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Article

Calculating the dynamic viscosity of a fluid using image processing of a falling ball

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SUMMARY

Dynamic viscosity is a fundamental property of fluids that measures their resistance to flow under applied forces or shear stress. This study aims to calculate the dynamic viscosity of pure glycerol at different temperatures, using the falling ball approach. In this method, a ball was released in a tube filled with glycerol, and its movements were then tracked and analyzed using image processing with a Python program. We then determined the viscosity and compared it with the actual viscosity of the liquid. We hypothesized that this method would yield overall accurate measurements when compared to established reference methods but that there would also be a rise in inaccuracies with the increase in temperature. Our results support our hypothesis and were accurate to within 6.9% error but found no correlation between rise in temperature and measurement errors. We concluded that this approach requires more specialized equipment to investigate low viscosity fluids. Despite this study's limitations, it provided valuable insights into the applicability of the falling ball method and emphasizes the accuracy of this method.

INTRODUCTION

Viscosity (η or μ) is a fundamental property of fluids that describes their resistance to flow. Fluids with low viscosities, like water (1.002 mPa-s at 20°C), flow more freely with minimal resistance, while fluids with high viscosities, like honey (1000 - 4000 mPa s at 20°C), resist flowing easily and exhibit thickness (1, 2).

Viscosity plays an important role in many fields, including lubrication to reduce friction in machinery, affects the coverage and drying characteristics of paints, facilitates the transportation of crude oil through pipelines, plays a role in food processing and pharmaceuticals as a factor of quality control, and is crucial in medical applications like blood flow, where it determines the blood's 'thickness' and resistance to flow (3-5). As a result, many techniques and methods to calculate viscosity have been developed. Various viscometers exist, such as capillary viscometers which are used to measure Newtonian fluids' viscosity in high accuracy, rotational viscometers which can be found in many industries to measure non-Newtonian fluids' viscosity in high accuracy, the vibrating viscometers, which are used for continuous monitoring of fluids' viscosity in industrial settings, and many others (6).

The falling ball viscometer is one common method to calculate viscosity. It is mostly used for quick viscosity estimations in Newtonian fluids. By measuring the constant velocity of a small ball in a liquid, it estimates the viscosity of that fluid using Stoke's Law which states that the drag force on a small sphere moving slowly through a viscous fluid is proportional to the sphere's radius, the fluid's viscosity, and the sphere's velocity (7). It is easy to use and requires inexpensive equipment with no heavy machinery needed. However, this simplicity can lead to inconsistent accuracies.

This study aims to test the accuracy of the falling ball method when using pure glycerol at a range of temperatures. We then compared our results to established values. The experiment analyzed how a fluid's viscosity affects a ball's velocity as it falls in the fluid. When the ball falls, three forces are applied to it: gravitational force, buoyant force, and drag force **(Figure 1)**. The ball accelerates as the net force on it is dominated by the gravitational force, increasing its velocity. Increasing velocity increases the drag force, which is the resistance force that the liquid exerts on the ball, subsequently decreasing the net force on the ball. This cycle continues until the net force reaches zero, at which point the velocity reaches a constant value known as the terminal velocity (7). Time measurements are taken for every known distance (or vice versa) to compute velocities and ascertain viscosity through the influence of drag force. The measurements are then converted into meters according to scale, and finally, viscosity is derived through the net force equation with the input of terminal velocity.

A prior study on the falling ball viscometer method created an algorithm to calculate the terminal velocity using image-processed footage of the experiment (8). In our study, we attempted to replicate their experiment, but instead of testing this method in different transparent liquids, we will test it with highly pure glycerol (99.6%) at different temperatures. With the rise of temperature, viscosity decreases, making the drag force less apparent and harder to measure. We hypothesized that this method would yield overall accurate measurements when compared to established reference methods but that there would also be a rise in inaccuracies with the increase in temperature. Our results displayed high accuracy, proving this method to be effective. However, there was no correlation between rise in temperature and measurement errors as we originally hypothesized.

RESULTS

Marbles with the same mass of 5.4g and a diameter of 16.5mm were dropped into cylindrical beakers filled with highly pure glycerol (99.6%) at different temperatures (10°C, 20°C, or 35°C) for a total of three trials at each temperature. We positioned a camera across the table to allow for video

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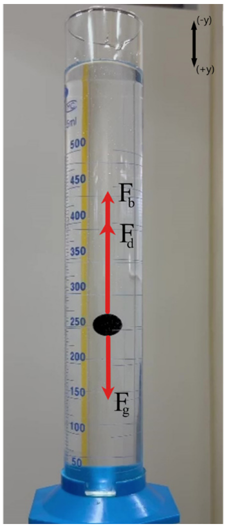

Figure 1: Illustration of the falling ball method with exerted forces. The image depicts a marble falling in a cylindrical beaker filled with glycerol. Arrows indicate the directions of the forces acting on the marble: gravitational force F_g pulls the marble downward, while drag force F_d and buoyant force F_b push it upwards. This frame is extracted from the experimental footage, showing the marble's motion and the forces at play.

tracking the marbles. The footage was then processed using the object tracking program in Python to calculate the distance the marbles fell every 10 frames. The velocity was derived from this, and the acceleration was determined to be near zero when the terminal velocity is reached, which is also determined after no further increase in velocity is observed.

