Studying the Viscosity of Various Engine Oils using a Rotational Viscometer

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Introduction

The study of viscosity of various fluids is critical to mechanical engineering as the methods used are not only numerous, but often mathematically complex. However, my summer research project was not only to find a mathematical model of viscosity, but to establish a rotational viscometer that could measure the viscosity of any fluid.

In this case, I wanted to study the viscosity of engine oils at various temperatures, as they would behave similarly in an engine block under high performance conditions. My research project is based on a previous rotational viscometer project performed by Davis Ferguson, which sought to build a viscometer and test fluids in a similar manner. However, his project was incomplete and had a few inaccuracies, therefore I decided to establish a rotational viscometer backed by a sound and simplistic mathematical formula that could be used by future students in their own lab work, whether they choose to study oil or not. This experiment saw me measure liquids such as glycerin, olive oil and shampoo as test liquids, to set up my viscometer, and testing 10W-40 and 15W-40 oil, both of which are used in many cars on the road today. Finally,my equation was utilized to easily establish our final viscosity values. This experiment should be easily replicated often, and at a great degree of accuracy. My expected values for 10W-40 and 15W-40 were 2.87P and 2.08P respectively.

Introduction and Mathematical Basis

To successfully undertake my experimental and research process, a strong mathematical and theoretical basis is needed to successfully model my viscometer and the rotational forces submerged in my liquid tests, such as the shear force of the spindle and current and rotational velocity of the DC worm gear motor involved. The development and reapplication of various mechanical and electrical features allowed for my final conclusions and this hardware modification successfully allowed for reasonable measurements. This process took the longest in my research, and these next few equations will demonstrate my mechanical and electronic theory that allowed for my measurements and experimental design. Each equation will be ordered in chronological order, and the variables will be defined as needed below.

Eq. 1: $P = ie$

This equation states that electrical power is a combination of two variables, i, which is current, and e, which is voltage of our motor. In this initial design, our current was a variable, and voltage was 12V. This allowed us to manipulate current to find certain future values, but we needed a basic equation to solve for motor specifications like power.

Eq. 2: $V = IR$

This equation is quite familiar to physicists as Ohm's Law, or a measurement of resistance in the closed circuit. This was used in conjunction with our power equation to find R resistance. I is current and V is voltage here. The resistance of the motor used in our design was 10.6 Ohms. If we know voltage and current, then we can solve for resistance and power, seen in Eq. 1.

Eq. 3:

$$\omega = \frac{4T}{4\pi\eta(l+k)}\left[\frac{1}{Da^{\ 2}} - \frac{1}{Db^{\ 2}}\right]$$

Equation 3 is our first model of viscosity using some spindle specifications and found data from the PASCO/Capstone Software and research material. T is torque of the motor here, which relates to power P seen above, η is our unknown viscosity value, while pi is itself. l is the thickness of the spindle which was 4.65mm, and k is the torque adjustment constant, which changes based on the liquid tested. Values of k were ignored in this model and in Equation 4 seen below. This value will be utilized later as we felt both Eq. 3 and 4 were both too complex to be done repeatedly and successfully every single trial. Da and Db is the diameter of the container and the spindle respectively. The 4's in the equation are due to the measurement of the diameter instead of a given radius, so we have to compensate for that. In this case, I found it easier to measure the diameter of the cup and compensate, then get a radius that may not be extremely precise. All measurements were done with electronic calipers and a ruler in cm.

Eq. 4:

$$\eta = \frac{\eta\omega R^2}{Th}$$

Equation 4 is a simplification of Equation 3, as the similar variables are still present, but in a more concise manner that allows for viscosity on one side, and our constants and variables on the other, making for a simple algebraic process in solving it. η is our viscosity value in poise, ω is rotational velocity of the spindle measured in rad/s, R is the diameter of the spindle in mm, T is the torque of the spindle, also called $k(l)$ which is the adjustment constant multiplied by the thickness of the spindle l. h is the clearance of the spindle between the top of the liquid and the bottom of the container. For these trials, I placed the spindle in the halfway mark of the 100mL of fluid so that h would be constant. It was 2.5mm for all tests.

