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A Low-cost Affordable Viscometer Design for Experimental Fluid Viscosity Verification and Drag Coefficient Calculation

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I am a young professional engineer who has graduated from Purdue University in Indianapolis with a masters in Mechanical Engineering. It should also be noted that I also received my B.S. in Mechanical Engineering from there as well. My graduate studies was focused in thermal/fluid sciences and systems/controls. Currently, my interests lie in aerospace applications with an emphasis in space propulsion and satellite design. Although my primary focus is with aerospace applications, I participate in many projects related to controls and heat transfer. Aside from my research, I focus heavily on the advancement of engineering education at the collegiate level. I work on revising and updating laboratory experiments to help improve student understanding of how concepts are applied and utilized. I also spend time writing design optimization MATLAB codes for various applications.

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Michael Golub is the Academic Laboratory Supervisor for the Mechanical Engineering department at IUPUI. He is an associate faculty at the same school, and has taught at several other colleges. He has conducted research related to Arctic Electric Vehicles and 3D printed plastics and metals. He participated and advised several student academic competition teams for several years. His team won 1st place in the 2012 SAE Clean Snowmobile Challenge. He has two masters degrees: one M.S. in Mechanical Engineering and an M.F.A. in Television Production. He also has three B.S. degrees in Liberal Arts, Mechanical Engineering, and Sustainable Energy.

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Dr. Jing Zhang's research interests are broadly centered on understanding the processing-structure-property relationships in advanced ceramics and metals for optimal performance in application, and identifying desirable processing routes for its manufacture. To this end, the research group employs a blend of experimental, theoretical, and numerical approaches, focusing on several areas, including:

1. Processing-Microstructure-Property-Performance Relationships: thermal barrier coating, solid oxide fuel cell, hydrogen transport membrane, lithium-ion battery 2. Physics-based Multi-scale Models: ab initio, molecular dynamics (MD), discrete element models (DEM), finite element models (FEM) 3. Coupled Phenomena: diffusion-thermomechanical properties 4. Additve Manufacturing (AM) or 3D Printing: AM materials characterization, AM process (laser metal powder bed fusion, ceramic slurry extrusion) design and modeling

(http://www.engr.iupui.edu/~jz29/)

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Abstract

Current laboratory equipment used for undergraduate engineering courses can be enriched inexpensively by adding acquisition boards and requiring students to write code to enable to obtain data from these devices. Programming can be completed prior to the lab session, and then the code will be tested. This paper presents one lab experiment developed at Indiana-University Purdue University Indianapolis (IUPUI). The primary objectives of the project were to develop a viscometer apparatus prototype (1) with a significantly lower acquisition cost compared to current model and (2) that enhances students' understanding of viscosity and drag principles. The apparatus is implemented for use in the IUPUI Mechanical and Energy Engineering Department's fluid mechanics laboratory. Current acquisition cost is shown to be expensive and can produce inaccurate data due to the method of testing. Increasing accuracy of the results will allow students to feel more confident in learning the fundamental theory they are being taught. A prototype was developed that met sponsor requirements, engineering requirements and abided by ASTM viscometer measurement standards. The fully built and assembled prototype provides a cost-effective way for students to accurately and precisely determine the viscosity of different oils. Compared to the older model, the newer model showed 30-40% reduction in error. An assessment study is a work in progress to identify the overall impact the redesign and programming add to student learning.

Introduction

The objective of the following project was to develop a replacement viscometer apparatus prototype for IUPUI's ME310 fluid mechanics laboratory. The Mechanical Engineering department had requested the apparatus be completely redesigned. The current apparatus occupied a large amount of space, hindered by experimental inaccuracy due to timing, and had a high acquisition cost. A newly developed prototype would have to take into account the limitations mentioned so that a smaller, cheaper, and more accurate device can be utilized in laboratory. The significance of this project pertains to the practical application within the IUPUI Mechanical Engineering department. Students taking fluid mechanics currently use the apparatus to conduct laboratory experiments. The apparatus provides students with hands-on experience and exposure to fundamental principles and concepts that govern fluid viscosity and drag coefficients. Viscosity is the measurement of a fluids resistance to flow. The drag coefficient is a dimensionless value used to quantify the resistance of an object in a fluid. Several

