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A Detailed Analysis of Capillary Viscometer

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A B S T R A C T

The purpose of this paper is to understand how a capillary viscometer is able to measure the viscosity of a fluid, which equals time required to empty a given volume of liquid through an orifice. A fluid analysis was done on a capillary viscometer in order to derive equations to theoretically describe the viscometer. In addition, physical experiments were undertaken in order to correlate empirical data with theoretical models. Various fluids were tested and their corresponding times were recorded. Time readings were taken at two separate temperatures of 25°C and 100°C. The kinematic viscosity of a fluid is measured in Saybolt Universal Seconds (SUS), which is related to the kinematic viscosity of the tested fluid.

1. Introduction

The viscometer used consists of a cylindrical cup with a capillary tube at one end. The cross-section of the viscometer is shown in Figure 1. It is assumed that the dimensions of the capillary tube play a key role in the function of the viscometer. A fluid analysis was done to determine how the dimensions of the viscometer affected its function.

Figure 1: Cross-section of Capillary Viscometer.

The following fluids were tested: water, honey, dish detergent (Ajax), mixtures of water and detergent; Car oils: SAE 5W-30, SAE 10W-30, SAE 10W-40, SAE 50W; Gear oil: SAE 75W-90. The reason detergent was used was to see possible relationships between surface tension and viscosity, since dish detergent is commonly used as a surfactant to change surface tension in various industries. Due to this, mixtures of water and dish detergent were tested to determine the effect of surface tension on the viscometer. The concentration ratio of water to detergent was varied 0% to 100%. The viscometer is tested according to regulations under the ASTM D88 and D2161 Standards (ASTM, 1972). The D88 standard ensures careful controlled temperature, causing negligible change in temperature during testing procedure. The time is in Saybolt Universal Seconds, which dictates the time required for 60 mL of petroleum product to flow through the calibrated orifice of a Saybolt Universal Viscometer (ASTM, 1972) . The viscometer used is calibrated to this standard. The D2161 standard relates the relationship between the kinematic viscosity units of Centistoke and Saybolt Universal Second (SUS) (ASTM, 1972). Saybolt Universal Second is also referred to as a Saybolt Second Universal (SSU).

2. Mathematical Model

The Navier-Stokes and Continuity equations are used to develop a theoretical expression that relates time taken for volume of fluid to empty to the dynamic viscosity of the fluid. We begin the

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analysis with the capillary tube itself in order to determine the velocity and volumetric flow rate, after which ,we apply the results to the overall viscometer in order to determine viscosity in terms of time (Hancock and Bush, 2002).

Table 1: Fluid Analysis Nomenclature.

Variable	Definition
μ	Dynamic viscosity
v	Kinematic viscosity
ρ	Density
r	r-direction
z	z-direction
θ	theta-direction
V_θ	Velocity in θ-direction
V_z	Velocity in z-direction
V_r	Velocity in r-direction
b	Viscometer radius
h	Fluid Column height
k	Capillary Tube length
a	Capillary Tube radius
g	Gravitational constant
Q	Volumetric flow rate
P	Pressure
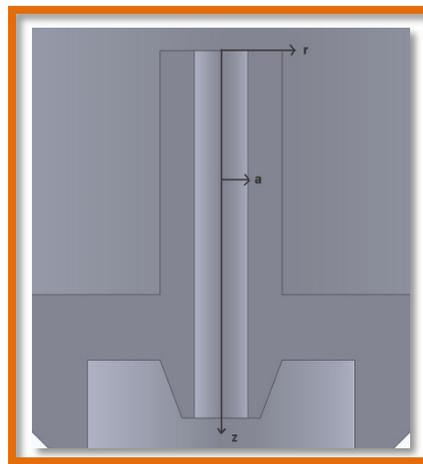
Figure 2: Capillary tube analysis coordinate system.

We wish to derive the velocity profile within the capillary tube. The following assumptions are made for the derivation:

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1. Fluid dynamic viscosity, μ, and density, ρ, remain constant.
2. Gravity occurs only in z-direction.
3. Pressure gradients occur only in z-direction.
4. The r and θ components of the velocity are equal to zero.
5. Flow is laminar and steady.
6. Temperature is constant.
7. Fluid is newtonian and incompressible.

The coordinate axis orientation of the analysis is shown in Figure 2.

The Navier-Stokes Equation in cylindrical coordinates for the z-direction is

$$\rho\left(\frac{dV_z}{dt} + V_r\frac{dV_z}{dr} + \frac{V_\theta}{r}\frac{dV_z}{d\theta} + V_z\frac{dV_z}{dz}\right) = \frac{-dp}{dz} + \rho g + \mu\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dV_z}{dr}\right) + \frac{1}{r^2}\frac{d^2V_z}{d\theta^2} + \frac{d^2V_z}{dz^2}\right) \quad (1)$$

Applying assumption 7 to (2) the Incompressible Continuity Equation in cylindrical coordinates, which is

$$\frac{1}{r}\frac{d(rV_r)}{dr} + \frac{1}{r}\frac{dV_\theta}{d\theta} + \frac{dV_z}{dz} = 0 \quad (2)$$

