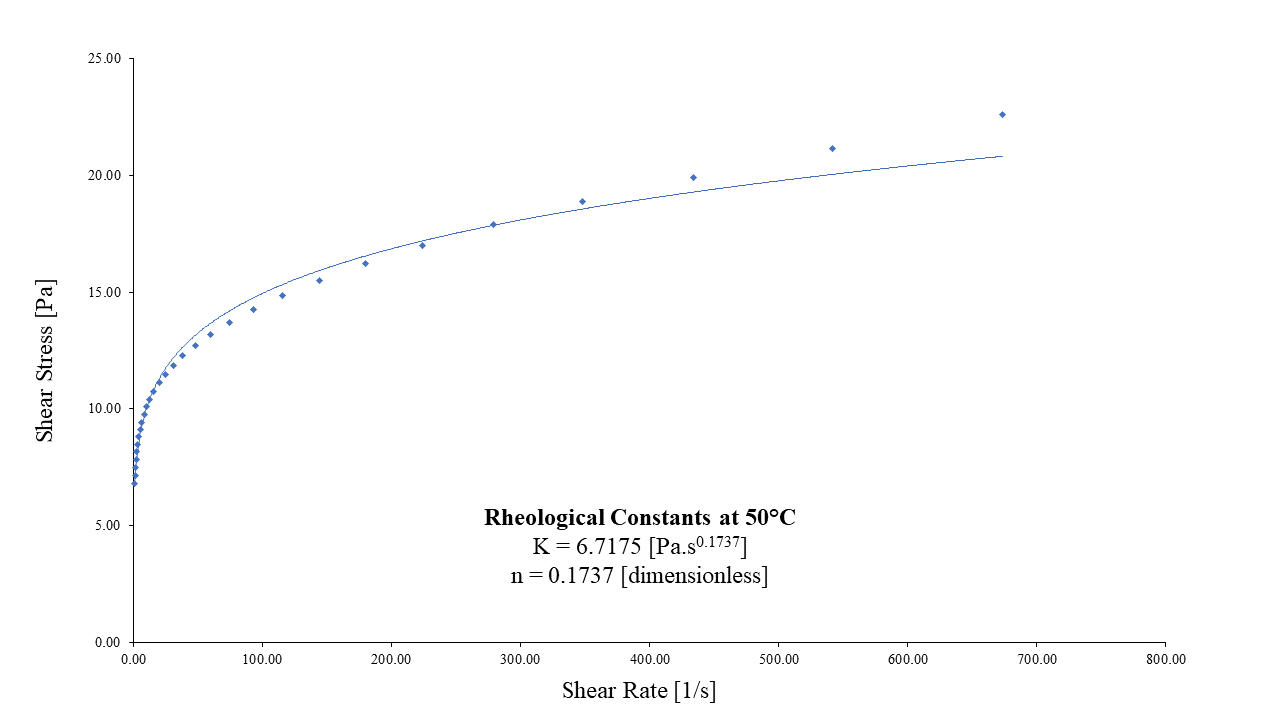


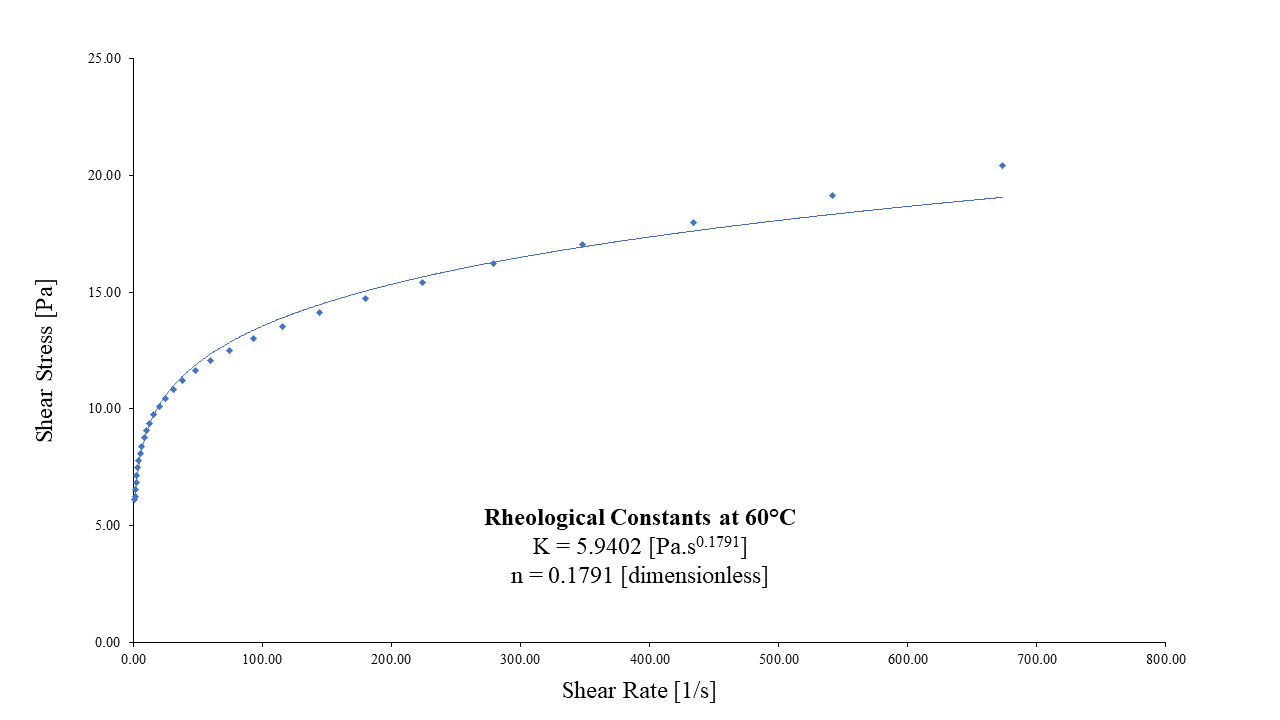
**Figure 1:** Schematic of Hamilton-Kettle agitated vessel. Figure 1A shows the schematic of the entire