Figure 1: Current Viscometer Apparatus

applications throughout different industries rely on engineers having the knowledge, understanding, and ability to apply viscosity principles to practical applications. The apparatus provides students with a chance to help develop those skills and understanding. The current apparatus has three cylinders mounted on an elevated platform (Figure 1). Each cylinder contains a different type of oil. To experimentally calculate the viscosity of each oil, students stand on a platform and drop spherical balls of different mass and volume into the oil. The spheres are timed as they pass through a designated region within the cylinder. The time is used to determine the velocity of the sphere. The velocity is the primary variable used to experimentally calculate the viscosity of each oil. After completion of the experiment, students compare the experimentally obtain results with the known theoretical values.

Design Specifications

Based on the wants and needs of the Mechanical Engineering department, a list was narrowed down to five primary requests:

Smaller Apparatus Size - The current apparatus cylinder height is 52" and requires a massive support structure. The new design needs to be compact and fit easily on a lab table.

Lower Acquisitions Cost - The acquisition cost needs to be significantly reduced and be within a range of $250-$700.

Accuracy – There is a need to eliminate experimental error associated with timing of the sphere drop.

Easy Maintenance - Apparatus maintenance needs to be unsophisticated and efficient.

Data Acquisition – The process must be capable of measuring and recording the sphere drop time over the drop interval.

Temperature Control - Viscosity of a fluid is significantly affected by temperature and needs to be considered.

Engineering requirements were created and based according to client requirements, ASTM standards and industry standards. The following table provides the engineering requirements necessary to meet the client requirement.

Table 1: Design Requests and Requirements

Requests	Requirements	Description
Lower Acquisition Cost	Total Apparatus < $500	1/5 of the current apparatus cost
Smaller Apparatus Size	Dry Weight (5kg ~ 7kg)	According to Cylinder Dimensions
	Cylinder Height < 660.6 mm Cylinder Diameter < 63.5 mm	Based off mathematical derivations and calculations for maximum allowable size
Easy Maintenance	5-10mins process to complete oil replacement	Oil replacement and ball bearing removal is most prevalent in

	Ball Bearing Removal < 60sec and separate of oil replacement	maintenance. Reducing the time increases the efficiency and ease
Data Acquisition	Sensor Selection (Accuracy: +/- 0.05)	ASTM Viscosity Measurement Standards
Improve Results Accuracy	Timing Device (Accuracy within +/- 0.07 s)	ASTM Viscosity Measurement Standards
Temperature Control	Temperature Control (Accuracy within +/- 0.02°C)	ASTM Viscosity Measurement Standards

Primary key factors considered when determining the engineering requirements.

I. *Cylinder Height*: Before timing of the sphere begins, it must reach terminal velocity. Knowing the distance required is critical to determining cylinder height. The terminal velocity is obtained when Stokes' force, buoyancy force, and gravitational forces are in equilibrium.

$$mg = \rho_f V g + 6\pi r \mu v$$

Where r is the radius of the sphere ($r = D_s/2$), V is volume of the sphere $\left(V = \frac{4}{3}\pi\left(\frac{D_s}{2}\right)^3\right)$, v is the terminal velocity ($v = U_s$), and m is the mass of the sphere $\left(m = \rho_s V = \rho_s \frac{4}{3}\pi\left(\frac{D_s}{2}\right)^3\right)$. ρ_s is the density of the sphere, ρ_f is the density of the liquid, D_s is the diameter of the sphere, and μ is the dynamic viscosity of the fluid.