Eq. 5: $$T = k(l)$$

This equation is our measurement of torque. The value k is dependent on the liquid test and the calibration values. These are found by measuring repeated current divided by velocity and voltage divided by velocity. This linear trend will give us a y-intercept of k. l is the constant amount of the liquid between the top and bottom of the beaker, which was 2.5mm. This torque value is critical to finding viscosity, and our final interaction of the equations and my experiment results are found in Equation 6 below.

Eq. 6: $$T(slope) = \frac{\eta h k}{\pi R^2}$$

This equation is just a re-application of Equation 5, but with one important change. The value T torque can be labeled as the slope of a line, as seen in a graph of current vs velocity. This nice trend allows for torque to be known in Excel, without having to deal with rather difficult mathematical associations between power and electronic variables like current, voltage and resistance in which can be difficult to measure the same values repeatedly in multiple trials, thus impacting my precision and validity of the final experimental design. This equation is simply used as a proof of concept that viscosity can be used to find other relevant variables in the experiment. This equation in conjunction with Equation 5 allows for simple data analysis as seen below in my graphs and data section in which I tested glycerin, mineral oil, and olive oil as calibration and test liquids, before moving onto 10W-40 and 15W-40 to get final viscosity values.

Methods

To successfully develop a rotational viscometer that would operate in the manner that which we planned, an accurate and replicable data collection system was needed. To study the rotational velocity, torque and motor parameters, a PASCO sensor was used to measure the velocity of the spindle in rad/s. The electric current was also analyzed using a PASCO sensor suite that contained a current sensor, voltage sensor and a power supply to easily manipulate the speed of the spindle in various liquids. The power supply was chosen due to the knobs on the device, which are easily rotated to change current (and velocity) for multiple tests that are easily repeatable. This measurement and analysis setup was rather effective in producing results with little preparation or reset time between trials, allowing for an in-depth analysis of all liquids. Images of the hardware setup are labeled below.

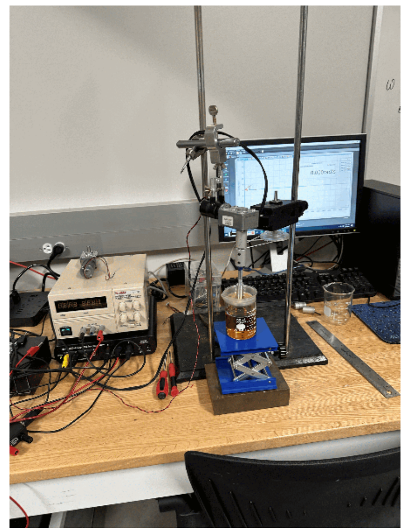


Image 1: This image is the initial setup of my viscometer. Note the lab jack in blue to raise and lower my test beaker. The power supply is in tan, and the knobs on the right of the device are used to change the current of the motor. The black velocity sensor is connected to the adjacent support bar to the spindle, and the rubber band allows for the actual measurement of the rotational velocity. The motor was connected to alligator teeth couplings to the power supply, and the sensors were connected to the desktop seen on the right. However, the velocity and current reading were variable and not quite as accurate as anticipated, so a new iteration was developed to gather data more accurately.