Applying assumption 4 to (2) yields

$$\frac{dV_z}{dz} = 0 \quad (3)$$

Applying (3) along with Assumptions 1-5, and 7 to (1) simplifies it to

$$\frac{r}{\mu}\left(\frac{dp}{dz} - \rho g\right) = \frac{d}{dr}\left(r\frac{dV_z}{dr}\right) \quad (4)$$

Integrating (4) twice to determine $V_z(r)$ yields

$$V_z(r) = \frac{r^2}{4\mu}\left(\frac{dp}{dz} - \rho g\right) + C_1 ln(r) + C_2 \quad (5)$$

C_1 and C_2 can be found by applying boundary conditions:
1. $\left.\frac{dV_z}{dr}\right|_{r=0} = 0$ (Due to symmetry)
2. $V_z(r = a) = 0$ (Due to no slip)

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Applying Boundary Condition 1

$$C_1 = 0 \tag{6}$$

Applying Boundary condition 2

$$C_2 = \frac{-a^2}{4\mu}\left(\frac{dp}{dz} - \rho g\right) \tag{7}$$

Therefore (5) reduces to

$$V_z(r) = \frac{r^2}{4\mu}\left(\frac{dp}{dz} - \rho g\right) + \frac{-a^2}{4\mu}\left(\frac{dp}{dz} - \rho g\right) \tag{8}$$

We wish to relate the volume of fluid emptied from the container in a given amount of time to the viscosity of the fluid. Therefore, using (8), we must find an expression for the volumetric flow rate (Q), which is

$$Q = 2\pi \int_0^a rV_z(r)dr = \frac{-\pi a^4}{8\mu}\left(\frac{dp}{dz} - \rho g\right) \tag{9}$$

Solving for Q

$$\frac{dp}{dz} = \rho g - \frac{8\mu Q}{\pi a^4} \tag{10}$$

With (10) known, we can begin to extrapolate this information to the viscometer itself. Figure 3 is used to accomplish this.

If, in terms of gauge pressure, p_i is the inlet pressure to the capillary tube, and the outlet pressure is zero. Then the pressure drop across the tube length, (10), can also be written as

$$\frac{dp}{dz} = \frac{p_i}{k} \tag{11},$$

where k is defined in Figure 3. Setting (8) and (9) equal to each other and solving for p_i yields

$$p_i = \frac{8\mu Q k}{\pi a^4} - \rho g k \tag{12}$$
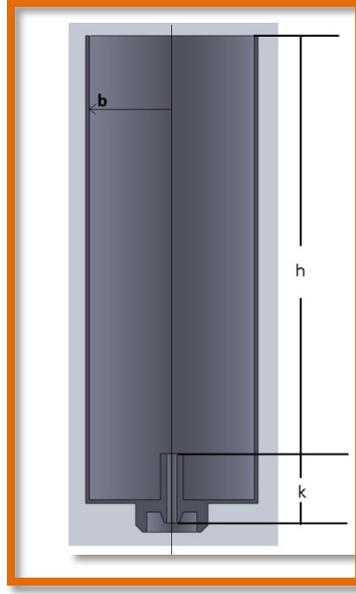
Figure 3: Capillary tube analysis coordinate system

Since the flow is gravity driven, it should be noted that p_i is proportional only to the height of the fluid column above it (From Figure 3). Therefore

$$p_i = \rho g h \tag{13}$$

Setting (12) and (13) equal to each other and solving for h, the height of the fluid column,

$$h = \frac{8\mu Q k}{\pi \rho g a^4} - k \tag{14}$$

Note (14) can be rewritten in terms of kinematic viscosity rather than dynamic,

$$h = CvQ - k \tag{15},$$

where $C = \frac{8k}{\pi g a^4}$ and $v = \frac{\mu}{\rho}$

Rearranging for the kinematic viscosity yields

$$v = \frac{h + k}{CQ} \tag{16}$$

Q can also be expressed in terms of volume, from Figure 3, and time as

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$$Q = \frac{\pi b^2 h}{t} \tag{17}$$

Substituting (17) into (16) yields

$$v = \frac{h+k}{C\pi b^2 h}\, t \tag{18}$$

(16) may also be rewritten in terms of the viscometer dimensions as

$$v = \left[\left(\frac{g}{8}\right)\left(\frac{1}{b}\right)^2 a^4 \left(\frac{1}{k} + \frac{1}{h}\right)\right] t = Mt \tag{19},$$

where M is a constant. It is worth noting that (19) shows important insights into the sensitivity of the function of the viscometer. The constant M is implicit and specific to each viscometer made, which is dependent on the dimensions of the viscometer. Although M depends on the dimensions, for proper calibration, the importance of each dimension must be known, such that each dimension's required tolerances can be assigned during manufacturing of the viscometer. (19) is powerful in aiding with these insights.

