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ii. Summary

The main objective of this experiment is to determine the dynamic viscosity of engine oil through obtaining the terminal velocity of falling small spheres submerged in the oil. Furthermore, other properties such as the sphere's diameter, weight, and its density as well the oil's density and specific gravity were measured to directly apply our derived equation for dynamic viscosity. Specifically, this experiment was conducted by initially measuring the specific gravity of the fluid via a hydrometer inside a graduated cylinder. Moreover, after weighting and measuring dimensions of the small spheres, they were placed inside the oil and timed at a certain distance range to extract values for their respective terminal velocities. However, when validating our results to known engine oil fluid properties, specifically SAE 30, some discrepancies were found mainly due to possible timing errors made during the experiment as well as possible temperature differences. Although, we were able to validate Reynold's number being less than 1 for most but not all trial runs which indicated that our dynamic viscosities mostly validated Stokes' law. Additionally, despite the discrepancies, we were still able to conclude that the relative accuracy of our measured dynamic viscosities, compared to known engine oil properties, decreased as Reynold's number approached to 1.

1. Introduction

In this experiment, the dynamic viscosity of engine oil is measured using the falling sphere method. Three spheres of different diameters were dropped into a container filled with oil, and their diameters and masses were recorded. The time taken for each sphere to travel a distance of 20 cm, after reaching terminal velocity, was measured. When the sphere reached terminal velocity, its acceleration ceased, meaning that the forces acting on it were in equilibrium. These forces included the drag force (F_D), the buoyancy force (F_B), and the sphere's weight due to gravity (W_S). Together, they satisfied the equation:

$$F_D + F_B - W_S = 0 \tag{1}$$

As the sphere moved downward through the fluid, an upward drag force resisted its motion. According to Stokes' Law, this drag force is directly proportional to the dynamic viscosity (μ) of the fluid, the radius of the sphere (r), and the terminal velocity (U) of the sphere [1]. The equation for drag force is:

$$F_D = 6\pi\mu rU$$

By expressing the radius as half of the sphere's diameter (D), the formula simplifies to:

$$F_D = 6\pi\mu\frac{D}{2}U$$

$$F_D = 3\pi\mu DU \tag{2}$$

When the sphere is submerged in a fluid, a buoyant force equal to the weight of the liquid displaced acted in opposition to the object, as stated by the Archimedes' Principle [1]. The buoyant force (F_B) was the product of the fluid's density (ρ_f), the volume of the displaced fluid (V), and the acceleration due to gravity (g). The volume of a sphere was derived using its diameter (D), and the expression for the buoyant force was formulated as follows:

$$F_B = \rho_f gV \quad \text{and} \quad V = \frac{\pi D^3}{6}$$

Thus, the buoyant force became:

$$F_B = \rho_f g \frac{\pi D^3}{6} \tag{3}$$

The weight of the sphere (W_s) was defined as the product of its mass and the acceleration due to gravity. By replacing the mass with the sphere's density (ρ_s) multiplied by its volume (V), the equation was reformulated as:

$$W_s = \rho_s \frac{\pi D^3}{6} g \tag{4}$$

By consolidating all these equations, an expression for dynamic viscosity was derived:

$$\mu = \frac{D^2 g(\rho_s - \rho_f)}{18U} \tag{5}$$

This equation was only valid for slow motion. To validate the calculated value of dynamic viscosity, the Reynolds number was used, which was obtained by multiplying the fluid's density, the terminal velocity, and the diameter of the sphere, then dividing the product by the dynamic viscosity. If the Reynolds number is less than 1, it indicated that the calculated dynamic viscosity was accurate.

$$\frac{\rho_f UD}{\mu} < 1 \tag{6}$$

2. Apparatus

- Tall graduated cylinder with measurement scale
- Quaker State gear oil
- Stopwatch (steady velocity)
- Micrometer (diameter of sphere)
- Hydrometer (specific gravity)
- Weight Scale (mass of spheres)
- Small tray
- 1 small nylon sphere
- 1 medium nylon sphere
- 2 large nylon spheres

3. Procedure

1. The hydrometer was placed in a tall graduated cylinder filled with Quaker State gear oil, ensuring it floated freely for an accurate specific gravity reading. The specific gravity was recorded.
2. The room temperature where the oil-filled graduated cylinder was located was measured using a thermometer and this temperature was recorded.
3. A weight scale was tared to eliminate the weight of the tray.
4. The small, medium and two large nylon spheres were weighed, and their mass, including uncertainty, was recorded.
5. A micrometer was used to measure the diameter of the small, medium and two large nylon spheres, with the value and uncertainty recorded.
6. The small nylon sphere was held at the center of the graduated cylinder filled with oil and released without applying any external force. The time taken for the sphere to fall between the 10 cm and 30 cm marks was recorded using a stopwatch. The same process was repeated for one medium sphere and two large spheres.

4. Results and Calculations

Table 1: Data collected in the lab regarding the diameter of each sphere, the mass of each sphere, and velocity of each sphere as it travelled down the oil.