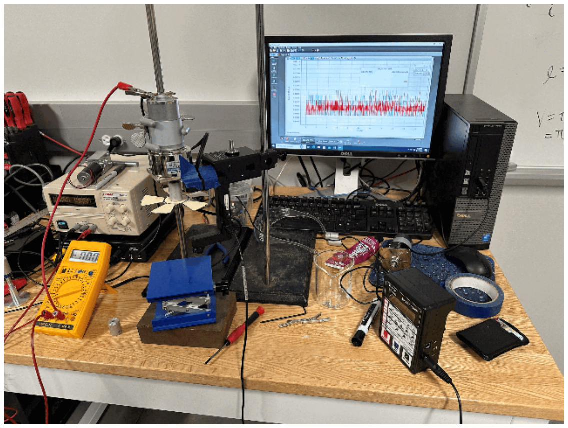


Image 2: This image is the second generation (and most accurate) iteration of my data collection hardware. The rotational velocity sensor was eventually replaced due to inaccuracies in the data, an attached time gate with a detector wheel was attached onto the spindle itself, allowing for exact and true to trial readings of velocity and more realistic calculations. The yellow current ammeter/voltmeter also replaced the PASCO one, as PASCO data on the desktop still struggled from inaccurate and variable readings during repeated trials. The sensor, wired directly into the motor, skips the computer's Capstone software entirely, while still relying on the power supply to change the rotational speed as needed during trials. The spindle in this photo was removed for cleaning after measuring a liquid. Note the black time gate measurement box on the right to record the rotations of the spindle. This data collection system was used in my final calculations, as the time gate contained less error than the PASCO system, which had various fluctuations in data collection.

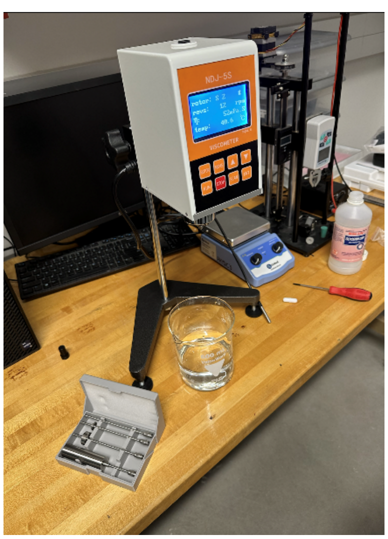


Image 3: This picture left, while not the final spindle design, demonstrates an important mathematical fact in my data analysis. The space between the upper bound of the oil in the beaker and the bottom of the beaker both relate heavily to the type of flow the oil undergoes. Laminar flow is ideal for all of my measurements and the clearance on the sides of the beaker should be kept to a minimum. This evaluation utilized basic fluid flow principles and Equation 4, as the final model used in calculating viscosity. The spindle was placed halfway in the oil to allow for equal liquid pressure on the spindle itself, stabilizing the rotational forces involved and eventually developing laminar flow. The rotational forces involved need to be kept to a constant level in order for accurate rotational viscometer readings to take place, therefore the spindle placement seen right in Image 4 is critical for effective research practices.

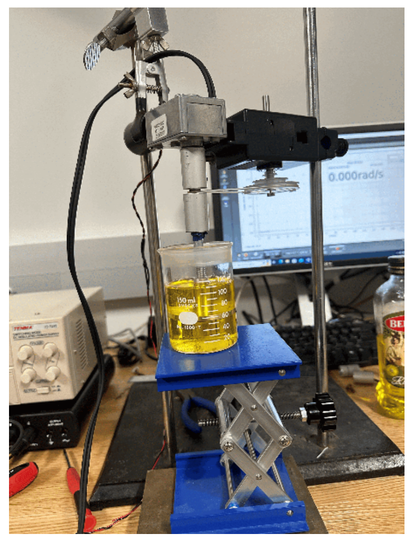


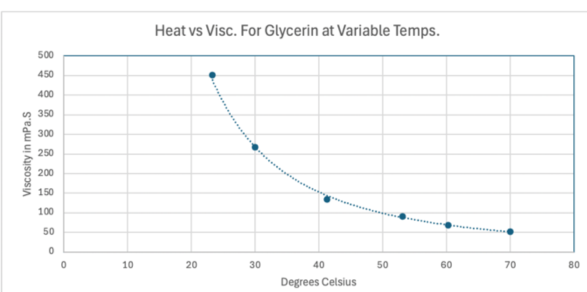
Image 4: Lastly, this photo demonstrates the basis of my entire hardware setup, and the methods I tried to replicate. This viscometer is property of Hampden Sydney and is considered the industry standard in rotation viscosity measurement. This allows for easy data collection using the control panel and a varied amount of machined spindles given. The viscometer shown was used to get my baseline readings for my test fluids and examine firsthand the sort of device I was trying to design and use. The readings and data collected for all the previous entries are listed below in the data collection section, featuring graphs and tables of my test results from my final hardware design seen in Image 2, while using the motor and spindle in Image 3. My data collection and calculations are backed by the machine seen in Image 4, to a very useful degree of accuracy seen above.

