Determination of Saybolt, Kinematic, and Shear Viscosity for a Variety of Liquids: Baby Oil, Biodiesel, Diesel, Jet Fuel, Yogurt, Ketchup, Glycerin, and Shampoo

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Abstract

Fuel viscosity can affect a number of properties such as fuel flow and fuel atomization. The viscosity of fuel can be affected by external climates and pressures which can ultimately cause engine problems such as pumping losses, reduced injection pressures, and reduced fuel atomization. Therefore, it is necessary to monitor and modify fuel and engine designs based on the climate in which the fuel is being utilized. Viscosity and additional properties such as shear rate, shear stress, and efflux time were analyzed and quantified by three different test methods. These test methods incorporated a Saybolt universal viscometer which determined the efflux time of baby oil. A Cannon-Fenske capillary viscometer was utilized to quantify diesel fuel, biodiesel, and jet fuel in terms of kinematic viscosity. A Bohlin viscometer was utilized to examine shear rates and shear stresses as well as shear viscosity of a variety of liquids such as ketchup, yogurt, glycerin, baby oil, and shampoo. Through the use of the Bohlin viscometer, relationships of Newtonian and non-Newtonian liquids could also be evaluated. The efflux rate was quantified and was shown to decrease with increasing temperature. This correlated to decreasing viscosity as expected. The kinematic viscosity of diesel was quantified to be 7.98 cSt, biodiesel was shown to be 4.00 cSt, and jet fuel was 9.58 cSt. These values were quantified for an equilibrium temperature at 24 °C. These values were similar to already logged values at 40 °C, but may have experienced some error along the process. The shear viscosity was quantified for shampoo, which exhibited a decreasing exponential relationship. The liquid was shown to be a non-Newtonian, shear thinning liquid, based on its viscosity relationship. Ketchup and yogurt were also evaluated based on shear rate and shear stress. The graph did not show a linear relationship for either substances, indicating non-Newtonian liquids. Based on the varying data points, it was hard to classify either substances as shear thinning or thickening liquids. Glycerin was quantified in a similar manner, and determined to show a linear relationship with proportionality in both shear rate and shear stress. This meant that glycerin was determined to be a Newtonian liquid. Baby oil was further evaluated again on a similar basis and was shown to exhibit an increasing exponential trend. This relationship was utilized to classify baby oil as a non-Newtonian, shear thickening liquid. Properties such as viscosity are being increasingly needed to make processes more economical. A well-logged table of viscosity data and critical evaluation as well as correlation is needed to help design engineers, scientists, and technologists optimize their areas of interest.

Introduction

Viscosity is a critical parameter often of concern in operations such as pumping oil from a well, flow of oil or its products through refinery piping, flow of fuels through fuel lines, and use of liquids for lubrication.[1] Liquid viscosity data is also needed by process engineers for quality control and by design engineers to optimize conditions for chemical processes and operations.[2]

Viscosity simply measures a fluid's resistance to flow.[1] Viscosity can also be termed drag force, and is a measure of the frictional properties of a fluid.[2] The viscosity of all liquids decreases with increasing temperature.[1] For most liquids the temperature dependence of viscosity is much greater than the influence of temperature on density, making it an extremely important parameter to monitor when considering viscosity behavior.[1]