system, including the steam inlet, Figure 1B shows the inner geometry of the vessel, and Figure 1C shows the shape of the anchor paddle impeller.

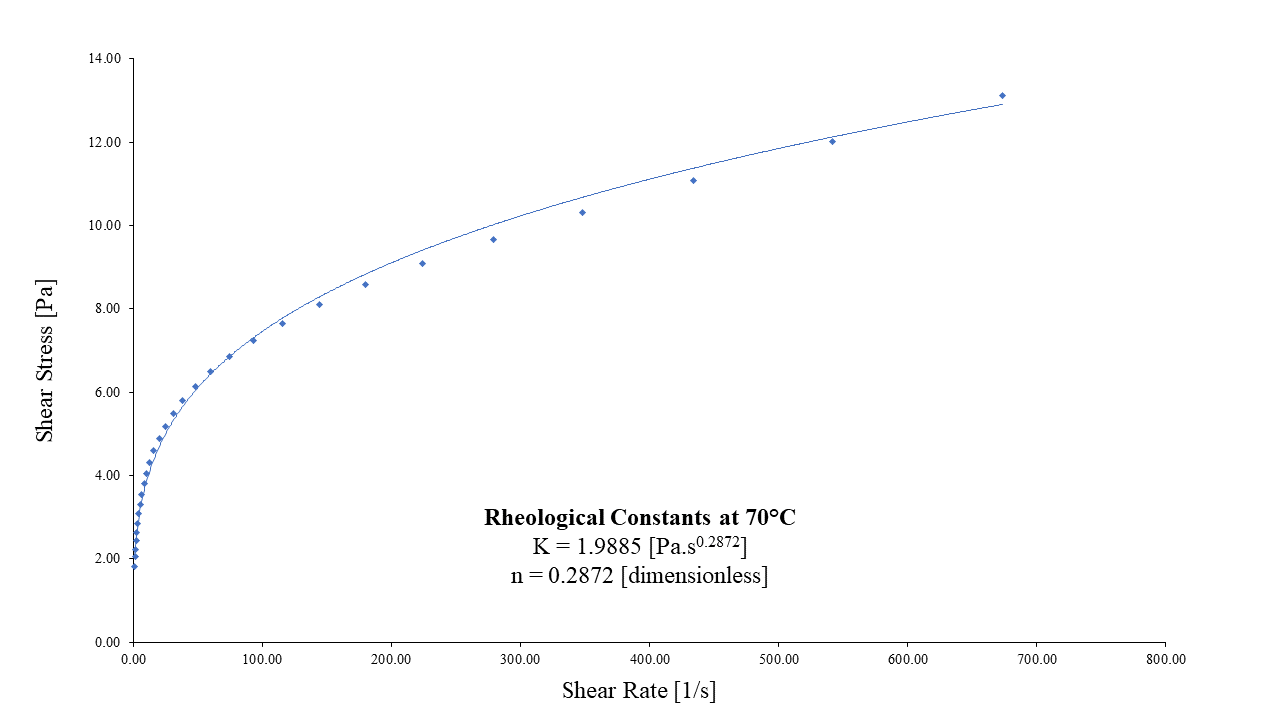