When tested, the tracking displayed an increase in velocity at a decreasing rate across all temperatures. The marble reached terminal velocity at higher temperature conditions, such as 35°C, and later than those at lower temperatures, such as 20°C and 10°C **(Figure 2)**. This is due to the inverse relation between the drag force (viscosity) and temperature. With the terminal velocity values measured, we used the equation for viscosity and input the known parameters, the diameter of the marble, *D*, the density of the marble, *ρs*, the density of the fluid, *ρf*, the velocity of the terminal velocity of the marble, *v*, and the acceleration due to gravity, *g*, to get the viscosity value for each trial **(Equation 5 in methods)**. For example, the viscosity of the glycerol at 10°C can be calculated by entering the measured terminal velocity of 0.0426m/s to get a result of 3.6 Pa·s. The corresponding measured terminal velocity values of one of the trials in 20°C and 35°C were 0.103 and 0.4108m/s respectively, from which we calculated viscosities of 1.5 and 0.38 Pa·s, respectively.

The same calculations were conducted in a total of three trials for each temperature and compared to viscosity references, all exhibited an average approximation error of around 5% **(Table 1)**. In many scientific and engineering applications, an error of this magnitude is considered relatively small, indicating that our results closely match the reference values and that our model or measurements are accurate. From the 10°C trials, the estimated viscosity value of 3.6 Pa·s had 4.9% error compared to the accepted value of 3.787 Pa·s (9). From our 20°C trials, the estimated viscosity value of 1.5 Pa·s had 6.9% error compared to the accepted value of 1.403 Pa·s (9). From our 35°C trials, the estimated viscosity value of 0.38 Pa·s had 5.8% error compared to the accepted value of 0.4032 Pa·s (9).

DISCUSSION

In this study, we used a falling ball viscometer alongside image tracking to measure the viscosity of glycerol at three different temperatures. Our results provide support for our initial hypothesis that this method would yield accurate measurements, as evidenced by our small percent errors observed across all trials, yielding similar results to established references (9). However, unexpectedly there was no correlation between the error rate and the rise in temperature as we hypothesized, with 20°C showing the highest percentage error of 6.9%, followed by 35°C at 5.8%, and 10°C at 4.9%. This suggests that this method can measure across possible ranges of temperatures without a corresponding change in accuracy.

Although approximation errors around 5% may be unfavorable by some industrial standards, one possible explanation for them could be temperature errors. The viscosity of glycerol is highly temperature-sensitive to the extent that a 1°C variation can substantially affect the viscosity value. When we compared the estimated viscosities to actual viscosities with 1°C variations, we found that all estimated viscosities fell within these ranges **(Table 1)**. With this, we can say that the falling ball method provided accurate results for viscosity, but temperature measurements were not as precise for determining the right reference viscosity values.

It is important to acknowledge the limitations of our falling ball method. Although this study showed no correlation between the decrees of viscosity value due to rise of temperature and the accuracy of the measurements, it did not test low-viscosity fluids, such as water and oil, due to the limited resolution and frames per second (fps) of our camera. Low viscosity fluids allow rapid acceleration due to a reduced drag force, which can make it difficult to track high velocity falling objects over short time intervals. Furthermore, liquids with low viscosity need more time to exert perceptible changes on the object's movement, necessitating longer tubes than we had for this study. Future studies aiming to investigate low-viscosity liquids using the falling ball method should utilize high-quality cameras and tubes with sufficient length to

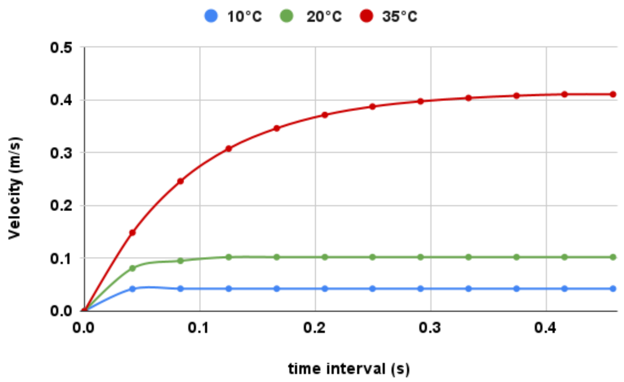

Figure 2: Velocity versus time for a ball falling in glycerol at different temperatures. This graph shows the velocity of a marble falling through glycerol at three different temperatures. Each line represents the velocity measured during a trial at the corresponding temperature: 35°C (red), 20°C (green), and 10°C (blue). The velocities were calculated through image processing using a python program.