Most fuels require viscosity properties to be monitored and optimized in engine processes.[2] Depending on external temperature and pressure conditions, liquid fuel viscosities may become too great or too low.[2] Problems with liquid fuels exceeding maximum viscosity specifications may lead to pumping losses and reduced injection pressures.[1] When liquid fuels do not meet minimum viscosity specifications, problems such as leakages at the fuel pump site or having the pump seize may occur.[1] The viscosity of gasoline is very low, typically around 0.5 mPas at 15 °C (half the value of water at same temperature), and therefore is not usually a concern.[1] The viscosity would never reach a point high enough that would cause engine problems.[1] However, other fuels such as diesel fuel and jet fuel happen to heavily rely on viscosity properties.[3] Jet fuel needs to remain liquid with a viscosity low enough to be pumpable under any anticipated operating conditions of the aircraft.[1] At high altitudes such as 10-12 km, the external air temperature is very low around -55 °C; the fuel must remain liquid to about -45 to -50 °C in aircraft fuel tanks.[1] If temperatures become too low, hydrocarbons may precipitate out of the solution mainly being paraffins.[3] Paraffins are of particular importance in petroleum fuels, because they have a high crystallization temperature and may form a wax crystal matrix after coming out of the solution.[3] The formation of wax from the paraffins prevents liquid fuel from reaching the boost pump inlet.[3] When operating in northern latitudes, alternative fuels or additives may be utilized by aircrafts to keep the viscosity relatively low and avoid cold-starting problems.[3] Diesel fuel requires optimal viscosity levels to prevent reduced injection pressures and reduced fuel atomization.[1] Fuel viscosity relates to the fuel's ability to atomize, producing fine droplets that will evaporate quickly and form the desired fuel-air mixture, and is therefore a limiting property in combustion processes.[1] Diesel fuel viscosities in the United States are typically in the range from 1.3 to 4.1 cSt.[4] Viscosity has additional importance in materials such as lubricants which help reduce metal to metal contact in engine systems.[3] Higher viscosities help prevent destructive wear of gears or surface damage.[3]

The objective of this study was to quantify viscosity in a variety of ways. There are numerous methods and theories to estimate and predict viscosity data of liquids. For this study, a Saybolt viscometer was utilized to quantify the efflux rate of baby oil. Kinematic viscosity was determined for diesel, biodiesel, and jet fuel using a Cannon-Fenske capillary viscometer. A Bohlin Viscometer was utilized to determine the shear viscosity of vanilla yogurt, ketchup, glycerin, and shampoo. Further evaluation and comparison of experimental data can be carried through existing viscosity data.

Theory

Flow characteristics of liquids are mainly classified according to three categories, Newtonian, Time-dependent Newtonian, and Time-independent Newtonian.[2] When the viscosity remains constant, it is independent of the applied shear stress, and is termed a Newtonian liquid.[2] For Non-Newtonian liquids, viscosity depends on the applied shear force and time.[2] Viscosity measures a fluid's internal resistance to flow and is a function of temperature and pressure.[2]

Viscosity is typically expressed in two forms, absolute/dynamic or kinematic.[2] Dynamic viscosity is the tangential force per unit area required to slide one layer (A) against another layer (B) as shown in figure 1.[2] The force (F) pushes against both layers (A and B) and causes them to slide at velocities (v_1 and v_2).[2]

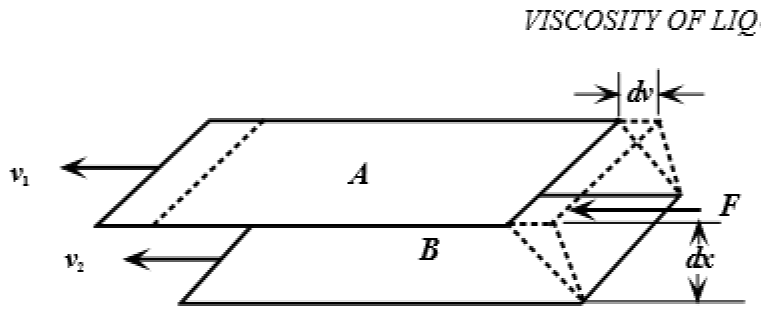

Figure 1. Shear Versus a Liquid Film.[2]

Viscosity is defined as a measure of how a fluid can resist flow and can therefore be represented by equation 1 where η is the dynamic viscosity.[2] The mathematical formula can be further derived based on strain rates to quantify dynamic viscosity according to equation 2.[2]

$$\text{Shear stress} = \eta\ (\text{Strain or shear rate}) \qquad (1)$$

$$\eta = \sigma\ (x/v) \qquad (2)$$

In equation 2, σ is the shear stress, x is the length, v is the velocity, and η is the dynamic velocity.[2] Kinematic viscosity is a measurement of viscosity that is often quantified for liquid fuels.[2] Kinematic viscosity relates to a fluid's ability to flow under gravity, and can be thought of as the ratio of dynamic viscosity to the density of the fluid.[1] Kinematic viscosity can be calculated by equation 3, where η is the absolute or dynamic viscosity, ρ is the density of the fluid, and v is kinematic viscosity.[2] This measurement requires the knowledge of the fluid's density at specified temperature and pressures and is often reported in terms of stokes or centistokes.[1] The kinematic viscosity of water at 20 °C is 1.0 cSt.[1]