It can be inferred from (19) that increasing or decreasing the capillary radius, a, exponentially affects M since it is raised to the fourth power. Due to this, it can be seen that the capillary radius is the most sensitive, and important, dimension of the viscometer in terms of its proper function. The viscometer diameter, b, is the second most important dimension regarding the functioning of the viscometer. It affects the function at an exponential rate, like capillary radius, but at a slower rate. The lengths of the fluid column and capillary rank equally, but are last in line in dimensional importance. Additionally, recalling from (15) about dynamic viscosity, (16) and (19) can be rearranged as

$$\mu = \rho\frac{h+k}{CQ} = \frac{\rho\pi g a^4 (h+k)}{8kQ} \tag{20}$$

$$\mu = \rho\left[\left(\frac{g}{8}\right)\left(\frac{1}{b}\right)^2 a^4 \left(\frac{1}{k} + \frac{1}{h}\right)\right] t = \rho Mt \tag{21},$$

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where M is a constant. It is important to note that although, in terms of function of the viscometer, the kinematic viscosity is not dependent on the density of the fluid, the relationship of dynamic viscosity is density dependent. The kinematic viscosity mainly depends on the geometry of the problem.
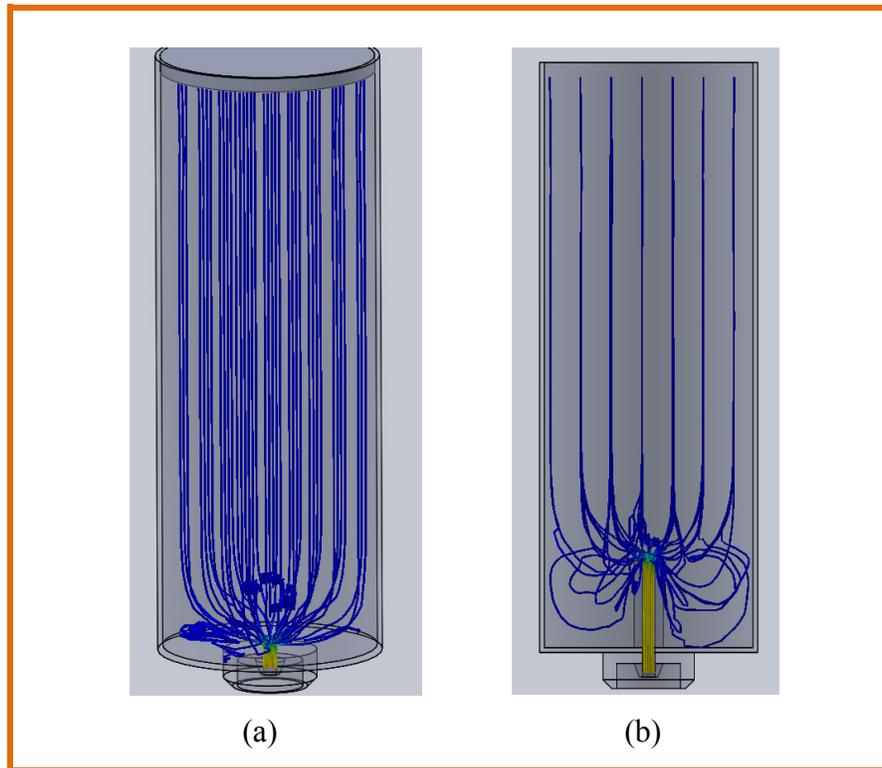
Figure 4: Streamline Depictions of: (a) Bucket with hole in bottom and (b) viscometer; blue indicates ~143 mm/s and yellow indicates ~36,800 mm/s velocity.

In addition to the above analysis, an elementary computational fluid simulation was done on the tested viscometer. It is known that previous capillary viscometers existed, where the capillary tube started at the bottom of the cup, not offset in height, k, as in Figure 3. It was assumed that fluid flow accounted for this height offset. In other words, the reason for the height is assumed to be due to the streamlines of the flow during use. In order to test this theory we must visualize streamlines for different designs, and to get a general idea of how these streamlines change with the design. Therefore, a CFD (Computational Fluid Dynamics) model was done. A model of the viscometer was created using Solidworks. The FloExpress Simulation Module of Solidworks was used to run a fluids simulation to predict streamlines of flow. The simulation input required specifying an inlet and exit. The simulation required inlet conditions, while the outlet conditions were auto-set to be to open air at STP. The inlet conditions that were input was a volumetric flow rate and inlet pressure,

which were 10 in^3/s, and 1 atm, respectively. The fluid was assumed be incompressible during the simulation, which was done through an iterated Navier-Stokes equation reduction. The first case considered was a tank with a hole at the bottom. The second case considered was the capillary viscometer. The result of this analysis is shown in Figure 4, where the color of the line corresponds to the speed of the flow; blue indicates lower speeds, whereas yellow indicate higher speeds.

Comparing the two pictures in Figure 4, it is easier to understand the reason for this height offset. As can be seen in Figure 4a, the fluid that gets to the bottom of the tank undergoes turbulence as it transitions into the capillary hole. In addition to this turbulence, slight rotation in the flow can be seen as it enters the capillary. When looking at Figure 4b, lot of turbulence can also be seen. The difference is that turbulence occurs due to vortices developing on the sides of the capillary tube. These vortices occur in a way such that the turbulence does not affect the fluid entering the capillary tube. Another observation is that there is minimum rotation in the flow.