Rewriting the equilibrium condition gives the following:

$$\rho_s \frac{4}{3}\pi\left(\frac{D_s}{2}\right)^3 g = \rho_f \frac{4}{3}\pi\left(\frac{D_s}{2}\right)^3 g + 6\pi\mu\frac{D_s}{2}U_s$$

From the equilibrium equation, an expression for terminal velocity can be determined.

$$U_s = \frac{gD_s^2(\rho_s - \rho_f)}{18\mu}$$

Integrating this equation and solving gives the minimum distance required to reach terminal velocity. The following table is the minimum distance need to reach terminal velocity within each oil type:

Table 2: Minimum Required Distance to Reach Terminal Velocity

Oil Type	Distance (m)
Superspin 10 (Low)	0.001232
WR Hydraulic WR68 (Medium)	0.0002
Supro R&O 220 (Heavy)	0.0000059

The distance required to reach terminal velocity is relatively small. The current apparatus dictated the cylinder height be relatively large to reduce the effect of any unforeseen error. With the addition of an electronic sensor a large height requirements are no longer necessary. Therefore, the height of the cylinder can be significantly reduced.

II. *Cylinder Diameter*: The cylinder diameter affects the amount of shear force acting on the sphere and negatively influences the experimental result. Stoke's Theorem is based on an ideal condition that the tube diameter is infinite compared to the sphere diameter. This assumption assumes no shear force interferes with the sphere. However, for this experiment, the assumption is does not hold and shear forces must be considered. To reduce error, the current experiment uses a correction factor to account for the shear forces:

$$V_s = \left(1 + 2.105\frac{D_s}{D_{cylinder}} + 1.95\frac{D_s}{H}\right) * V_m$$

Where $D_{cylinder}$ is the cylinder diameter, H is the cylinder height, and V_m is the measured velocity for sphere drop.

Since the new apparatus has a different diameter and height, the correction factor should be changed. Correction factor:

For light fluid,

$$\beta_1 = \left(1 + 2.4\frac{D_s}{R}\right)\left(1 + 3.3\frac{D_s}{H}\right)$$

For medium and heavy fluid,

$$\beta_2 = \left(1 + 2.4\frac{D_s}{2R}\right)\left(1 + 3.3\frac{D_s}{2H}\right)$$

Here D_s is the diameter of sphere (m), R is the radius of cylinder (m), and H is the distance of two sensors (m).

Since the Reynold's number of the light oil is significantly smaller compared to the other oils, it requires the use of a different correction factor. By using a correction factor in the final design, the tube diameter can be relatively small compared to the current apparatus.

III. *ASTM Standards*: American Standard Test Method (ASTM) guidelines provided the baseline requirement to ensure the newly designed apparatus meets industry standards. These standards ensure the accuracy and the validity of the design. Engineer requirements for the sensor, electronics and material were based on ASTM standards

Design Generation

A major part of the design generation was sensor selection. It was narrowed down to two sensor types: (a) Hall Effect and (b) Infrared. The Hall Effect sensor involved a magnetic sphere as the detector. An experimental test proved the design to be problematic. The magnetic field orientation of the north and south poles (of the sphere) needed to align perpendicular to the sensor (Figure 2).

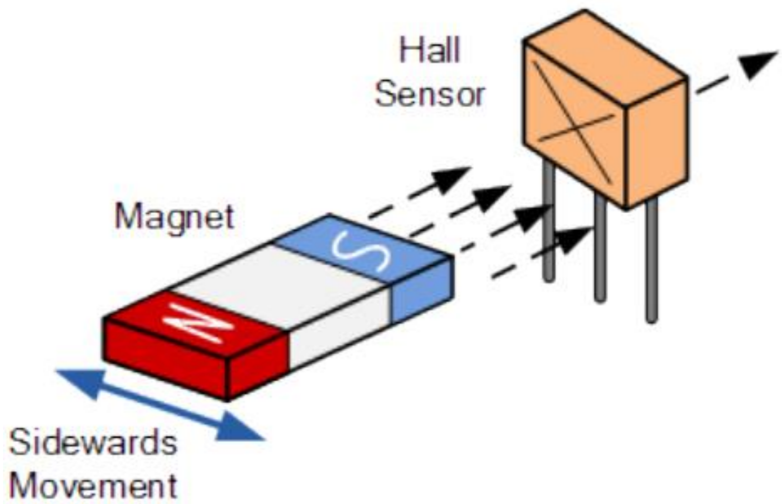

Figure 2: Magnet Sphere Alignment

The magnetic field orientation of sphere constantly changes while falling through the oil. The problem required multiple attempts of the experiment to get the time data. Therefore, the infrared sensor was chosen. Infrared sensors emit and receive infrared radiation (light invisible to the human eye) to detect objects. As the sphere passes between the sensor (emitter and receiver) it alters the amount of light being detected by the receiver. The effect alters the voltage within the sensor and indicates the sphere passed by (Figure 3). The sensor changes improved the overall dependability and reliability of the design.