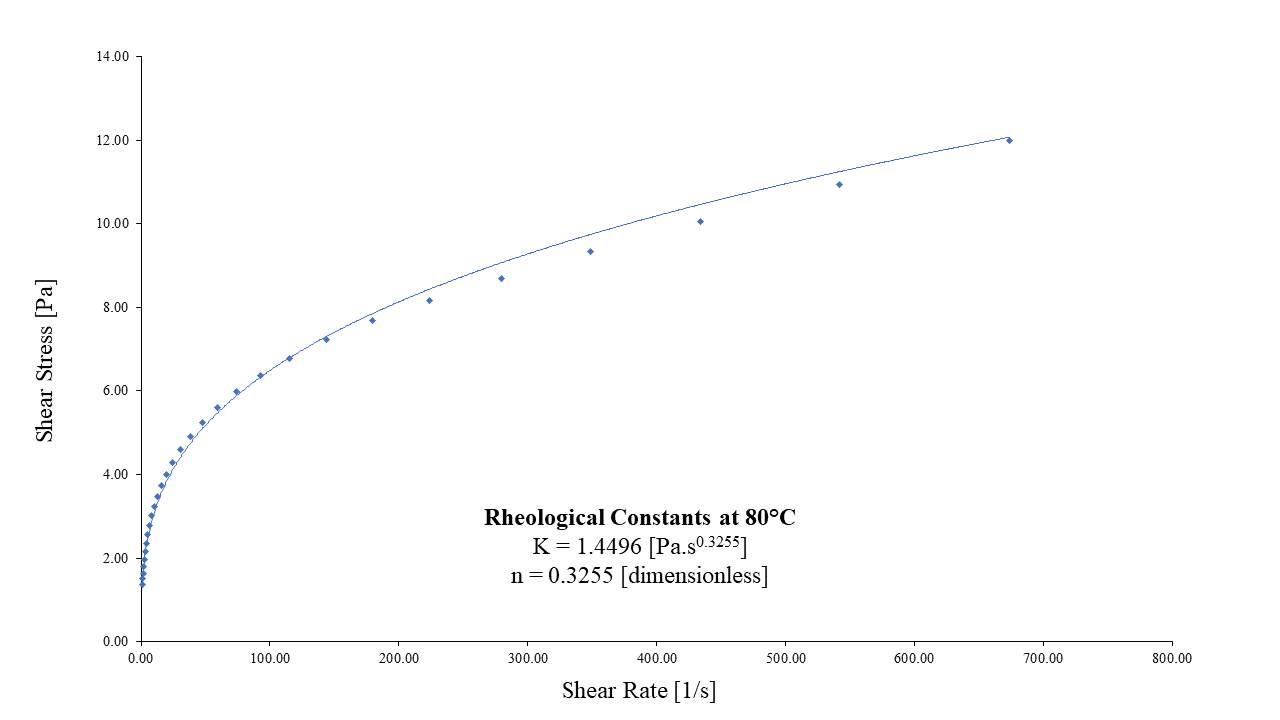
**Figure 2:** Plot of rheological data at 25°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.