		Terminal Velocity (m/s)	Estimated Viscosity (Pa·s)	Actual Viscosity	Percentage Error	Actual Viscosity (Pa·s) with 1°C variation	Mean for Set of Trials (Pa·s)	Standard deviation for Set of Trials (Pa·s)
10°C	Trial 1	0.0426	3.6	3.787	4.90%	3.407 – 4.218	~3.6	~0
	Trial 2	0.0422	3.6		4.90%			
	Trail 3	0.0425	3.6		4.90%			
20°C	Trial 1	0.103	1.5	1.403	-6.90%	1.281 – 1.541	~1.5	~0
	Trial 2	0.104	1.5		-6.90%			
	Trial 3	0.103	1.5		-6.90%			
35°C	Trial 1	0.4132	0.38	0.4032	5.80%	0.3744 – 0.4349	~0.377	~0.0000224
	Trial 2	0.4159	0.37		5.80%			
	Trial 3	0.4132	0.38		5.80%			

Table 1: Data showing terminal velocity (m/s), estimated viscosity (Pa·s), actual viscosity (Pa·s), the percent error between the estimated viscosity and the actual viscosity for each trial, ranges of actual viscosity values from 1°C below to 1°C above the target temperature of each set of trials, the mean for each set of trials, and the standard deviation for each set of trials (9).

facilitate accurate results. An alternative approach taken in another study bypasses these challenges by conducting the experiment within a tilted tube set at a known degree (7). While this can lead to more complex calculations, the introduction of a tilt force on the falling object can slow it down, making the viscosity measurements more manageable. When compared to our approach, this can provide even more accurate measurements for liquids like glycerol and especially liquids with low viscosity like water.

In conclusion, our study demonstrated the falling ball method is a straightforward and effective way to calculate viscosity, as the equipment required for it is both inexpensive and widely available, developing an algorithm is a simple process, and the observed viscosity results had low inaccuracies. Future investigations may address the limitations we outlined herein such as errors due to temperature variations and limited equipment by employing more advanced equipment and methodologies.

METHODS

Deriving the viscosity equation

To derive the viscosity from the change in velocity we must be familiar with the three forces that act upon the sphere in the liquids, which are the gravitational force of the sphere, the buoyancy force, and the drag force. The buoyant force and the drag force oppose the gravitational force, as seen in Equation 1.

$$F_{net} = F_g - F_b - F_d \qquad \textbf{(Equation 1)}$$

When expanding the equation, we used Stokes' law, which relates the drag force on a spherical object in a fluid with laminar flow to the viscosity of the fluid. Here, *r* is the radius of the sphere, *v* is its velocity, and *η* is the viscosity of the fluid.

$$ma_{net} = mg - \rho_f V g - 6\pi r v \eta \qquad \textbf{(Equation 2)}$$

To solve for viscosity, we first set the net acceleration to 0, as the object has reached terminal velocity. Then we can equate the drag force to the remaining forces.

$$6\pi r v \eta = mg - \rho_f V g \qquad \textbf{(Equation 3)}$$

Now we can isolate the viscosity on one side and then simplify the equation by writing it in terms of density. This requires that we substitute the mass of the sphere (*m*) with $\rho_s V$, where ρs is the density of the sphere and *V* is its volume.

$$\eta = \frac{mg - \rho_f V g}{6\pi r v}$$

(Equation 4)

$$\eta = \frac{V(\rho_s - \rho_f)g}{6\pi r v}$$

Next, we expand the volume and cancel the common factor in numerator and denominator, turning the radius into diameter *D* in the process.

$$\eta = \frac{\frac{4}{3}\pi r^3(\rho_s - \rho_f)g}{6\pi r v}$$

(Equation 5)

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

Finally, we get our viscosity equation, where *ρf* is the density of the fluid, *ρs* is the density of the sphere, *D* is the diameter of the sphere, *g* is the acceleration due to gravity, and *v* is the terminal velocity.