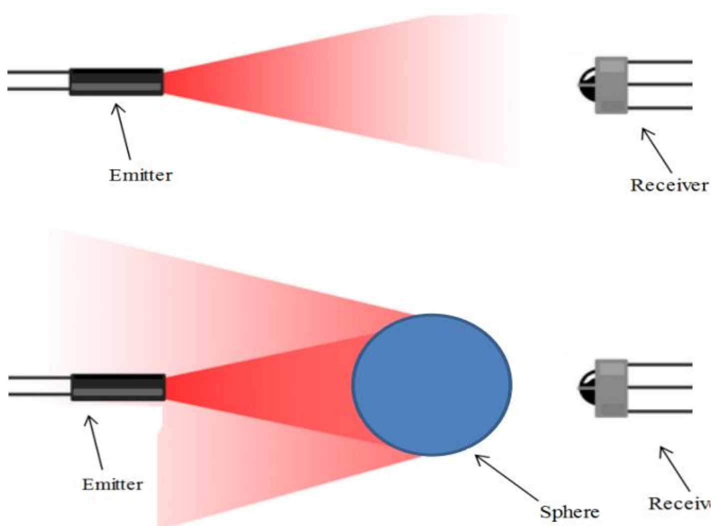

Figure 3: IR Sensor

In the final stages of design development, modification to the material selection and layout were altered to better fit with the IR sensor. The cylindrical rods and connection joints were changed to angle aluminum rods to better accommodate the infrared sensor. A project box was added to contain all the electronics (microcontroller, switches, internal power supply, LCD screen). The CAD model below is the product design model (Figure 4).

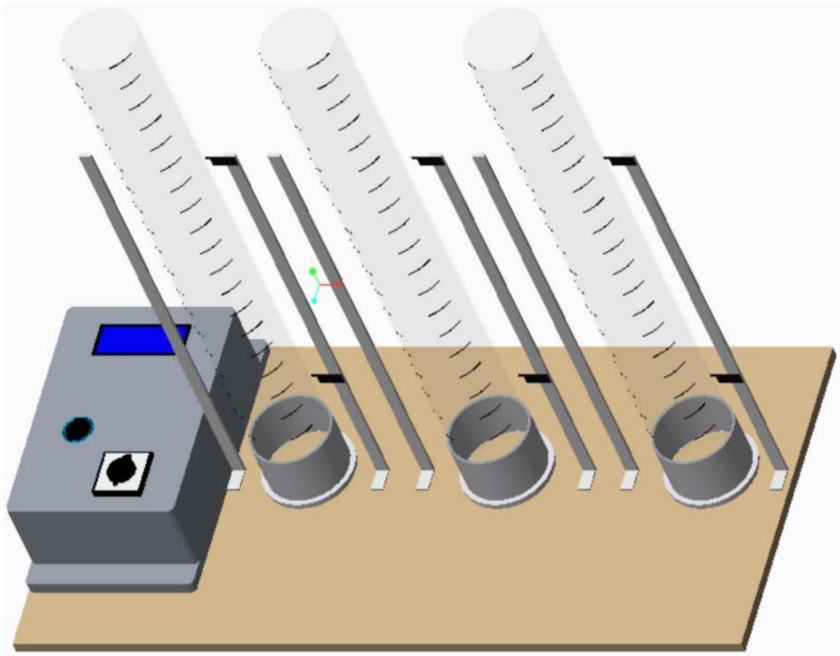

Figure 4: Final Selected CAD Design

Component & Material Selection

The component selection for the design focused on useable off-the-shelf parts. The decision enabled lower acquisition cost and quicker part acquirement. The component parts needed to be acquired in the shortest amount of time possible. The requirements for material selection focused on cost and oil resistance. All selected materials are resistant to oil, excluding the wooden base and electrical components.