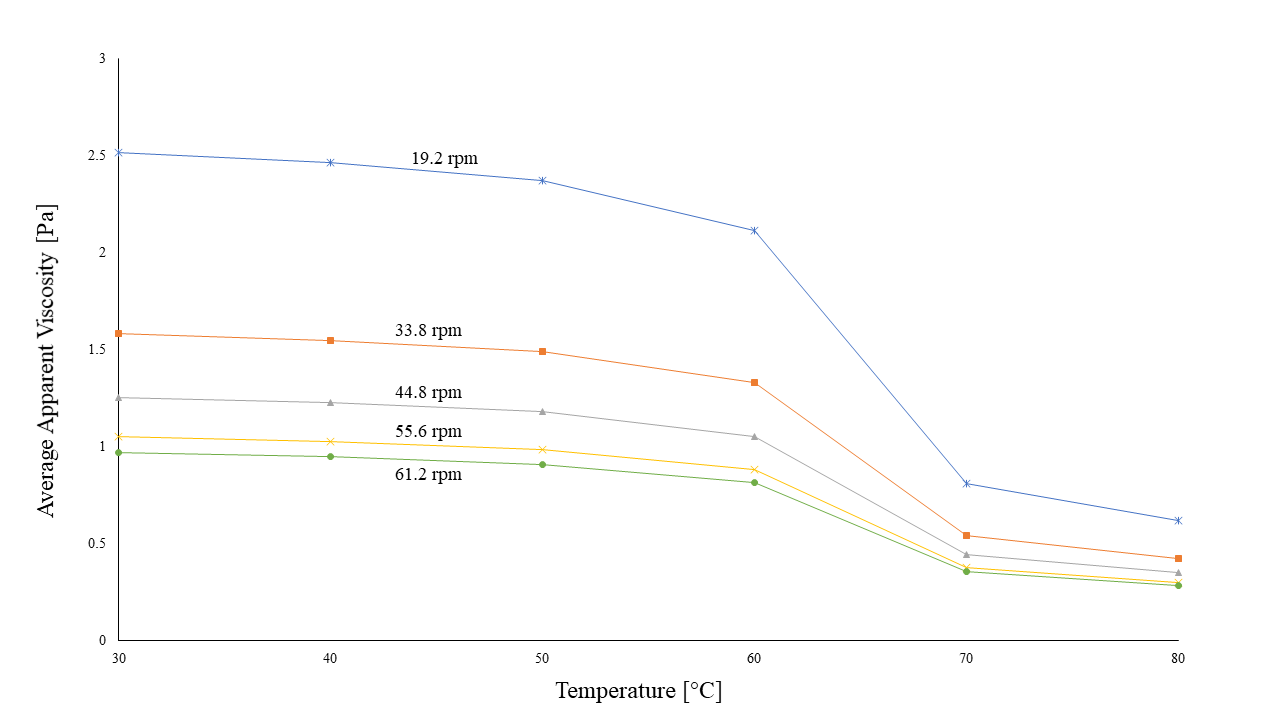
**Figure 3:** Plot of rheological data at 30°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.