$$v = (\eta/\rho) \qquad (3)$$

There are a variety of instruments utilized within industry practice to accurately predict and estimate viscosity.[2] A few of these instruments include, capillary, orifice, and rotational viscometers.[2] There are additional instruments as well that may combine one or more features of different viscometers.[2] Capillary viscometers are widely used to measure the viscosity of a transparent Newtonian liquid.[2] They are simple and require only a small volume portion of the liquid fuel.[2] The volumetric flow rate of the liquid flowing through a capillary is measured by noting the time it takes for the liquid to pass through two graduation marks usually under the influence of gravity.[2] The capillary viscometers are first calibrated by utilizing liquids with known viscosities and obtaining constants.[2] The driving force behind capillary viscometers is often the hydrostatic head itself.[2] A Cannon-Fenske viscometer was the capillary viscometer utilized in this study.[2] The instrument was a modified version of the Ostwald viscometer and is depicted in figure 2.[2]

Figure 2. Cannon-Fenske Viscometer Diagram.[2]

The Cannon-Fenske viscometer was developed to reduce the error associated with the mean head caused by the deviation of the viscometer lying in a vertical position.[2] The upper and lower bulbs lie in the same vertical axis to reduce this error.[2] The viscometer is typically designed to calculate the kinematic viscosity of transparent Newtonian liquids from a range of 0.5 to 20,000 cSt.[2] The instrument measures viscosity according to ASTM D-445 and D-446.[2] The apparatus is placed in a bath which allows the liquid to reach equilibrium temperature.[2] Applying suction to the viscometer will draw the column of liquid 3 mm in diameter up and allow for observation of kinematic viscosity.[2] The Cannon-Fenske viscometer calculates the kinematic viscosity based on specified dimensions and the usage of equation 4.[5]

$$v = (10^6 \pi g D^4 H t)/(128VL) - E/t^2 \qquad (4)$$

In equation 4, t is the flow time (s), E is the kinetic energy factor (mm^2s), L is the length of the capillary tube (m), V is the volume flow of the liquid (m^3), H is the mean distance between the graduated marks (m), D is the diameter of the capillary (m), g is acceleration of gravity (m^2/s), and v is the kinematic viscosity (mm^2/s or cSt).[5] The term E/t^2 is used for corrections and if the flow time exceeds 200 s, than the equation may be reduced to equation 5. In equation 5, C is the constant consisting of parameters found from equation 4.[5]

$$v = Ct \qquad (5)$$

A Saybolt viscometer was first utilized as a standard by chemists from Standard Oil Co. in the United States.[2] Saybolt viscometers come in two different types either, Saybolt universal viscometer or Saybolt-Furol viscometer.[2] The viscosities of lubricating oils are generally measured through the use of Saybolt universal viscometer while the Saybolt-Furol viscometer measures fuel oil viscosities.[2] The Saybolt universal viscometer should never be utilized when a lubricating oil's outflow time is less than 32 s.[2] A diagram of the Saybolt universal viscometer utilized in this study is shown in figure 3.[2] The apparatus consists of an oil tube fitted at the top with an overflow cup, and is surrounded by a bath.[2] An outflow capillary tube is fitted at the bottom of the oil tube, and is comprised of corrosion resistant materials.[2] The receiving flask is marked to hold 60 mL (±0.15 mL) at 20 °C.[2] The lower end of the outflow tube is sealed by a cork; when removed the oil will flow out.[2] The oil is heated to the required temperature by an electric heater and monitored by thermometers before pouring into the flask.[2] The results are expressed in Saybolt Universal Seconds (SUS).[2] The SUS is defined as the efflux time required for at least 60 mL of petroleum derived oil to flow through the orifice in the Saybolt viscometer.[2] When the efflux time differs from the certified Saybolt viscosity by more than 0.2%, a correction factor (F) is implemented using equation 6.[6] In equation 6, V is the certified Saybolt standard, t is the measured efflux time, and F is the correction error.[6]

