An Improved Design for a Viscometer Apparatus

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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

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Abstract

A new viscometer was created to provide a cost-effective way for students to accurately and to precisely determine the viscosity of different fluids. The challenge of designing a viscometer is providing enough distance between tube wall and for vertical tube length. This is because the influence of these two parameters have on the sphere as it falls through the fluid. The cylinder wall affects the fall velocity of the sphere while length is required to reach terminal velocity. Due to the significance of viscosity and helping students understand the governing principle, the design must be reliable, accurate, and assist in the understanding of viscosity. The design is compact enabling placement on a lab table. 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.

Introduction

Effective learning and quality teaching material\tools are two key factors needed for students to develop into independent, practical, and knowledgeable young engineering professionals. One effective way this is accomplished is through small-group learning. Many studies over the years have been analyzed and reviewed in many Science, Technology, Engineering, and Mathematics (STEM) fields on the effects of small-group learning. Small-group learning through either collaboration (unstructured form of small-group learning) or cooperation (structured form of small-group learning) has shown to be more effective over lecture based learning [4]. Another study which made reviewed research in order to quantify the effects of small-group learning showed that other research\reviews suggested that small groups led to positive benefits such as improved attitudes toward learning, higher order of thinking, and increased self-esteem[2]. Small-groups though important is one aspect of effect learning. Active learning is essential as well. This plays a major role in laboratory instruction for STEM students. It is in laboratory that students must validate what they have learned in class. In many ways, it is an opportunity to engage in active learning with the equipment provide to them. In a paper published in PNAS (Proceedings of the National Academy of Sciences). The researchers indicated with their data that active learning increased student performance across STEM fields[3]. Therefore, in order to provide effective learning, the tools used (laboratory equipment) need accurate and precise. Given that most universities tend to have space issues due to most viscometers taking up quite a decent amount of area, it is crucial that lab equipment be small and compact as well as accurate and precise. This also allows for small-groups to be formed for maximum effectiveness.

Switching focus to the issues faced by academic laboratory instructors today. Laboratory instructors today are always looking to upgrade or to replace equipment used to demonstrate fundamental principles taught to students throughout their courses. When assessing new equipment, the instructor must be aware of cost, sizing, and performance. Cost is a definite consideration as it allows for more money to be allocated elsewhere depending on priorities. Sizing becomes an issue as a program size program increases. The performance is critical since many students expect results to match well. These three areas are the driving force behind the decision to improve academic laboratory equipment. As a starting point, the viscometer design was chosen due to its simplicity. The objective is to generate a much smaller, cheaper, and more accurate testing device.

Seeing as to how there is a need to provide better more affordable, effective equipment, this paper uses the pre-existing fluid mechanics laboratory experiment on falling sphere in a fluid as experiment. A further description of a viscometer is provide in next paragraph.

Viscometer apparatuses for determining dynamic viscosities have been around since it was developed in the 1930s. The classic falling-sphere viscometer experiment is quite simple. The experiment consists of relatively long tube containing the fluid of which the dynamic viscosity is going to be measured and determined. A sphere of known mass, m, and diameter, D_s, is selected and dropped down the tube filled with the fluid being analyzed. As the sphere moves down the tube, a designated length interval, H, is selected to record the time it takes for the sphere to pass through it. The selection of the interval is of extreme importance. Selecting to start as soon as the sphere hits the fluid will greatly impact the results as the initial impact on fluid affect the time recorded. Giving enough space between top air-fluid interface (where sphere is dropped) and start of time interval is key to obtaining accurate results. Once enough samples are taken of the same sphere, the average measured velocity can be calculated.

$$U_m = \frac{H}{t_{avg}} \qquad (1)$$

Where t_{avg} is the average time of all samples of the designated length interval.

The measured average velocity however does not represent the terminal velocity. In order to achieve true terminal velocity, a much longer tube and wider tube diameter would be needed as an infinite medium is needed. Considering the tube diameter, D_c, and finite tube length interval, H, Brenner's correlation can be applied as a correction to the measured average velocity[1].

$$U_s = \left(1 + 2.105\frac{D_s}{D_c} + 1.95\frac{D_s}{D_c}\right) U_m \qquad (2)$$

Then, applying Stoke's formulations where the Reynolds Number dictates the formulae to be applied, the dynamic viscosity can be determined.

$$\mu = \frac{g{D_s}^2(\rho_s - \rho_f)}{18U_s} \quad \ldots \quad Re < 1 \qquad (3)$$

$$\mu^2 + \left(\frac{3U_s\rho_f D_s}{16}\right)\mu - \left(\frac{gD_s{}^2(\rho_s - \rho_f)}{18U_s}\right)^2 = 0 \quad \ldots \quad Re > 1 \qquad (4)$$

Additionally, the drag coefficients can be determined in a similar fashion.

$$C_D = \frac{4gD_s(\rho_s - \rho_f)}{3U_s\rho_f} \quad \ldots \quad Re < 1 \qquad (5)$$

$$C_D = \frac{24}{Re}\left(1 + \frac{3}{16}Re\right)^{\frac{1}{2}} \quad \ldots \quad Re > 1 \qquad (6)$$

Traditionally, academic laboratories utilized this method for calculating viscosities of oils. These methods are acceptable for fluid analysis bearing in mind that it applies to many real world applications. Despite this, the added cost of purchasing hydraulic oils, which require daily clean up and ultimate disposal, can be problematic to many universities. Hence, the focus of this improved viscometer design is to test with a common fluid that is essentially free and easy to dispose of. Water. Water is readily available to everyone and can be easily disposed of through sink drain without contacting your local university Environmental, Health, & Safety (EHS) Office. The only drawback is its high sensitivity at lower temperatures. This is further discussed in the next section.