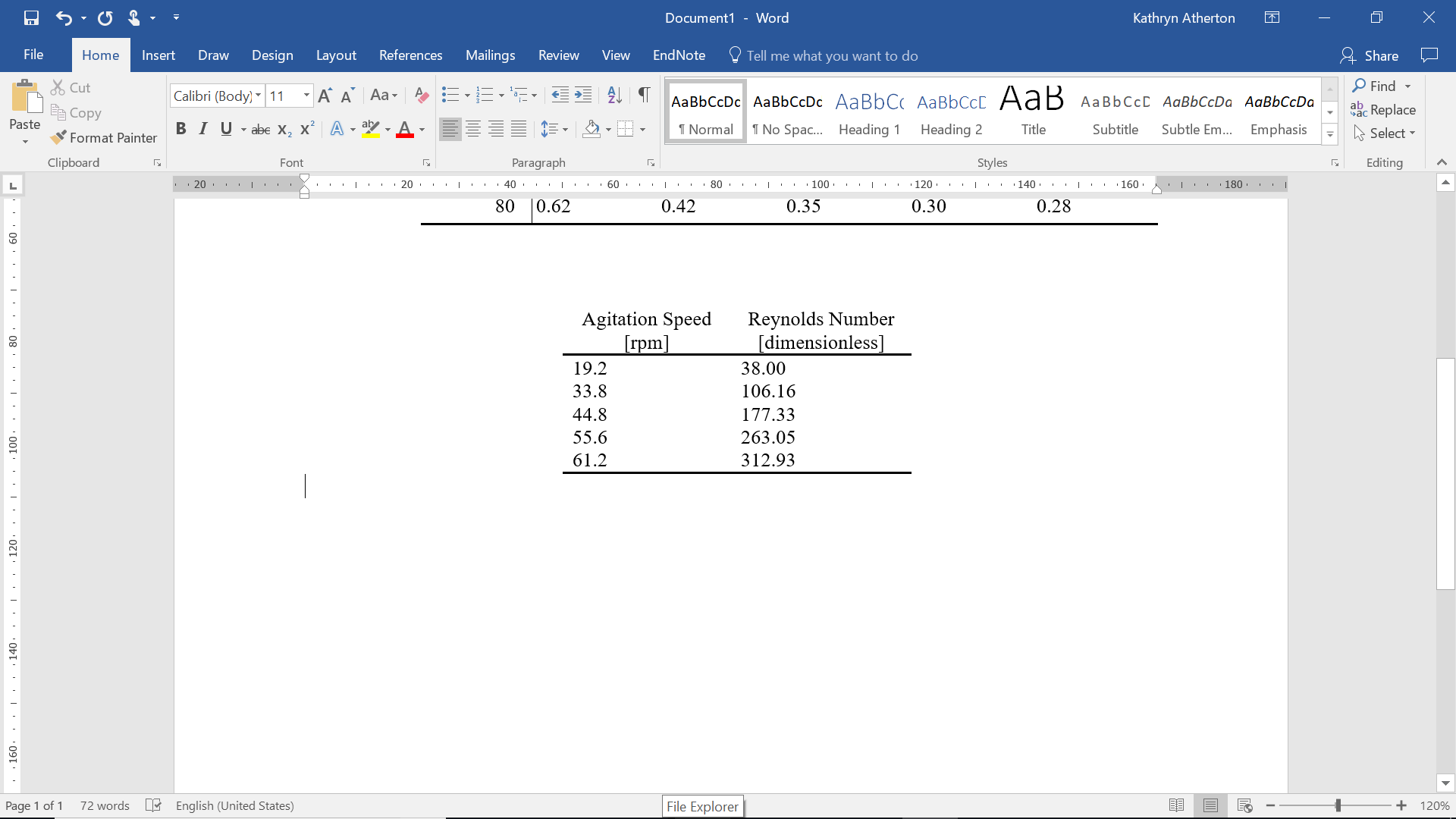
**Figure 4:** Plot of rheological data at 40°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.

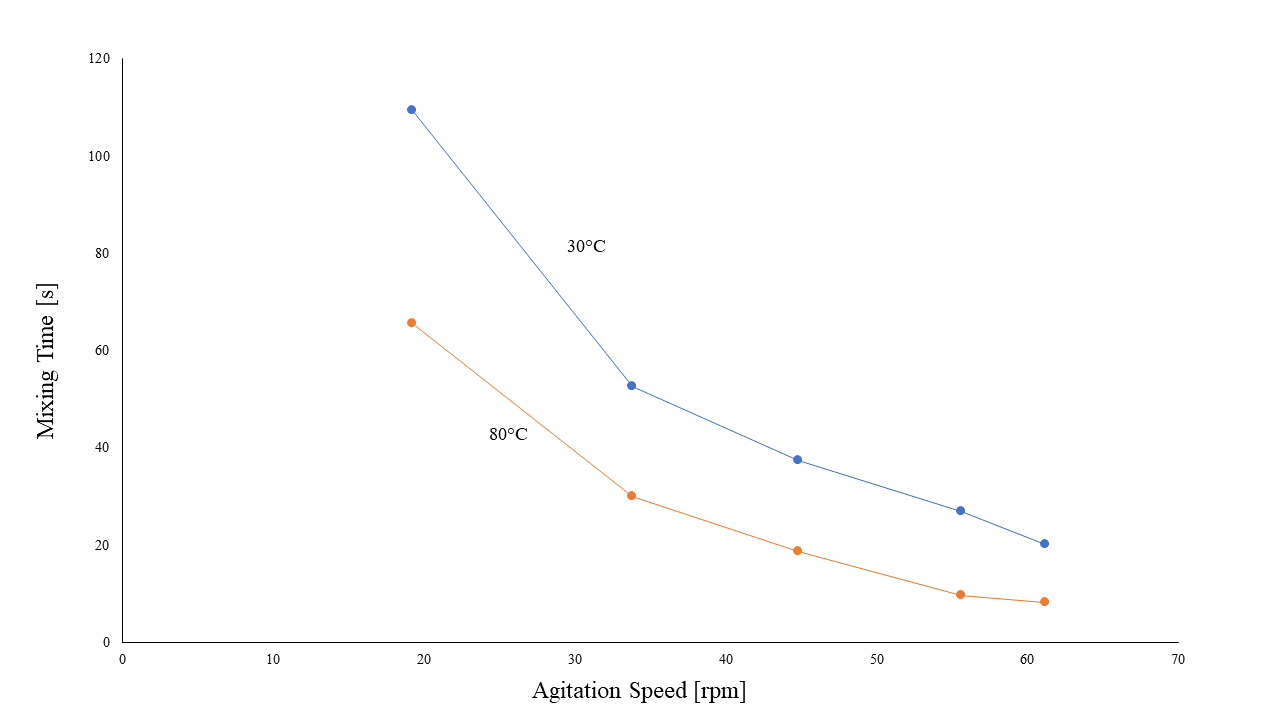