$$F = V/t \qquad (6)$$

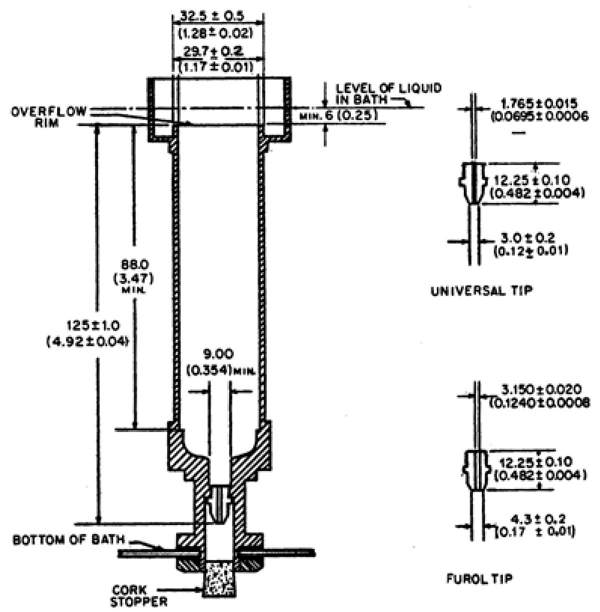

Figure 3. Saybolt Universal Viscometer Diagram.[6]

A rotational viscometer operates on the principle of measuring the rate of rotation of a solid shape in a viscous medium upon application of a known force or torque required to rotate the solid shape at an angular velocity.[2] In this study, a Bohlin viscometer was utilized to quantify viscosity for a number of liquids such as yogurt, ketchup, glycerin, and shampoo.[2] Rotational viscometers are more elaborate than capillary viscometers but are often less accurate for Newtonian liquids.[2] Rotational viscometers do however have several key advantages mainly being measurements under steady conditions, multiple measurements with the same sample at varying shear rates, and continuous measurements of a material with properties that are a function of temperature.[2] There is also little or no variance in the rate of shear within the sample.[2] A diagram of the V88 Bohlin viscometer is depicted in figure 4.[7]

Figure 4. Visco 88 Bohlin Viscometer.

The apparent shear viscosity is defined as the ratio of shear stress to the shear rate contained in a unidirectional simple shear flow field at steady state conditions.[7] The shear viscosity can be determined through the extrapolation of apparent shear viscosity while the shear rate is zero.[7] When the viscosity of the liquid being tested is independent of shear rate, the substance is a Newtonian liquid.[7]

Viscosity is an important parameter to consider in regards to liquid fuels, but most of the time, other property specifications must be met.[1] Certain cloud-point specifications vary from one region to another depending on the prevailing climate, and in some cases vary with season or month.[1] Diesel fuel has particular importance regarding cloud points.[1] At temperatures below the cloud point, more and more wax will crystallize.[1] This is due to paraffins that precipitate out of solution and are derived from higher branched alkanes.[1] A point can be reached at which the wax crystal buildup cannot pass through the fuel filters.[1] This causes a partial or complete blockage of the fuel filters which may slow the flow of the fuel or even stop it.[1] Continued cooling will cause even further increasing wax crystal mass which will prevent any liquid to flow.[1] A way of reducing cloud point is to reduce the distillations cuts by reducing the temperature.[1] By doing this, it will remove some higher molecular-weight alkanes that attribute to wax crystallization.[1]

Methods

Three instruments were utilized to determine different viscosities for liquids such as diesel, biodiesel, jet fuel, yogurt, ketchup, glycerin, shampoo, and baby oil. The efflux time of baby oil was quantified through the use of a Saybolt universal viscometer. The Saybolt viscometer was first calibrated and then brought to an equilibrium temperature around 78 °C before allowing the oil to flow. Baby oil was allowed to flow out of the viscometer and fill a 60 ± 0.05 mL flask. The efflux time was quantified by monitoring the rate at which the oil filled the flask. This test was performed in accordance with ASTM D88-94 standard.[6] Additional data was also used to compare the SSU's of the baby oil. A Cannon-Fenske capillary instrument was used to quantify kinematic velocities for diesel, biodiesel, and jet fuel. Each fuel was submerged in a bath with an equilibrium temperature of around 24 ± 1°C. Suction was then applied to each viscometer to allow for the test to take place. The kinematic velocity was quantified by timing the fuel's ability to flow between two graduated marks on the viscometer. Each test was also performed in triplicate to assure accurate data. The capillary test method was performed in accordance with ASTMs D-445-09 and D-446-07.[6,8] Shear viscosity was explored through the use of a rotational viscometer known as a Bohlin viscometer. The shear viscosity of ketchup, yogurt, glycerin, and shampoo was quantified. The viscometer was allowed to reach an equilibrium temperature before the test was performed. Viscosities, shear rates, shear stress, and percent ranges were explored through the use of this instrument. The instrument was further utilized to quantify whether the liquid would be classified as a Newtonian or non-Newtonian liquid based on varying rpm rates.