Data

My data and graphical analysis of my research was paramount in getting sound results. As my math process seen in the Mathematical Basis section built on each subsequent development in the experiment, so did my data analysis. The measurement of my variables and known values found in my oil measurements allowed for a rather easy final evaluation of my tests, which further reduced percent error.

Glycerin Visc. Measurements in deg. C		
300mL of Glycerin		
20-60 C		
Temp in deg. C	Visc. Trials in mPa.S	Rotor used: 2
23.3	451	Scan: Yes
30	267	
41.3	134	
53.1	91	
60.3	69	
70	52	

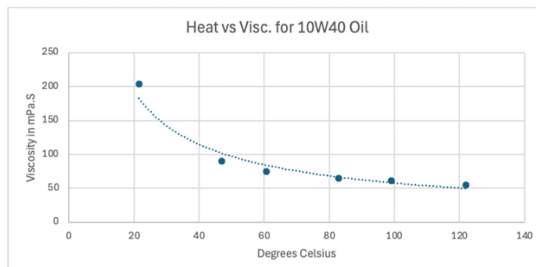
Table 1: This table was simply a proof of concept, to get my supposed solution values using the viscometer seen in Image 4. I tested 300mL of Glycerin at various temperatures that would affect my readings. The downward trend seen in Graph 1 is the result of my work seen in the table, with the rotor and findings listed. This pattern is seen in Tables and Graphs 1-3, and is the hallmark of an effective viscometer, as heat and viscosity are inversely related. This is how I got my solution values for my tests liquids so to compare them at the end of my own tests.



Graph 1: This graph shows the trend seen in the table above. Note the trendline seen here demonstrating the relationship between heat and viscosity. These data points were critical in creating a solid experimental base for my future tests.

10W-40 300mL	
Temp in deg. C	Visc. Trials in mPa.S
21.5 C	204 mPa.S
47 C	90 mPa.S
60.6 C	75 mPa.S
82.9 C	65 mPa.S
99 C	61 mPa.S
122 C	55 mPa.S

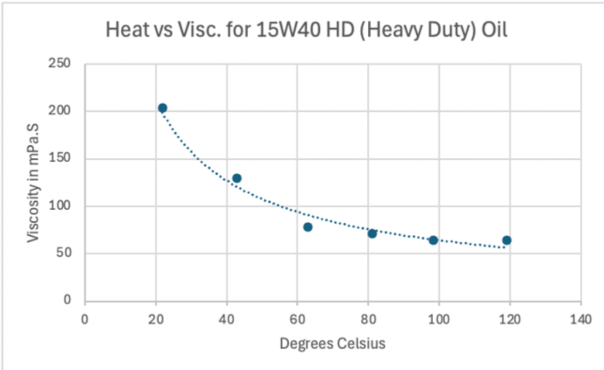
Table 2: This table is the same procedure used for 10W-40 motor oil, one of my future test liquids that will directly affect my results. I found a similar solution to Graph and Table 1 for 10W-40.