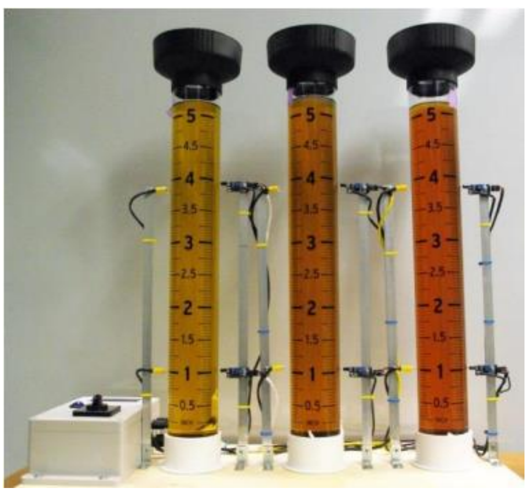

Figure 5: New Viscometer Apparatus

Figure 5 above shows the completed assembly of the final viscometer apparatus. Table below contains the components selected with a brief description and explanation.

Table 3: Component Selection

Component	Description	Explanation
Infrared Sensor	Detects the sphere by emitting and receiving infrared light. The sphere alters the amount of light being detected by the receiver. The effect alters the voltage and enables the microcontroller to record the time	Sensor monitors in real time. Tube and fluid properties do not interfere with detection. Inexpensive cost at $1.00 per sensor.
Microcontroller	Takes input data from the infrared sensors, records the sphere drop time, and sends output time to the LCD Screen	Large aftermarket support community with components and programming language.
LCD Screen	Displays the total time sphere took to pass between the magnetic sensors	Output the time without the need for a computer or software application.
Aluminum Rod	3-ft x 1/2-in Solid Angle Aluminum Rod. Provides support structure and attachment location points for sensors.	Uniform (no bending or warping), corrosion resistant.
Neodymium Sphere	3/4" diameter nickel plated magnetic sphere	Provides quick and easy retrieval of sphere.
Funnel	Custom designed 3D-printed Funnel	Enables sphere drop to be centered within cylinder.
Project Box	Plastic electrical enclosure	Waterproof, protects sensitive electrical components from oil.
Battery Pack	4xAA internal battery pack holder	Provide internal power source eliminating the need for external power cord.