Results and Discussion

A Saybolt universal viscometer was utilized to quantify the efflux time of a particular baby oil. The efflux time was plotted for a variety of points in the standard SSU units. Figure 5 shows the plotting of efflux time points along axes of temperature and efflux time. As the temperature increased, there was a noticeable decrease in efflux time. Since efflux time was decreasing, the viscosity of the liquid was also decreasing. Although, this was clearly expected as all liquid viscosities decrease with increasing temperature. The maximum efflux rate of the baby oil on the plot was 158 SSU and the minimum point was 43 SSU.

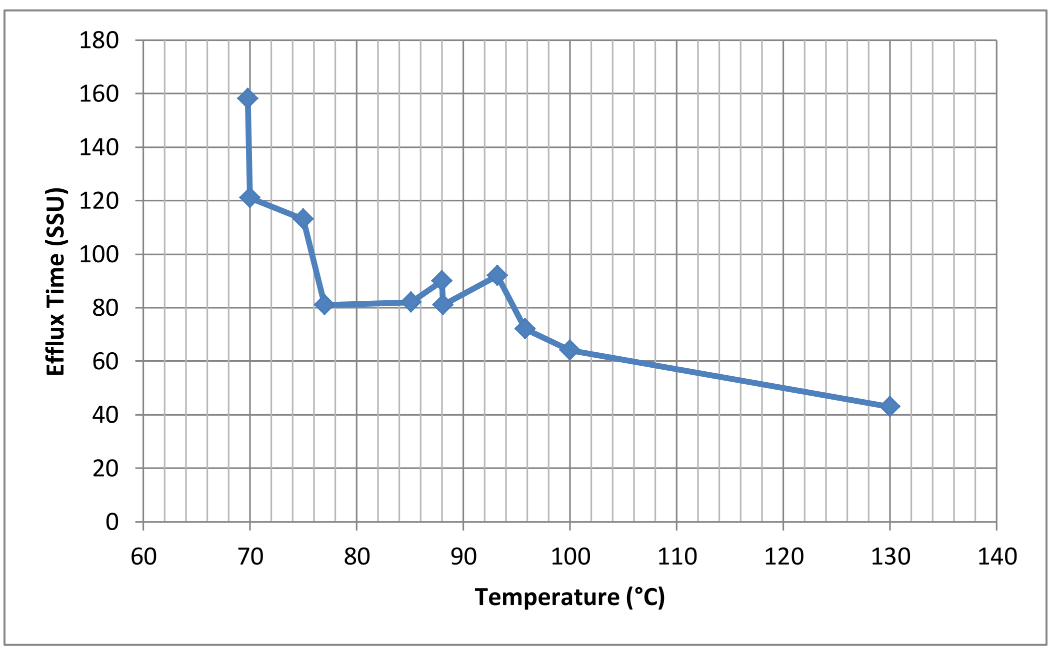

Figure 5. Efflux Time of Baby Oil Varying with Temperature.

The cannon-Fenske capillary viscometers were used to calculate the kinematic viscosity of diesel, biodiesel, and jet fuel. Table 1 shows the mean time it took for the liquids to flow through the capillary device and their kinetic energy. The kinematic viscosity of petrodiesel at 40 °C is 1.9-4.1 cSt, and biodiesel is 1.9 to 6.0 cSt. The data that was collected from this study was at a temperature of 24 °C, so the values differ from literature values, but are still comparable.

Table 1. Mean Passage Times, Kinematic Viscosity, and Kinematic Energy of Diesel, Biodiesel, and Jet Fuel.