Graph 2: Graph 2 is very similar to Graph 1, and still keeps my ideal graphical shape that correlates with my research background

15W-40 (HD) 300mL	
Temp in deg. C	Visc. Trials in mPa.S
21.9 C	204 mPa.S
43 C	130 mPa.S
62.9 C	78 mPa.S
81.2 C	71 mPa.S
98.3 C	64 mPa.S
119 C	64 mPa.S

Table 3: This table is for 15W-40 Heavy Duty (HD) oil, as I strove to maintain my base values in correlation with the trends found in my background research. This was successful here as well, allowing me to plot it in Graph 3, and move on to my next tests in conjunction with my hardware development seen above in Images 1-4. Interestingly, the oil worked well at higher temperatures, as the viscosity stagnated, a sign of correct usage of my materials and liquids involved.



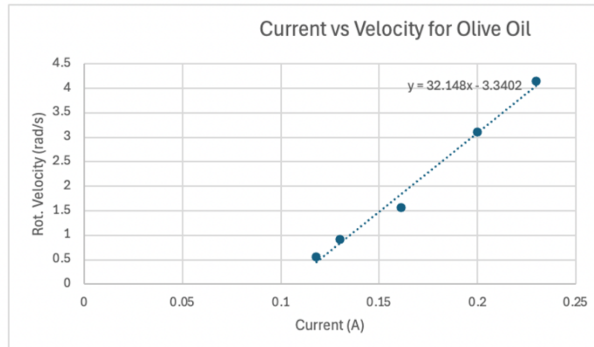
Graph 3: is the trend between heat and viscosity for 15W-50, as seen with my other test liquids above.

After I received sound values for this setup, I took to my hardware design, and utilizing Equation 3 and the spindle/motor design seen in Image 3-4, I tested other oils/liquids to gauge my own viscometers validity. The following data is from this process.

100mL of Each	Displacement is 2.5mm						
Olive Oil is 1.089P		Shampoo is inconclusive, new spindle needed		Glycerin is 2.994P		Mineral Oil is 4.037P	
Current (A)	RVelo. (Rad/S)	Current (A)	Rvelo (rad/s)	Current (A)	Rvelo (rad/s)	Current (A)	Rvelo (rad/s)
0.118	0.55	0.135	0.349	0.126	0.49	0.129	0.582
0.13	0.91	0.171	0.814	0.155	1.047	0.165	1.396
0.161	1.571	0.2	1.41	0.2	2.269	0.187	2.327
0.2	3.1	0.245	2.211	0.242	3.27	0.202	2.8
0.23	4.14	0.277	3.142	0.262	3.84	0.225	3.782

Table 4: This table is a solid measurement of four test liquids with their viscosities solved in Poise next to each liquid name. The current and rotational velocity of my spindle are being measured, to operate in conjunction with Equation 6, using principles found in Equations 4-5. Current vs. Velocity will be a staple of my measurements and math to find sound viscosity values. Shampoo was an inconclusive test, as the spindle used was simply too small to generate laminar flow. The involvement of various sized spindles for new fluids could be a future addition to my work here. However, my current spindle used was exemplary at measuring oils and similar fluids.

Note: Each descending graph between 4-7 are for their corresponding fluid in this table. (Ex. olive oil is graph 4, Shampoo is 5, Glycerin is 6…). The fact that these graphs do not meet 0 as a y-intercept is due to the lack of my adjustment constant k, seen later in my oil tests and included in the viscosity calculations. For each of these tests, torque is the slope of each line as seen in Equation 6, giving my math a sound replication in my experimental design. Graph 4: This graph of current and velocity for olive oil. The linear trend here is exactly what I wanted to see, as it demonstrates the notion that the speed of the spindle and the current involved in the motor are related, thus producing some form of torque as seen in my mathematical basis for these tests.