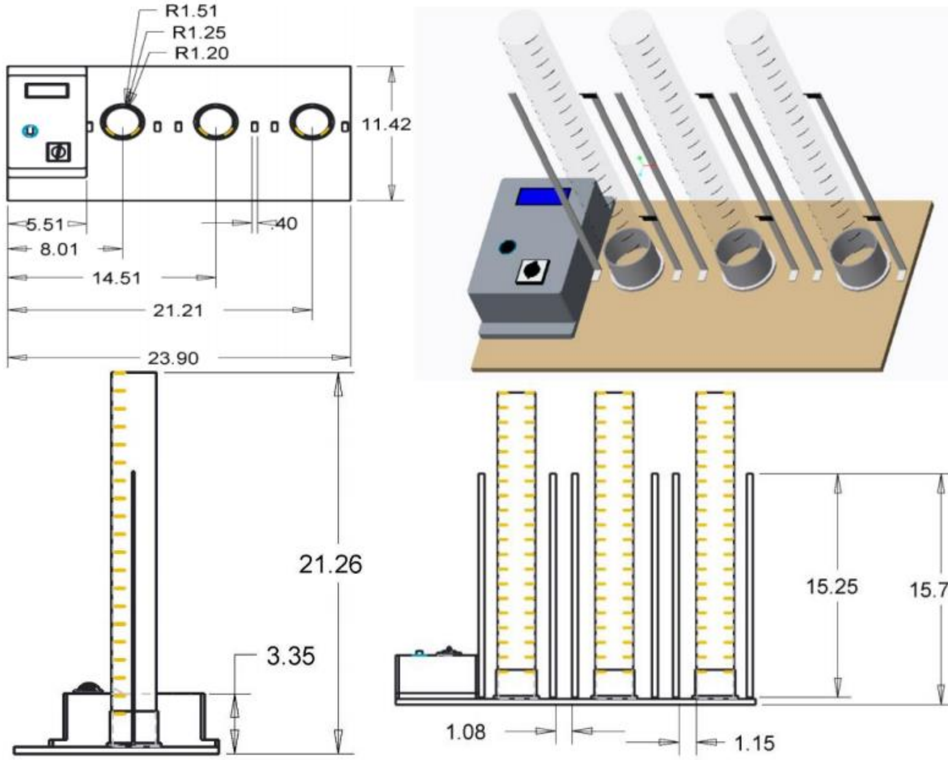

Figure 6: Model Drawings

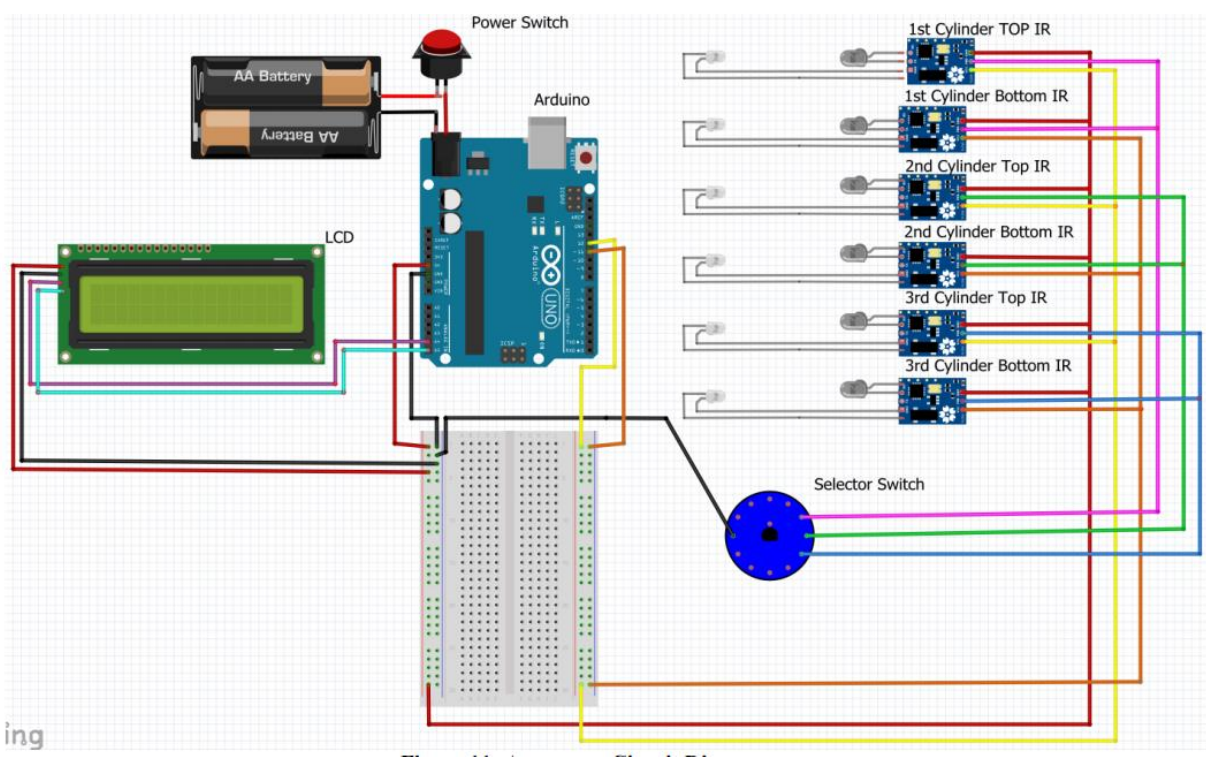

Figure 7: Circuit Diagram

Evaluation & Testing

The newly redesign viscometer apparatus outperformed the old apparatus in every single category. The apparatus size and acquisition cost is substantially smaller compared to the old apparatus (Figure 11). Additionally, the experimental results showed a higher degree of accuracy. Table 5 gives a detailed comparison between the old and new apparatus.