Sphere Size	Diameter (mm)	Mass (g)	Velocity (m/s)
Small	6.21	0.150	1.381×10^{-2}
Medium	9.37	0.500	2.614×10^{-2}
Large 1	12.65	1.226	4.405×10^{-2}
Large 2	12.60	1.226	4.750×10^{-2}

Table 2: Recordings of the calculations for the dynamic viscosity, slow criterion magnitude, and if the slow flow criterion was met for each sphere. Sample calculations for the dynamic viscosity and Reynolds number can be found in **Appendix C** and **Appendix D** respectively.

Sphere Size	Dynamic Viscosity (kg/m·s)	Reynolds Number	Slow Flow Criterion Met (Yes/No)
Small	0.460	0.167	Yes
Medium	0.488	0.449	Yes
Large 1	0.520	0.956	Yes
Large 2	0.504	1.062	No

Appendix A indicates that SAE 30 oil, commonly used as engine oil, has a dynamic viscosity of $3.8 \times 10^{-1}\ kg/(m \cdot s)$ at $15.6°C$. To ensure the accurate comparison between the known dynamic viscosity of engine oil and experimentally obtained values, the variation of viscosity with temperature must be taken into consideration. The experiment was conducted in $22°C$ environment. The dynamic viscosity SAE 30 oil at $22°C$ is determined to be $2.17 \times 10^{-1}\ kg/(m \cdot s)$ through the use of linear interpolation of industry values in **Appendix E**.

Table 3: Comparison of experimentally derived dynamic viscosity values of engine oil with the known dynamic viscosity for SAE 30 oil at 15.6℃ and 22℃ to take the variation of viscosity with temperature into consideration.

Sphere Size	Experimental Dynamic Viscosity (kg/m·s)	Percent Error in reference to known Dynamic Velocity at 15.6℃	Percent Error in reference to known Dynamic Velocity at 22℃
Small	0.460	21.1%	112%
Medium	0.488	28.4%	124%
Large 1	0.520	36.8%	140%
Large 2	0.504	32.6%	132%

5. Discussion

Through the calculations shown in **Appendix C**, the dynamic viscosity of the engine oil with the small, medium, and large spheres was calculated and recorded in **Table 3**. Despite minor deviations, the dynamic viscosity values for the different spheres revolved around a consistent value. This is expected as Newtonian fluids, like engine oil, exhibit a constant dynamic viscosity regardless of the shear rate being applied [1]. The deviations in these values can be attributed to sources of error within the data collection process, such as timing the movement of the spheres through the oil, measuring the mass and diameter of the spheres, and reading the specific gravity of the oil from the hydrometer.

Taking the deviations in the dynamic viscosity values for the different spheres into account, it's apparent that the small sphere gave the most accurate result in relation to the known value of the oil. As stated in **Table 3**, this size resulted in the smallest percent error, 21.1% at 15.6℃ and 142% at 22℃, with respect to the other sizes. The small sphere yielded the smallest Reynolds number, which led to the most accurate dynamic viscosity from Equation (6). The "slow flow" criterion being met with the smallest Reynolds number also resulted in the small sphere's flow pattern closely resembling "Stokes flow."

In comparison with the property table in **Appendix A**, the dynamic viscosity of the small sphere resembles that of SAE 30 oil. The experimental viscosity, $4.60 \times 10^{-1} kg/(m{\cdot}s)$, differs from the tabular value of SAE 30 oil at 15.6℃ , $3.8 \times 10^{-1}\ kg/(m{\cdot}s)$ by approximately 21.1%. However, an accurate comparison would include the room temperature variation in the experiment. At 22℃, the dynamic viscosity of SAE 30 oil was determined using linear interpolation with industry values in **Appendix E**. With the calculated viscosity of $2.17 \times 10^{-1}\ kg/(m{\cdot}s)$, the experimental value differs by approximately 112%. The differences observed in these comparisons can be attributed to sources of error during the experiment, such as timing the velocity of the sphere and reading the oil's specific gravity from the hydrometer. The differences in the associated densities of the industry viscosity values used for linear interpolation and the measured density of the oil could also be a contributing factor.

6. Conclusion

The purpose of this experiment was to determine the dynamic viscosity of engine oil by observing the movement of different sized spheres through the oil. Small, medium, and large spheres were dropped into the oil, with data collected on their diameter and terminal velocity in the oil. Using the derived Equation (6), the dynamic viscosity of the oil was calculated and it was assumed to be SAE 30 oil. The smallest sphere yielded a viscosity of $4.60 \times 10^{-1} kg/(m \cdot s)$, which was most accurate with a percent error of 21.1% in relation to SAE 30 oil at 15.6℃ and 112% in relation to SAE 30 oil at 22℃. The range of viscosity values from the other spheres in **Table 2** indicate that Equation (6) and "Stokes flow" are most accurate with a low Reynolds number. The discrepancies between the experimental and tabular/industry values of the viscosity may be due to measurement errors. Despite these differences, the experiment successfully explored the viscous property of engine oil through the motion of spheres at different shear rates.

7. References

[1] Young, D. F., Munson, B. R., Okiishi, T. H., & Huebsch, W. W. (2011). *A brief introduction to fluid mechanics* (5th ed.). Wiley.