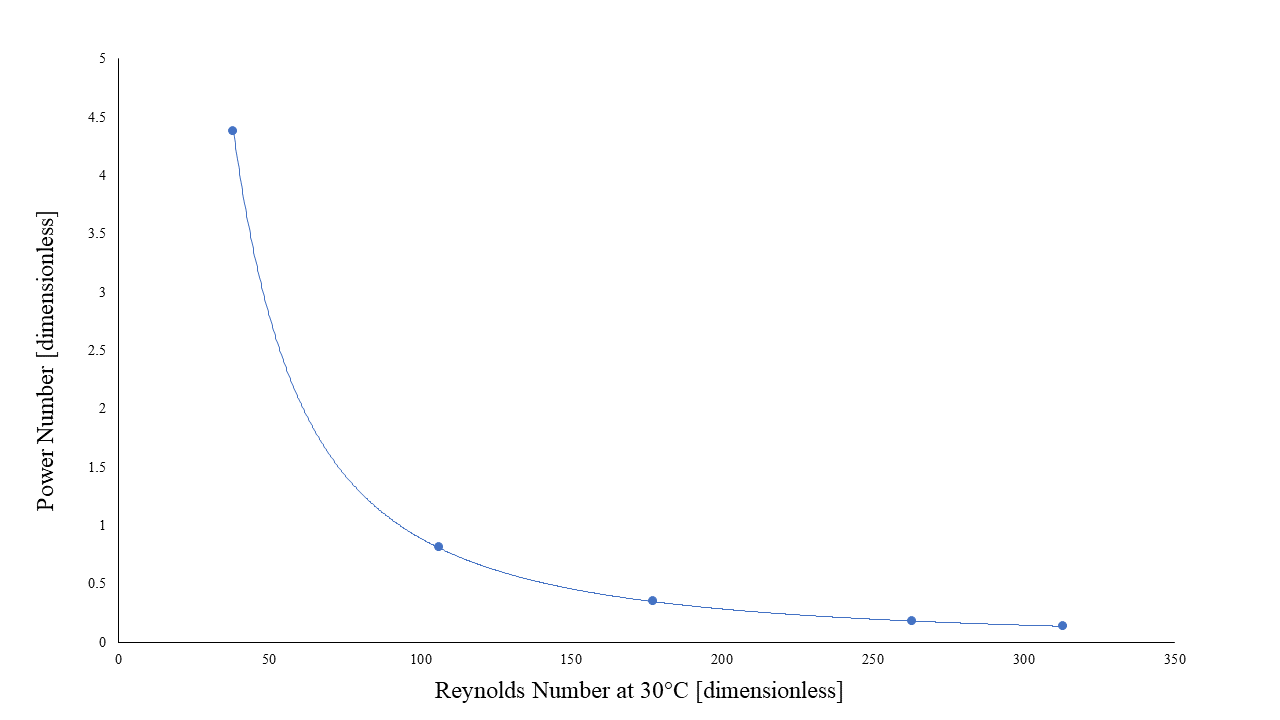
**Figure 5:** Plot of rheological data at 50°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.