In effect, the transition the flow undergoes going from the viscometer into the capillary is a lot smoother when the capillary is offset in height. This allows Assumptions 4 and 5 of the Capillary Tube Analysis to be more valid, causing the overall fluid analysis to have greater validity, causing higher accuracy of (19). It can also be seen from Figure 4b that the result from (3) seems viable since fully developed flow is depicted for most of the capillary tube. As an added case of support, the Reynolds Number was calculated for the capillary tube, using water as the fluid, which was 95. Note that this number is very low, so laminar flow is viable.

An interesting digress related to history is that Ford had a viscosity cup, Figure 5, which attacked the previous problem in a different way (Wikipedia).

Figure 5: Ford Viscosity Cup (Wikipedia).

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Notice the conical extrusion at the bottom of the cup. This conical profile allows the flow to follow more of the streamline pattern as in Figure 4b. This ensures straight laminar entrance into the capillary at the bottom. This method does have its disadvantages. Due to the profile of the conical section, the fluid velocity accelerates as it gets near the outlet of the cup. This acceleration may be more observable as angular rotation rather than laminar velocity. Although this does create a stream tube as in 4b, there is a possibility of turbulence/angular rotation. The height offset as shown in Figure 3 ensures a similar stream tube profile and also reduced chances of turbulence/angular rotation.

The above analysis must then be applied for the viscometer used. Table 2 shows the measured values for the dimensions of the viscometer being analyzed.

Table 2: Viscometer parameters.

a (mm)	b (mm)	h (mm)	k (mm)	g (mm/s)
1.19	19.05	95.25	9.525	9810

Substituting these values into (19), the approximate equation for the capillary viscometer is

$$v = 0.78254t \tag{22}$$

The kinematic viscosity, from (21), is given in mm^2/s due to the units used from Table 2, and t represents the SUS (Saybolt Universal Second). It is useful to note that 1 mm^2/s is referred to as 1 centiStoke (www.engineeringtoolbox.com).

Standard values of kinematic viscosity of water at 25°C are known to be 1 centiStoke and 31 SUS (www.engineeringtoolbox.com). So why is it that, when plugging in 31 SUS for t in (22), the corresponding kinematic viscosity is 24.3 centistokes? The reason for this answer takes a bit more insight, where the ASTM D88 standard is referred. Remember that the original ASTM D88 standard for measuring viscosity uses 60 mL of liquid through a carefully calibrated orifice. What is this calibration? This calibration is such that it takes a certain time, t, to empty 60 mL of a standard, pre-agreed upon, liquid. Note that the time, t, and the liquid used are pre-agreed upon. For example, the standard to be tested against is water. Through the ASTM D88 standard, it takes 31 seconds for 60 mL of water (at 25°C) to empty from the viscometer.

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What would occur if the liquid being tested, whose viscosity is unknown, is very viscous, such that the time required for it to empty is very large (on orders of tens of minutes to hours)? What would occur if the liquid being tested is so inviscid, such that the time elapsed for emptying 60 mL is on the orders of few seconds, not long enough to gather data? Both of the above scenarios, which are encountered in larger frequency after the industrial revolution, would be hard to handle by one size of viscometer. Both of the above scenarios can be solved by changing the height of the fluid column, h, such that the time it took to empty that volume is kept in a second range that is workable out in the field/application. But changing the fluid column height also changes the volume of the fluid, causing it to differ from the traditional 60 mL, causing the test to not follow the ASTM standard.

This is actually not a real problem. The reason why is because of the nature of the definition of viscosity, tied in with ASTM. The unit known as viscosity is not a physical unit. It is a theoretical unit which describes a physical presence, like gravity. This is the reason the ASTM D88 standard was created. Since viscosities of fluids greatly differ and difficult to define, a theoretical zero-bar is created, to which all other viscosities are related to. This zero-bar is through the ASTM D88 standard. Therefore the problem of changing the initial volume can be fixed if the time required for that volume to empty can be analogous for the time it takes for 60 mL to empty. Due to this, the relationship between units of kinematic viscosity (centistokes and SUS) is not related to the geometry of the viscometer, which is displayed in Figure 6. It is also interesting to note that the relationships in Figure 6 change depending on the temperature.

At 100 F, Saybolt Universal $= 4.6324$ cSt

$$+ \frac{1.0 + 0.03264 \text{ cSt}}{(3930.2 + 262.7 \text{ cSt} + 23.97 \text{ cSt}^2 + 1.646 \text{ cSt}^3) \times 10} \quad (5)$$

At t F Saybolt Universal $= \text{cSt}_t[1 + 0.000061(t - 100 \text{ F})]$ (SUS 100 F)/(cSt 100 F) (6)

At 122 F, Saybolt Furol $= 0.4717 \text{ cSt} + [13924/(\text{cSt}^2 - 72.59 \text{ cSt} + 6816)]$ (7)

At 210 F, Saybolt Furol $= 0.4792 \text{ cSt} + [5610/(\text{cSt}^2 + 2130)]$ (8)

Figure 6: Centistoke to SUS conversion courtesy of "Standard Method for Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity" ASTM Standard 2161 (ANSI M9101).