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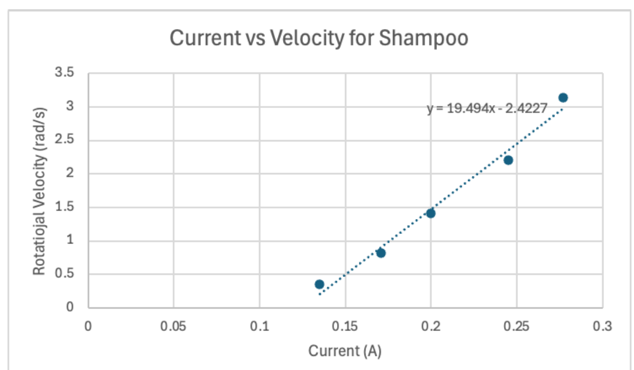
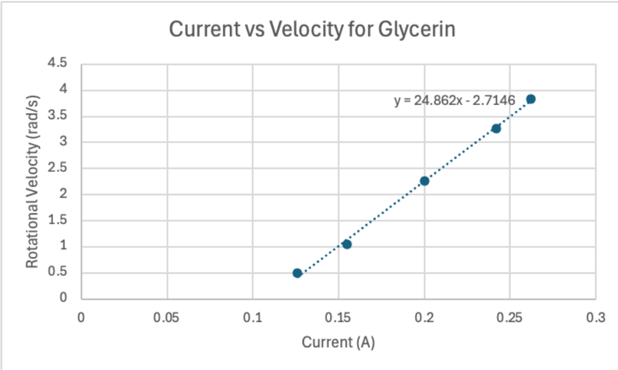
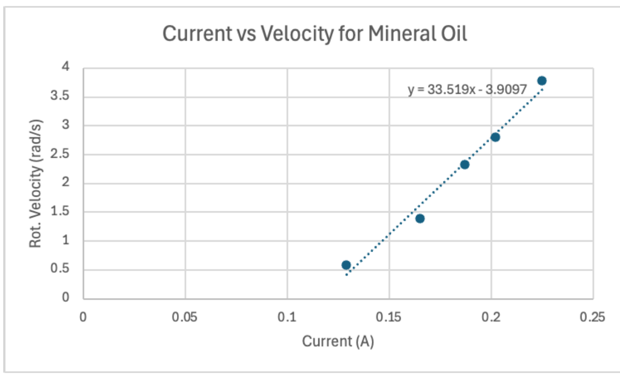


Graph 5: While the graph for shampoo is linear, the calculations did not produce the values required. I believe this is due to the viscosity of the shampoo being too high, while the electrical systems in my design functioned correctly, but the spindle didn't generate laminar flow. This is a correct example of how spindle surface area can affect results on different fluids.



Graph 6: The graph for glycerin was similar to my previous results, and the trend seen in these few data points arrived at the same conclusion I was attempting. The linear shape of all of my test fluids seem to arrive at the conclusion that the hardware seen in Image 3-4 is sound and is ready for oil testing.

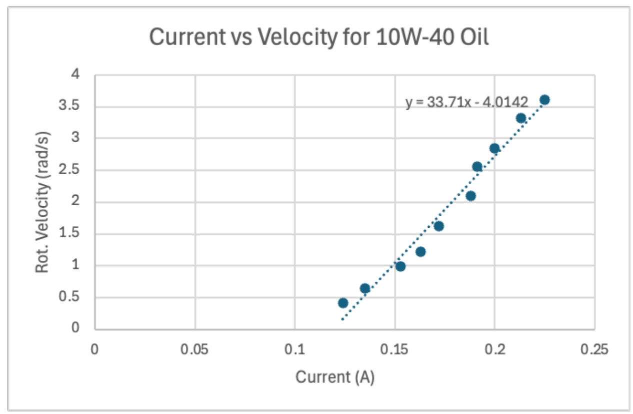


Graph 7: Mineral oil was also tested and found to perform effectively in my design. The viscometer now had been calibrated through many different fluids with a wide range of viscosities, thus giving me confidence that my final few tests could be done in a repeatable and precise manner.

The oil tests below follow the same methods I used for the test liquids and were met with some successful results as well as some areas of improvement. The oils used were put into the beaker and tested as seen in Image 1, with my new setup analyzing my inputs of current and the velocity resulting from it. More trials were also done to improve accuracy and make data trends easier to spot.