Liquid Fuel	Mean Time (s)	STD Deviation (s)	Kinematic Energy Factor (cSt)	Kinematic Viscosity (cSt)
Diesel	242.03	1.56	2.52	7.98
Biodiesel	40.1	0.26	12.0	4.00
Jet Fuel	19.1	0.10	7.3	9.58

There may have been a large amount of error in the calculations of these values due to inaccurate flow times. There may have also been improper usage of equations and confusion upon utilizing different constant values and equations. This kinematic viscosities seem to be off from what would be expected which concludes the fact of error with these calculations.

A Bohlin viscometer was used to quantify the shear viscosity of ketchup, shampoo, yogurt, glycerin, and baby oil. The temperature of the shampoo analysis was held constant around 20 °C while the shear rate varied. Figure 6 depicts the shear viscosity versus shear rate. The shampoo heavily depended on the shear rate which classified it as a non-Newtonian fluid. As the shear rate increased, the viscosity decreased in an exponential trend making it a shear thinning liquid.

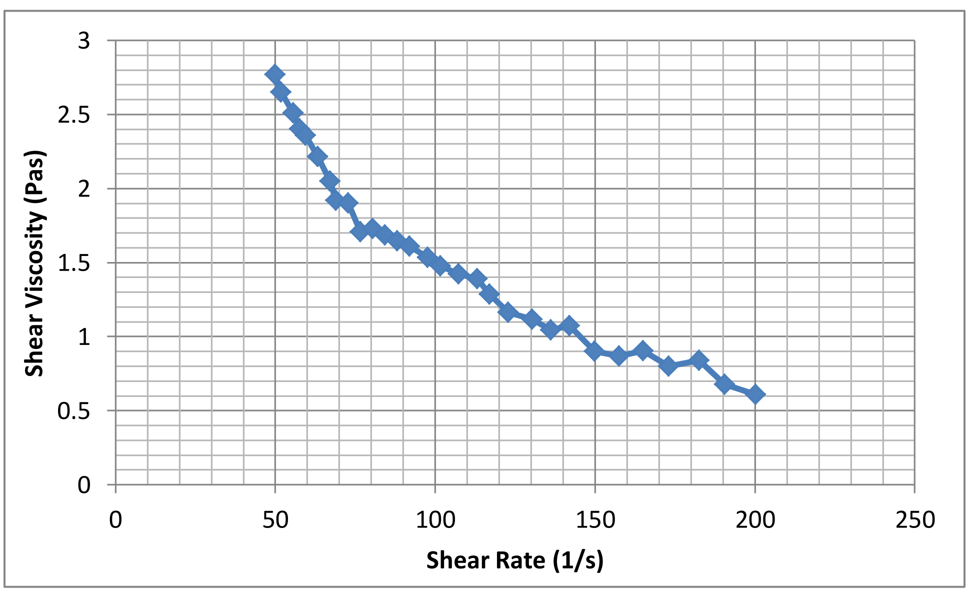

Figure 6. Shear Viscosity versus Shear Rate for Shampoo.

Ketchup and yogurt were plotted in the same manner, but the axes were changed to shear stress and shear rate. This plot was constructed to determine whether they were Newtonian or non-Newtonian fluids. The viscosity of the substances varied in almost a zig-zag pattern and was unclear what factor was affecting the viscosity. Based on the plotted points, the fluids were not Newtonian fluids, because their relationships were not linear. Because of the varying trend lines, it was difficult to classify the liquids as either shear thinning or thickening.