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It is also interesting to note that, using the values from Table 2, the volume of the fluid column in the viscometer tested is actually about 105 mL, not the standard 60 mL. The higher volume allows for a larger range of viscosities to be tested, but only if the fluids fall within a specific gravity range. But for this viscometer to work with 105 mL of initial volume and still relate to the standard, the capillary radius is calibrated. The capillary radius is changed because it has the highest effect on the function of the viscometer as discussed above. The capillary radius of the viscometer is properly calibrated if it takes 31 seconds for 105 mL of water to empty through this viscometer. Remembering that the time taken for discharge is the SUS (Saybolt Universal Second) value for that fluid, the relationships from Figure 6 hold to convert between centistoke and SUS.

The key thing to note from above is that (19) and (21) contain a constant, M, inherent to the geometry of the viscometer. It is important to note that the constant depends on the dimensions of the viscometer. As long as the fluids being tested are within the specific gravity range of the viscometer's calibration, the constant M, from (19), also equals the ratio of kinematic viscosity, in centistokes, to kinematic viscosity, in SUS. This ratio is in accordance to the ASTM standard for conversion between SSU and Centistokes (ASTM D2161). For every SSU value, there is a corresponding Centistoke value at that temperature.

Therefore, for fluids with higher viscosities, the same capillary viscometer can be used, if the dimensions are changed such that the stream tube of Figure 4b is valid, making the Navier-Stokes Derivation valid, in addition to proper time calibration. If a fluid is very viscous, just changing the fluid column height and the capillary radius to replicate the stream tube is not enough. In addition to above, it must be ensured that the time it takes for the fluid to empty is in accordance with analogous to the standard. If, by changing the height and capillary radius to account for the new fluid, the viscometer's new volume composed of water emptying through the new capillary radius does not equal 31 seconds (aka SUS), then all the times from the viscometer cannot be compared to the standard. The balance between the two previous sentences is what ensures proper calibration of the viscometer with assurance of proper functioning. It should be noted that the above is also only for distinct densities or density ranges.

3. Study Details

The following fluids were tested: water, honey, dish detergent (Ajax), mixtures of water and detergent; Car oils: SAE 5W-30, SAE 10W-30, SAE 10W-40, SAE 50W; Gear oil: SAE 75W-90.

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These car/gear oils are engineered to have specific viscosities at two distinct temperatures during operation. These temperatures are known as the cold start temperature and operation temperature. The cold start temperature is the temperature at which the engine is turned on, which is also usually when the oil is at its lowest temperature. The operation temperature is assumed to be 100 $^{\circ}$C (Celsius). Ambient temperature of 25 $^{\circ}$C was chosen for simulating the cold start temperature due to the fact that the temperature at which the engine is turned on can vary depending on altitude, location, and other variables.

1. The following are procured: viscometer, stopwatch, fluids to be tested, containers, and a gas flame.
2. The viscometer is cleaned thoroughly prior to each use.
3. A reservoir of liquid is heated over a gas flame, until the desired temperature is reached.
4. Once the fluid has become the desired temperature, the viscometer is submerged into the fluid.
5. The viscometer is allowed to be submerged in the fluid to fill it up and held long enough to ensure it, and the fluid, are at the desired temperature.
6. The viscometer is pulled out of the fluid; when the bottom face of the viscometer clears the top of the liquid in the container, which allows the fluid to begin to fall out, the stopwatch is started.
7. The liquid is allowed to empty from the viscometer.
8. The following times recorded from the stopwatch: start time, time at which flow change from stream to drips occurs, and time when liquid flow stops.

Note: If needed, multiple trials can be done for same liquid to average the times by repeating Steps 2-8. During the procedure, the temperature of the liquid was monitored to ensure temperature was constant.

The viscometer acquired for the analysis was designed for fuel oils. Most of these fuel oils have a specific gravity range between 0.8-1.0 (www.engineeringtoolbox.com). Therefore, preliminary testing was done with automotive car and gear oils, due to the fact that most automotive oils have specific gravities between 0.88-0.94 (www.engineeringtoolbox.com). The

results of the experimental procedure are summarized in Table 3 below.

Table 3: Summary of Experimental Results.

| Oil Type | Time (s) | | | |
| | 25 ° Celsius | | 100 ° Celsius | |
	Stream to Drip	Full Stop	Stream to Drip	Full Stop
C: 5W-30	268	406	-	70
C: 10W-30	289	469	-	70
C: 10W-40	383	581	-	84
C: 50W	-	1395	-	97
G: 75W-90	318	775	-	81

In Table 3, the column "Stream to Drip" represents the time at which the fluid flow out of the viscometer changed from a steady stream to drips. The "C" or "G" before the oil type dictates whether it is crankcase or gear oil. If the fluid flow never changes from a stream to drip, no time is recorded. Whether the fluid drips or streams depends on the viscosity and surface tension of the fluid. The column "Full Stop" is the overall time it took the volume of fluid to empty from the viscometer.   It is important to note that the Full Stop time at 100 ^{o}C corresponds to the kinematic viscosity of the oil tested in Saybolt Universal Second. Car oils with an increasing number in front of the W dictate an increase in viscosity. The physical representation of this can be inferred from Table 1 since the Full Stop time increases as the number increases.