Table 4: New vs Old Comparison

Apparatus		New	Old
Cost		\$230.00	\$2,500.00
Cylinder Size		21"	52"
Results % Error	Light Oil	17.57%	30.10%
	Medium Oil	16.20%	24.20%
	Heavy Oil	27.78%	45.30%

Figure 8: New vs Old Size Comparison

The weight of the new apparatus is relatively light at 8.5lb (3.86kg) dry weight. The compact size and weight of the apparatus makes it extremely portable. The device can be easily stored or moved to different locations. The device maintenance takes an average of 8 minutes to completely change and replace the old oil. Retrieval of the sphere takes less than 15 seconds and is accomplished by using a metal rod to retrieve the magnetic sphere. To validate the accuracy of the new apparatus's ability to record time, a standard deviation comparison was conducted on both the old and the new apparatus.

An experimental test conducted on both new and old apparatuses provided the multiple data points needed to accurately represent the standard deviation. The standard deviation for the older model was shown to be significantly larger compared to the newer model. The large standard deviation of the older model is an indication of the inaccuracy of a student's ability to obtain consistent time data. The small standard deviation demonstrates just how consistent and accurate the new apparatus was at recording the drop time. The addition of the IR sensors eliminated large amounts of error associated with recording the sphere drop time.

The new apparatus needed a correction factor to account for finite extent of the fluid. The influence of the boundaries (cylinder wall) of the container reduces the fall velocity of the spheres due to the production of shear forces. Corrections for the finite extent of the fluid may be made to measure velocity U_m to obtain the free stream terminal velocity U_s in an infinite fluid by modifying the Stoke's equation:

For light fluid,

$$\beta_1 = \left(1 + 2.4\frac{D_s}{R}\right)\left(1 + 3.3\frac{D_s}{H}\right) = 3$$

For medium and heavy fluid,

$$\beta_2 = \left(1 + 2.4\frac{D_s}{2R}\right)\left(1 + 3.3\frac{D_s}{2H}\right) = 1.938$$

Table 5: Resulting Correction Factors

Oil	Light	Medium	Heavy
Modified Factor	3	1.938	1.938

Adding the correction factors increase the results accuracy by accounting for the fluid effects.

Conclusion

In summary, the objective of developing a smaller, affordable, and more accurate viscometer apparatus was successful. Due to the significance of viscosity and helping students understand the governing principles and concepts, it's important the design be reliable, accurate, and assists in the understanding of viscosity. The design is compact, enabling placement on a laboratory tables and in storage cabinets. The built-in electronics and LCD screen output the time without the need for a computer or software application. Component and material selection insured the prototype provides accurate and precise results.

With the completion of the testing apparatus, the plan moving forward is to implement the newer model into the laboratory curriculum and means to assess its effects. This will be accomplished by operating the newer model alongside the older one. Prior to coming to laboratory, students will be take a quick survey on the fundamental principles that pertain to the experiment. Students will then be split up so that half uses one or the other apparatus. After completing the experiment, students will then be assessed through with an exit survey with will contain similar questions as first survey. Additionally, a quick survey on apparatus visuals and functionality will also be taken to compare new and old.

Recommendations

Two primary recommendations for future prototype designs.

I. *Replacement of the Superspin 10 oil*

The Superspin 10 oil generates turbulent effects due to the oils lower viscosity. The effect can cause the sphere to drift within the cylinder. The drift results in the sphere moving closer to the cylinder walls increasing the amount shear force. The drift can also cause inconsistencies with sensor detection. The unpredictability makes account for the turbulent drift effect problematic. The best solution is to replace the Superspin 10 with higher viscous oil. Increasing viscosity reduces the velocity of the sphere and effectively eliminates turbulent flow.

II. *Increase the cylinder diameter*

The final recommendation would be to increase cylinder diameter. Increasing the cylinder diameter reduces the shear force and results in an improvement to the experimental accuracy.

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