[2] *Viscosity of engine oil – viscosity table and viscosity chart: Anton Paar Wiki*. Anton Paar. (n.d.). https://wiki.anton-paar.com/ca-en/engine-oil/

8. Appendix

TABLE 1.5
Approximate Physical Properties of Some Common Liquids (SI Units)

Liquid	Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight, γ (kN/m^3)	Dynamic Viscosity, μ ($N \cdot s/m^2$)	Kinematic Viscosity, ν (m^2/s)	Surface Tension,[a] σ (N/m)	Vapor Pressure, p_v [N/m^2 (abs)]	Bulk Modulus,[b] E_v (N/m^2)
Carbon tetrachloride	20	1,590	15.6	9.58 E − 4	6.03 E − 7	2.69 E − 2	1.3 E + 4	1.31 E + 9
Ethyl alcohol	20	789	7.74	1.19 E − 3	1.51 E − 6	2.28 E − 2	5.9 E + 3	1.06 E + 9
Gasoline[c]	15.6	680	6.67	3.1 E − 4	4.6 E − 7	2.2 E − 2	5.5 E + 4	1.3 E + 9
Glycerin	20	1,260	12.4	1.50 E + 0	1.19 E − 3	6.33 E − 2	1.4 E − 2	4.52 E + 9
Mercury	20	13,600	133	1.57 E − 3	1.15 E − 7	4.66 E − 1	1.6 E − 1	2.85 E + 10
SAE 30 oil[c]	15.6	912	8.95	3.8 E − 1	4.2 E − 4	3.6 E − 2	—	1.5 E + 9
Seawater	15.6	1,030	10.1	1.20 E − 3	1.17 E − 6	7.34 E − 2	1.77 E + 3	2.34 E + 9
Water	15.6	999	9.80	1.12 E − 3	1.12 E − 6	7.34 E − 2	1.77 E + 3	2.15 E + 9

[a] In contact with air.
[b] Isentropic bulk modulus calculated from speed of sound.
[c] Typical values. Properties of petroleum products vary.

Appendix A: Approximate physical properties of some common liquids in SI units.

SAE 30

Temp. [°C]	Dyn. Viscosity [mPa.s]	Kin. Viscosity [mm²/s]	Density [g/cm³]
0	1124.10	1257.25	0.8941
10	491.10	553.20	0.8878
20	239.39	271.56	0.8815
30	128.42	146.70	0.8754
40	74.55	85.76	0.8693
50	46.43	53.80	0.8630
60	30.58	35.69	0.8569
70	21.17	24.89	0.8506
80	15.28	18.10	0.8444
90	11.42	13.62	0.8383

Appendix B: Dynamic viscosities of SAE 30 engine oil at varying temperatures [2].

In order to calculate the dynamic viscosity using the data recorded from the lab, the volume of the sphere must be found first. Then the density of the sphere must be calculated next. Finally, the dynamic viscosity can be calculated.

$$V_{sphere} = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3$$

$$V_{small\ sphere} = \frac{4}{3}\pi\left(\frac{6.21\times10^{-3}}{2}\right)^3$$

$$V_{small\ sphere} = 1.25 \times 10^{-7} m^3$$

$$\rho = \frac{m}{V}$$

$$\rho_{small\ sphere} = \frac{0.15\times10^{-3}}{1.25\times10^{-7}}$$

$$\rho_{small\ sphere} = 1196.24 \frac{kg}{m^3}$$

$$\mu = \frac{D^2 g(\rho_s - \rho_f)}{18U}$$

$$\mu_{small\ sphere} = \frac{(6.21\times10^{-3})^2(9.81)(1196.24-894)}{18(0.01381)}$$

$$\mu_{small\ sphere} = 0.460 \frac{kg}{m\cdot s}$$

Appendix C: Sample calculation of the dynamic viscosity of the small sphere using the data recorded in the lab from **Table 1**.

$$Reynolds\ Number = \frac{\rho_f\ UD}{\mu}$$

$$Reynolds\ Number_{small\ sphere} = \frac{(894)(0.01381)(6.21\times10^{-3})}{0.460}$$

$$Reynolds\ Number_{small\ sphere} = 0.167 < 1$$

Appendix D: Sample calculation of Reynolds number for the small sphere.

$$y = y_1 + \frac{y_2 - y_1}{x_2 - x_1}(x - x_1)$$

$$y = 239.39 + \frac{128.42 - 239.39}{30 - 20}(22 - 20)$$

$$y = 217.196\, mPa \cdot s = 0.217\, kg/m \cdot s$$

Appendix E: Sample calculations for linear interpolation to find dynamic viscosity of SAE 30 Oil at $22°C$ using property values at $20°C$ and $30°C$.

$$\delta = \frac{\mu_E - \mu_T}{\mu_T} \times 100\%$$

$$\delta = \frac{0.460 - 0.380}{0.380} \times 100\% = 21.1\%$$

Appendix F: Sample calculations for the percent error of the experimental dynamic viscosity of engine oil from the small sphere compared to the known value of dynamic viscosity for SAE 30 oil at 15.6°C.