Table 4 shows the standard values (www.engineeringtoolbox.com), in SUS, of the oils tested in Table 3. The values in Table 4 correspond to the Full Stop values at 100°C in Table 3. As seen from Table 4, it is worth noting that the experimentally found kinematic viscosity, in SUS, of car/gear oils tested is within 5% of the standard value.

Table 4: Standard Values of Car/Gear Oils.

Oil Type	Standard Value @ 100°C (seconds)
C: 5W-30	70
C: 10W-30	70
C: 10W-40	85
C: 50W	110
G: 75W-90	74

The viscosities, at different temperatures, from Table 2 are in Figure 7.

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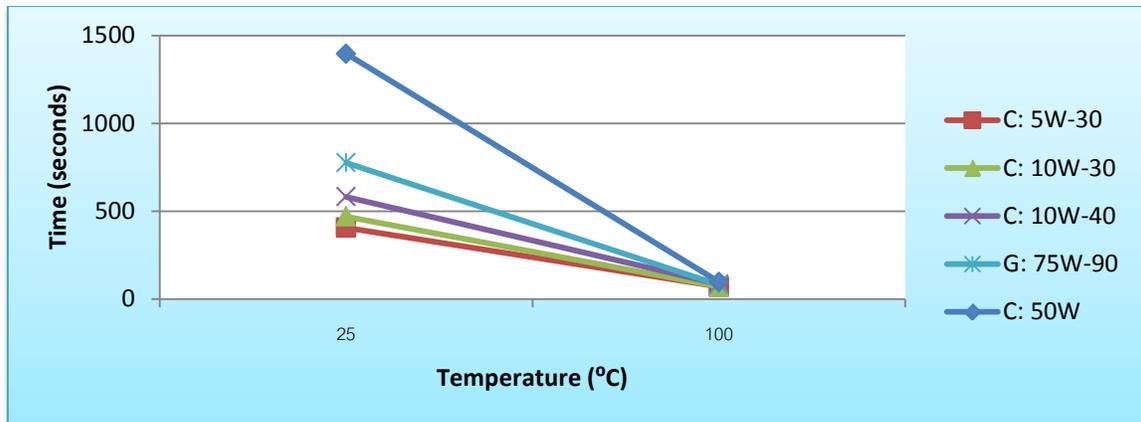
Figure 7: Full Stop Time vs Temperature for Car/Gear oils.
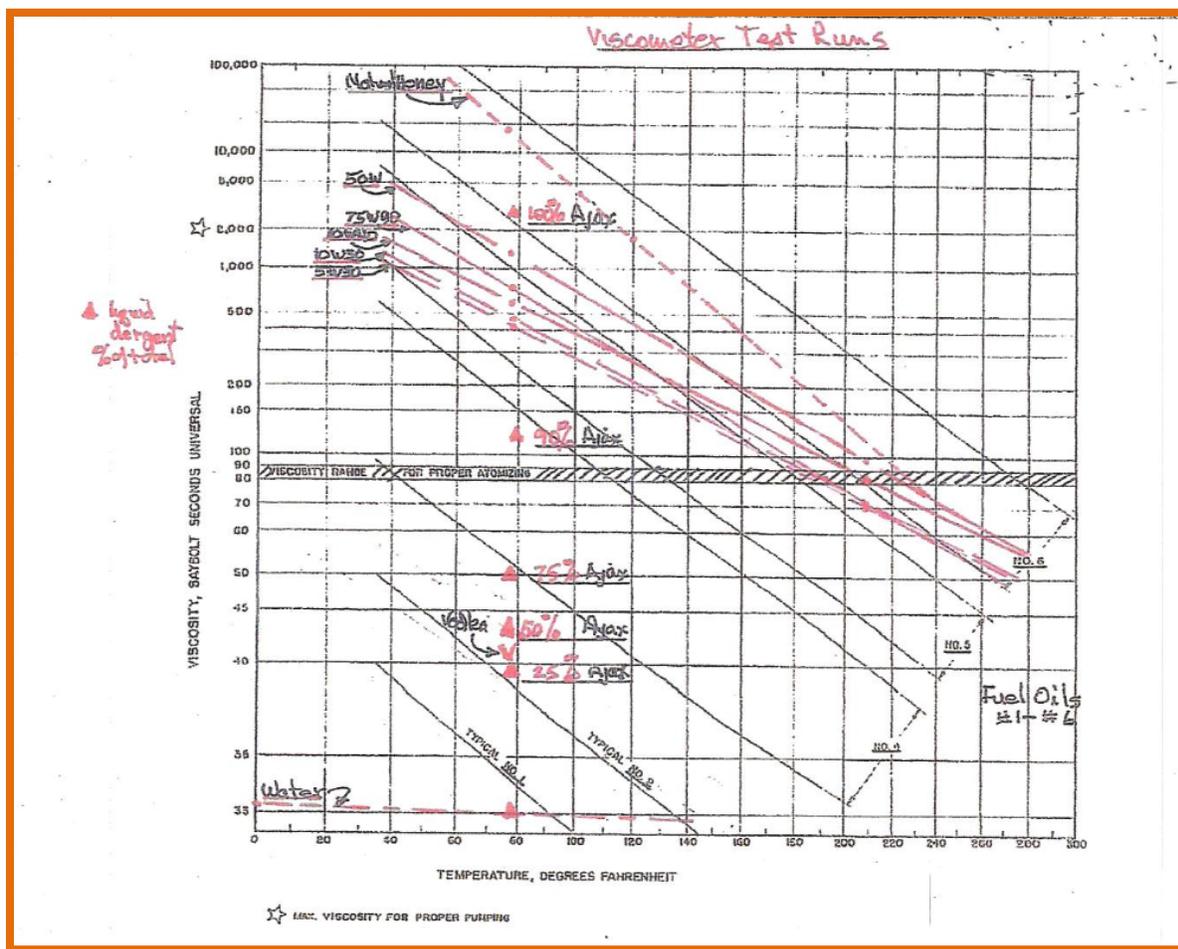
Figure 8: ASTM Viscosity Chart.