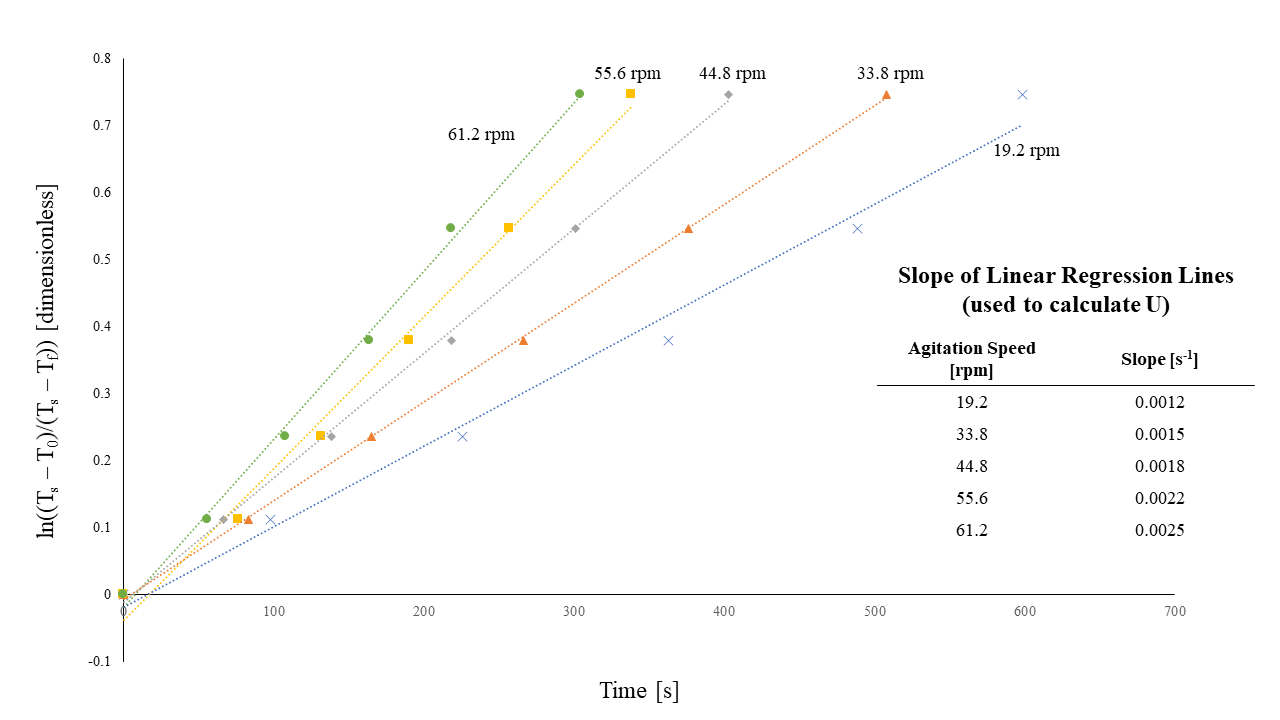
**Figure 6:** Plot of rheological data at 60°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.

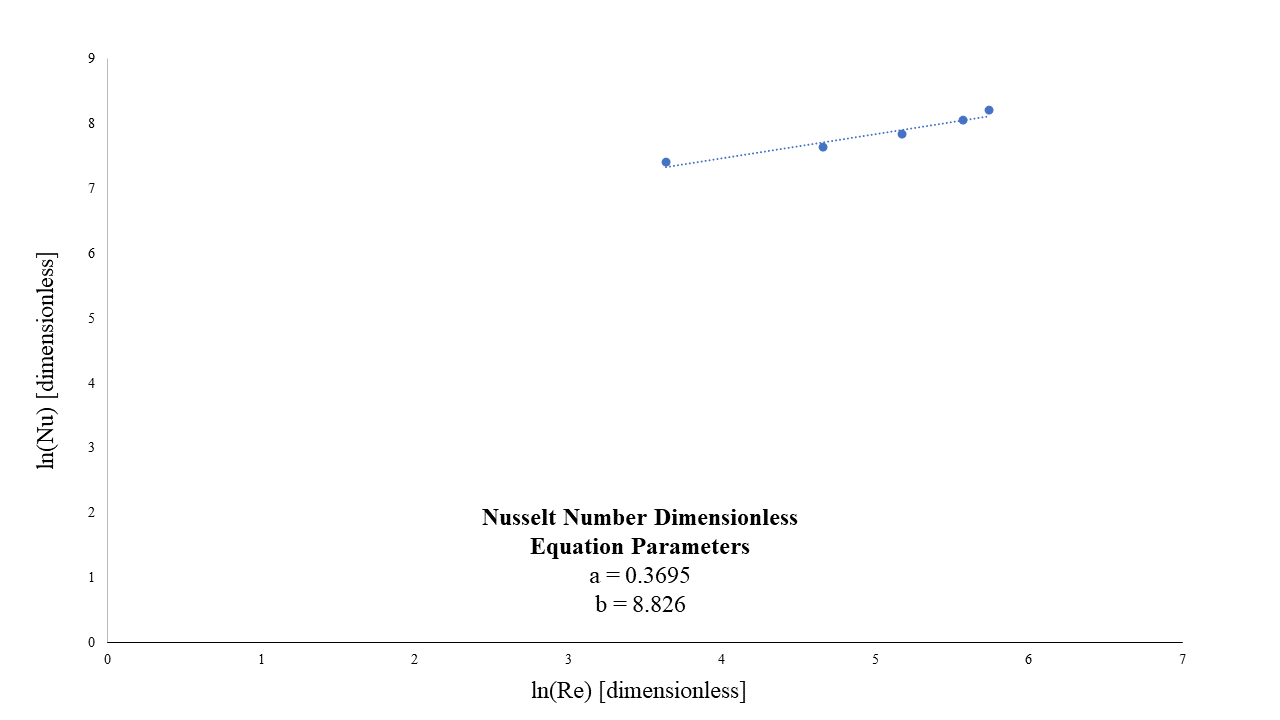
**Figure 7:** Plot of rheological data at 70°C. The shear stress was graphed against the shear rate. From the power regression line, the constants K and n were found.











**Appendix B: References**

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