Calculating the approximation error

To compute the accuracy of the results, we used the below formula for percent error, where *δ* is the percent error, *vA* is the actual value observed, and *vE* is the expected value.

$$\delta = \left|\frac{v_A - v_E}{v_E}\right| \cdot 100\%$$

Python program

The Python program we developed analyses video footage by processing each frame through color enhancement, thresholding for binary image conversion, and applying morphological operations to refine shape detection **(Figure 3A)**. Using contour detection, it outlines objects that meet the size and shape criteria of the marble with green borders **(Figure 3B)**. The program computes centroids for these shapes at each time interval to track their vertical movement, measuring the distance the centroid travels between each 10-frame interval. The program then converts these distances to meters and the time interval to seconds based on the

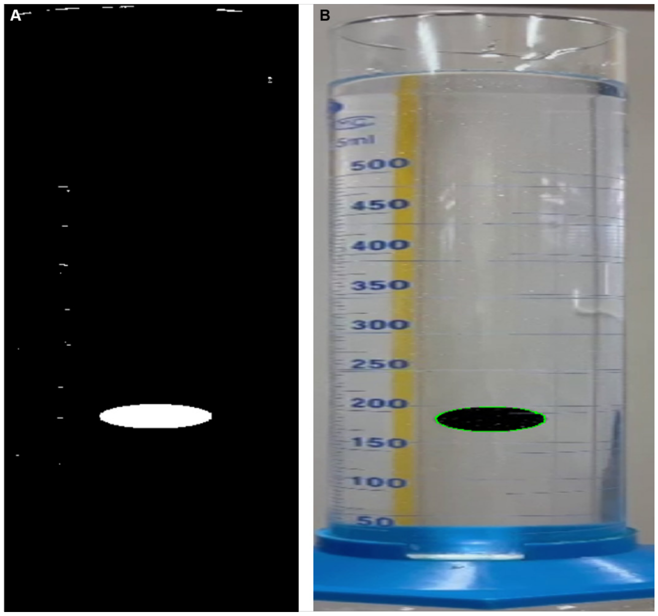

Figure 3: Object detectoion applied via Python image processing techniques. A) Binary image of a single frame from the experiment. The frame is processed using Python image processing techniques. The frame was converted to binary format to analyze the ball's movement in glycerol. B) One frame from the experiment showing object detection. The program uses contour detection to draw a green outline around the ball, highlighting its position within the frame. This visualization demonstrates the tracking of the ball’s movement in the glycerol.

video›s scale, and finally calculates the velocity.

Equipment and measurements

Identical black marbles were measured using a standard digital weighing scale for mass and a vernier caliper for diameter. A 500 ml cylindrical beaker with an internal diameter of 49 mm was first measured in height to establish the pixel scale, which computed to 0.01325 cm/pixel. The beaker was then filled to the top with glycerol at various temperatures. The marbles were finally fully submerged into the glycerol before being dropped to ensure consistency in calculations. An iPad camera with 240 fps and 1080p resolution was used to capture the footage.

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REFERENCES

1. “Dynamic viscosity.” Engineering Edge. engineersedge.com. Accessed July 2023.
2. Santos, Francisco K G et al. “Rheological and some physicochemical characteristics of selected floral honeys from plants of caatinga.” Anais da Academia Brasileira de Ciencias, vol. 86, no. 2, June 2014, pp. 981-94, https://doi.org/10.1590/0001-3765201420130064
3. Niculuta, Marian Ciprian, and Adrian Gabrial Ghiaus. “A Review of the Usage of Highly Viscous Fluids in Industrial Applications.” IOP Conference Series: Earth and Environmental Science, vol. 664, no. 1, May 2021, https://doi.org/10.1088/1755-1315/664/1/012099
4. Igbax, Saanyol Ityokumbul. “Design Fabrication and Testing of a Viscometer for Testing Viscosity of Liquids.” International Journal of Engineering Research & Technology (IJERT), vol. 8, no. 5, May 2019, https://doi.org/10.17577/IJERTV8IS050388
5. Nader, Elie et al. “Blood Rheology: Key Parameters, Impact on Blood Flow, Role in Sickle Cell Disease and Effects of Exercise.” Frontiers in physiology vol. 10, no. 1329. 17 Oct. 2019, https://doi.org/10.3389/fphys.2019.01329
6. Quqazeh, Mohammed et al. “Characteristics and Analysis for Mechanical Instrumentation Used to Measure Fluid Viscosity.” International Journal of Innovative Science and Modern Engineering (IJISME), vol. 4, no. 3, Feb 2016, pp. 1-6, Retrieved from ijisme.org.
7. Tang, Jay X. “Measurements of fluid viscosity using a miniature ball drop device.” Rev. Sci. Instrum., vol. 87, no. 5, 1 May 2016, pp. 054301, https://doi.org/10.1063/1.4948314
8. Ali, Sarah H, et al. “Measure liquid viscosity by tracking falling ball Automatically depending on image processing algorithm.” Journal of Physics: Conference Series, vol. 1294, no. 2 Sept. 2019, article no. 022002, https://doi.org/10.1088/1742-6596/1294/2/022002
9. “Calculate density and viscosity of glycerol/water mixtures.” University of Reading. reading.ac.uk Accessed Nov. 2023.