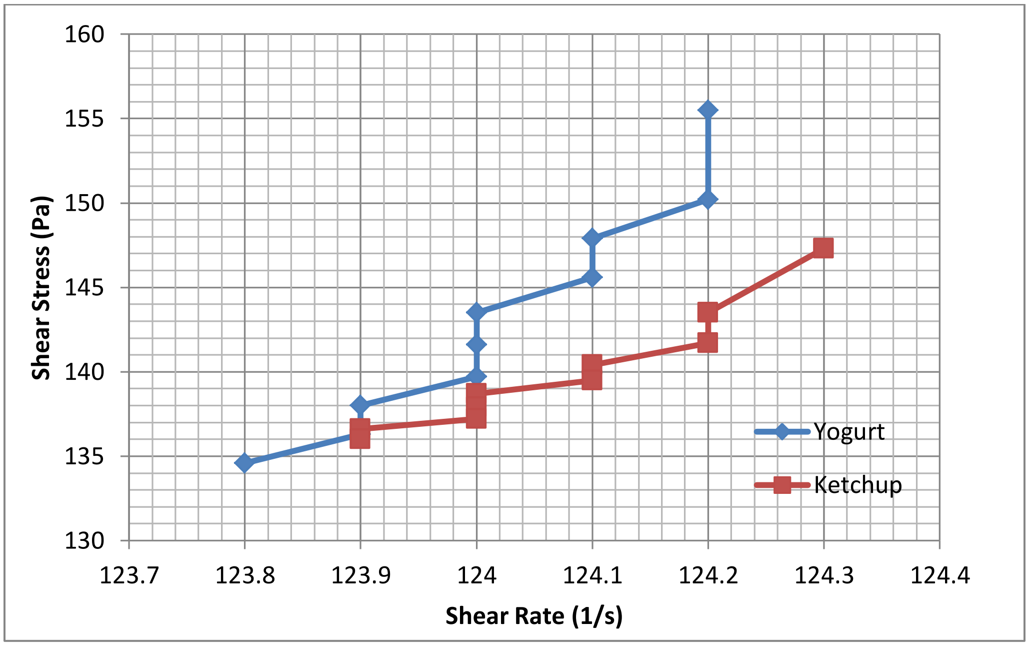

Figure 7. Sheer Stress versus Shear Rate for Ketchup and Yogurt.

Glycerin was plotted again in a similar manner in figure 8 to determine if the fluid was a Non-Newtonian fluid or a Newtonian fluid. From the graph constructed below, it can be seen that the shear rate and sheer stress are directly proportional to one another. From this it can be determined that the fluid is in fact a Newtonian fluid.

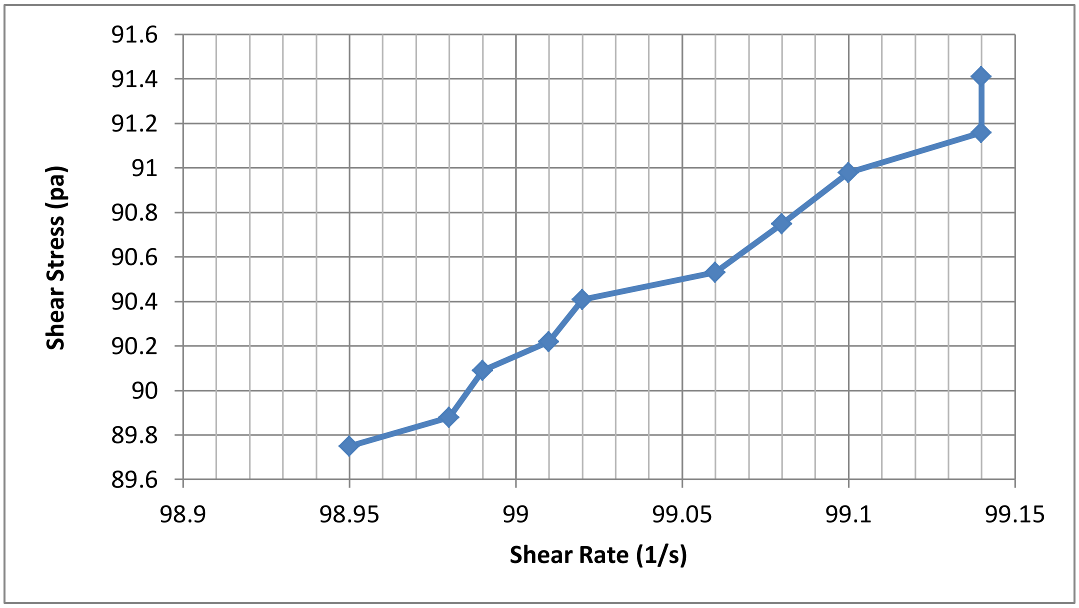

Figure 8. Shear Rate versus Shear Stress for Glycerin.