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It is well known that detergent is used in industry as a type of surfactant to change the surface tension of fluids. A set of trials were done were concentration of detergent to water was varied in different mixtures of dish detergent (Ajax) and water. The time required to empty the viscometer (SUS) was tabulated for these, which is shown in Table 5. The purpose of these trials is to discern some type of relationship between surface tension and viscosity of Ajax and/or Water. It seems that

Table 5: SUS values of Mixtures of Ajax and Water.

Ratio of Ajax to Water (%)	Time (seconds)
0	31
8.3	40
16.7	40
25	41
50	43
62.5	49
75	52
88	3651
100	3780

A graphical representation of Table 5 is shown in Figures 9 and 10. Figure 10 is a close up of first seven rows of Table 5, whose correlation is not discernible from Figure 9.
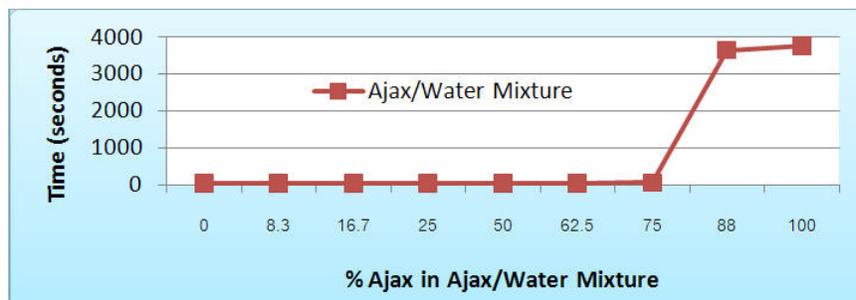
Figure 9: Ajax Mixture % vs Time.
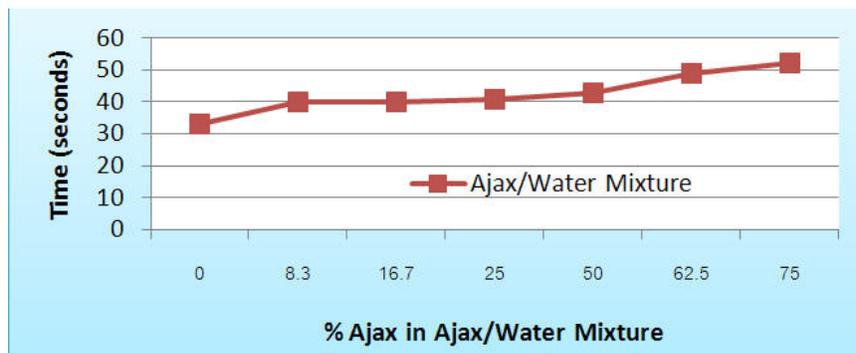
Figure 10: Close up of 0-75% range from Figure 9.