10W-40	
Current (A)	R. Velo (rad/s)
0.124	0.407
0.135	0.648
0.153	0.989
0.163	1.222
0.172	1.629
0.188	2.094
0.191	2.56
0.2	2.851
0.213	3.316
0.225	3.607

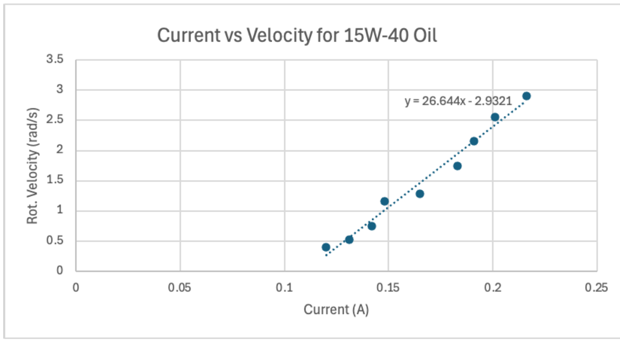
Table 5: The measurements for 10W-40.



Graph 8: The oil tests also followed my desired linear trend, a sign that the experimental design was operating well and within the ranges that I wanted for precise measurements of viscosity. This is also for 10W-40.

15W-40 (HD)	
Current (A)	R. Velo (rad/s)
0.12	0.407
0.131	0.524
0.142	0.756
0.148	1.164
0.165	1.28
0.183	1.745
0.191	2.153
0.201	2.56
0.216	2.909
0.246	3.723

Table 6: The table for the measurements found for 15W-40 HD oil is recorded below, with everything operating as normal up to this point, with the graphical display showing that familiar linear relationship between current and rotational velocity. Note the similar rise in both values for each data point, the tell-tale sign of my experimental theory in action.



Graph 9: The oil test for 15W-40 HD resulted in the same shape as previously seen in the table, with the line looking similar to my test points seen above.

Once all these plots were found, it was time to solve for viscosity using my Equation 6 and a new constant called K. K is the adjustment constant used to correlate my values into a y-intercept of 0, to give me my actual viscosity values. Current multiplied by K is the torque or slope of my graphs, so it was easy to solve for. With K found, all of the variables seen in Equation 6 are accounted for, allowing for viscosity to be solved for.

Findings and Discussion

My final findings for viscosity for both the 10W-40 and the 15W-40 HD were 3.2P and 4.06P respectively at a percent error of 11.7% for the 10W-40 and 95% for the 15W-40. The 10W-40 was a very accurate result for my viscometer developed in the lab without precision calibration as seen in the industry standard machine. This result demonstrates the accuracy of the viscometer using certain liquids, as well as my understanding of the mechanics involved. My tests of the 10W-40 have led me to believe that this project was not only conceptually but mechanically sound, and I'm open to its development by future students at Hampden Sydney. The 15W-40 HD viscosity value was certainly surprising as multiple trials were run with this similar result, leading to the conclusion that the spindle was simply of incorrect size for the liquid, even if laminar flow was found. As seen in my pre-run tests, the size of the spindle and liquid involved can greatly affect results as seen here. The development of a new spindle with a different surface area was manufactured but was not tested in time before my research period ended. However, I found this project to be a resounding success, as I improved on Davis Ferguson's original design, all while calibrating and testing more liquids to further the rotational viscometer's accuracy and usage requirements. The design and reliability of the viscometer, as well as sound and rather simple mathematical basis that can be easily learned by other students is exactly what I was aiming for, all while improving my foundation of physics knowledge in the realms of fluid mechanics and laboratory work in establishing this project. Future improvements are in the works, with a heating element added to affect the viscosities of my oils under testing, as they would in the engine block of a car. Heat and viscosity are intimately related as seen in my first three graphs. The heating of certain liquids can cause real world implications, especially when studying oil's protective nature in everyday travel. I am looking forward to adding this new development step in my research project and will most likely be doing so in the fall of 2024.

Acknowledgements

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References

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