The last substance, baby oil, was once again plotted in the same manner of shear rate versus shear stress. Figure 9 depicts this graph, and it can be seen that the baby oil does not follow a proportional relationship. The trend line is not linear, which classifies the liquid as a non-Newtonian liquid. The liquid follows a rather increasing exponential trend which can further classify the liquid as shear thickening.

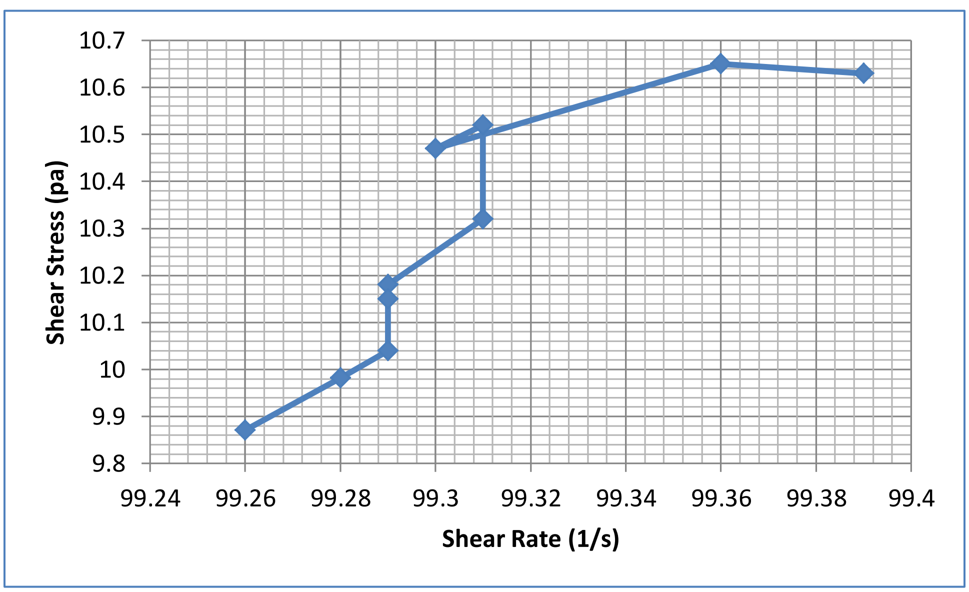

Figure 9. Shear Rate versus Shear Stress for Baby Oil.

Conclusions

Three different test methods were carried out in this study to quantify viscosity relationships of fluids. A Saybolt universal viscometer was utilized to quantify the relationship between temperature and efflux rate of baby oil. The efflux rate decreased with increasing temperature indicating that the viscosity of the liquid was decreasing. This was expected as the viscosity of all liquids decreases with increasing temperature. The kinematic viscosity was calculated through the use of a Cannon-Fenske capillary instrument for diesel, biodiesel, and jet fuel. The kinematic viscosities were determined to be 7.98 cSt, 4.00 cSt, and 9.58 cSt respectively at 24 °C. The values are comparable to typical values of already logged data, but may have encountered some error. A Bohlin viscometer was utilized to quantify shear viscosity along with additional properties of a variety of substances. These substances consisted of baby oil, glycerin, ketchup, yogurt, and shampoo. The shear viscosity of the shampoo was dependent on the shear rate and was classified as a non-Newtonian liquid. It could also be seen that as the shear rate increased, the viscosity decreased which would further classify it as a shear thinning liquid. Ketchup and yogurt were harder to classify due to varying data. The shear rate and shear stress were not proportional which would indicate non-Newtonian liquids, because the plot was not linear. A graph was constructed for glycerin in a similar matter. The shear stress and shear rate were proportional which displayed a linear relationship. From this, glycerin was able to be classified as a Newtonian liquid. One more graph for baby oil was constructed again in a similar matter. It was shown that the baby oil was not linear and could be classified as a non-Newtonian liquid. The plot of shear rate versus shear stress also exhibited an increasing exponential trend which could further classify the liquid as a shear thickening liquid. Viscosity is an important parameter in terms of fuel economy and fuel performance, and must be monitored to ensure that thermal efficiency is maximized. Therefore, a variety of substances were quantified and qualified in this study to exhibit viscosity trends and relationships. The most important relationship deals with viscosity's dependence on temperature. Through these quantifications, process and design engineers can further enhance and optimize chemical processes and operations.

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