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Recall, that the ASTM standard for determining viscosity requires constant temperature. The reason is because viscosity is greatly affected by temperature; therefore to get an accurate viscosity reading to hold for a specific temperature, isothermal conditions must be ensured. In order to illustrate this, trials with honey were done, were the honey was allowed to cool during the run. The temperatures tested were ambient conditions, 25^oC, and 49^oC, shown in Figure 11.
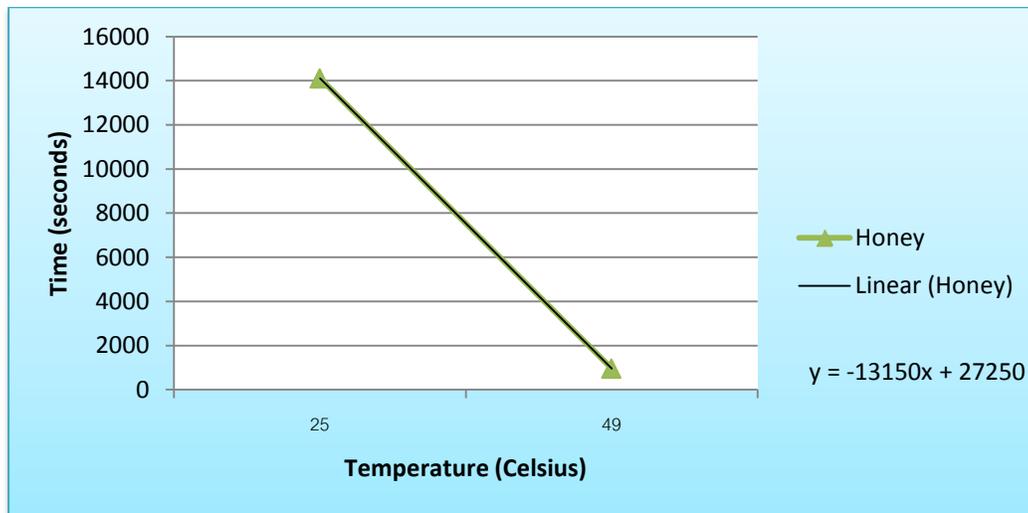
Figure 11: Honey SUS values at different temperatures.

4. Discussion

It can be seen from Figure 7 that all the car oils share a similar slope. This means that, in terms of viscosity, their response corresponding to change in temperature is similar. It is also interesting to note that the specific gravity range of the oils used is 0.88-0.94 (www.engineeringtoolbox.com). Therefore, the observation of similar slopes may be tied into the fact that they share similar densities, along with how their viscosity is affected by temperature.

In order to show the relationship of the measured data to applicable experience, Figure 8 was created. Figure 8 shows a comparison of typical fuel oils ranging from lightest of oils, #1, to the

heaviest, #6. It is important to note that the heaviest and most viscous fluid presented on the chart is honey. In terms of specific gravities, the oils tested range between 0.88-0.94; water is approximately 1; honey was measured to be approximately 2; pure Ajax was measured to be approximately 0.8. Excluding honey, the specific gravity range for all liquids tested lie in the range of 0.8-1 (within 20% of water). Although, from (21), the dynamic viscosity is density dependent, Figure 6 shows wide range of viscosities corresponding to a small specific gravity range.

Making note of Figure 8, there is a narrow band of acceptable viscosity of 80 to 100 SUS where a fuel oil must be heated in order to have clean combustion of the oil. Similarly the accuracy of the fuel oil heating and circulation system has to maintain a fairly narrow range of control. In other applications, such as paint spraying, coating etc. viscosity has to be accurately controlled to prevent "orange peeling" or a wavy texture to the paint to enlarged droplet size. Droplet size and fluid temperature are very dependent on one another.

As can be seen from Figures 9 and 10, the surfactant, dish detergent, does not affect the viscosity of water as much as water affects the viscosity of it. It is interesting to note, that 100% Ajax has an SUS value of approximately 3780. A decrease in concentration of just 15% decreases the SUS value to 3619 (decrease of approximately 4.26% with respect to the value at 100% Ajax concentration value). But a decrease of another 15% in Ajax concentration causes the SUS value to decrease to 52 SUS., which is a decrease of approximately 98.6% of the 100% Ajax concentration value.

Regarding Figure 11, the line named "Linear (Honey)" is a linear regression fitted to the Honey data. The equation of this regression is shown on the Figure. We will use this equation to extrapolate the viscosity of Honey (in SUS) at 100°C. Plugging in 100 for x in the equation, the corresponding y (time aka SUS) comes out to -1,287,750 seconds. Obviously, this is incorrect. The reason for this error is due to the Honey trial at 49°C. The time for the honey to empty is 950 seconds (15.8 minutes). During this time the honey decreased in temperature from 49°C at the start

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of the trial to 32.2^{o}C. The honey is very viscous, requiring the time for a given volume to empty to increase. If insulation is not present, temperature of the honey will change, especially if the time required for trial increases. This decrease in temperature causes a change in viscosity, since viscosity is temperature dependent. Due to this reason, the data from the 49°C trial is very erroneous, causing large errors in the linear regression. If the honey was well insulated, the linear regression will be a better fit, giving a viable value when extrapolating to 100°C.

5. Conclusion

It was found that of the main dimensions of the viscometer, the capillary radius and viscometer radius greatly affected the performance of the viscometer compared to the fluid column height or capillary tube height. The reason why the capillary tube was "inset" was found to help the transition the fluid flow experiences going into the capillary tube. Creating the height offset minimized turbulence and rotation of the flow entering the capillary tube. Constant temperature is essential to the accuracy of the viscometer. Car/Gear oils were tested with the viscometer and all viscosity results of the oils were with 5% of the real values.

Surface tension also was found to play a role in the viscometer. Once the surface tension force is larger than the pressure force, in this case due to gravity, forcing the liquid down, the flow does one of two things. If the flow was a steady stream out of the viscometer, it will either turn into dripping flow and/or stop altogether. If the flow out of the viscometer was through drips to begin with, the surface tension force then stops the flow of the fluid when it exceeds the pressure force.

6. References

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