Design

The benchmark comparison to the new viscometer is the current viscometer used by the Mechanical and Energy Engineering Department at IUPUI for several decades. As the department grows and continues to expand, downsizing of equipment for more compact devices with equal or more functionality is the desire. Figure 1 shows the current viscometer in use for the academic laboratory. Currently, there is only one device for usage in the department. With limited space and laboratory class sizes reaching 30 students, the problem becomes more challenging to solve. Additionally, the cost of another viscometer of equal size is quite expensive as it costs up to $2500.00.

Figure 1: Benchmark Viscometer

Modifications & Improvements

For the new design, the following bill of materials was generated with a total cost just over $200.00. To time the fall of the sphere, a standard video camera from a phone was utilized. The video recorder was placed at a sufficient distance away to capture the height interval. The video can then be upload to the computer where a more accurate playback of the time stamp can be used to capture fall time.

Table 1: New Device BOM

Description	Cost
Load Cell	$50
Load Cell Amplifier	$50
100mm Tube OD plastic Clear	$50
Data logging DVM	$25
Plastic Weld glue	$10
0.5" block 4 in x 4 in	$10
12 Volt power supply	$5
M16 X 1.5 mm 25 mm	$2
Wood Block 2" x 6" lumber	$2
8 Wood Screws	$1
Total	$205

Figure 2: The third attempt in making a Viscometer.

Evaluation & Testing

Four spheres were looked at for the first batch of runs. The relevant information regarding each sphere has been summarized in the table below.

Table 2: Test Sphere Information

	Sphere			
	#1	#2	#3	#4
Diameter (mm)	3.1	2.9	5.4	4.6
Mass (g)	0.04	0.11	0.24	0.44
Material	Aluminum	Steel	Aluminum	Steel
Re	877	1877	2220	4019

Each sphere was dropped 30 times and the time was recorded for each. The average time was taken as the measured time and used to calculate the viscosity. The temperature of the water was recorded to be 40˚F at the base of the viscometer

The results obtained are quite ranged in terms of error. It was shown sphere #1 achieved an error of les than 5% indicating that it followed the theory of the empirical relation presented by Brenner's equation. Sphere #2 showed the second-best results with a little more than 50% error. As for the remaining two spheres #3 and #4, the error exceeded 100%. It is believed that the increased diameter in the sphere of each material caused the increase in the Reynolds number leasing to a large deviation in the prediction. The ratio of the sphere diameter to diameter of the cylinder was a known dependency. However, the initial limit that was set before testing was likely greatly overestimated and thus the wall shear stress affected our results. Below is a table showing associated errors.

Table 3: Error Results (Compared to Theoretical Values)

	Sphere			
	#1	#2	#3	#4
Re	877	1877	2220	4019
Error (%)	4.85	54.57	144.65	152.13

Due to the drop in error as the Reynolds number decreased, the suspicion is that if the sphere tested can be kept below a designated value, the error can be controlled. The next steps will be to test this hypothesis. Additionally, we will look at using common viscous fluids to achieve a $Re < 1$ so that the Stokes Theory can be verified for the equipment.

Conclusion

Improving laboratory experiments, such as one as simple as the viscometer, to allow for smaller group usage per laboratory section leads to more effective learning and better teaching equipment. To do this, equipment needs to become more compact while retaining its accuracy and precision. The apparatus constructed has met the compactness requirement set forth. However, it is the accuracy that still falls short of our expectations. Further testing and theory refinement are needed as some results for a particular sphere configurations met expectation with a viscosity prediction error of less than 5% while others did not by exceeding 100%. Additionally, more testing with other viscous fluids is need to validated Stokes Flow theory ($Re < 1$).

Recommendations

For further recommendations, it is recommended that further trials be conducted to confirm our hypothesis. Currently, aluminum and steel spheres are being tested at varying diameter and mass. This way we get a curve of Reynolds number versus error. It is then that we will be able to recommend the appropriate sizes to be used for the experiment in order to ensure there is no confusion as to the result.

We are also looking to improve accuracy and reduce time through au adding two sensors. One is a time capturing sensor to eliminate any error associated with the recorded phone used or with timing used by stopwatch (classic method of timing). The second sensor is thermocouple addition. The thermocouple addition will allow for accurate temperature measuring of the fluid under measurement. The temperature sensor will provide a better theoretical viscosity value since viscosity is a function of temperature.

References

[1] J. Happel and H. Brenner. *Low Reynolds Number Hydrodynamics.* Martinus Nijhoff Publishers, 1983.

[2] L. Springer, M. Stanne, and S. Donovan. *Effects of Small-Group Learning on Undergraduates in Science, Mathematics, Engineering, and Technology: A Meta-Analysis*. American Educational Research Association. Vol. 69. 1999.

[3] S. Freemana, S. Eddy, M. McDonough, M. Smith, N. Okoroafor, H. Jordta, and M. Wenderotha. Active learning increases student performance in science, engineering, and mathematics. 2014.

[4] S. A. Kalaian, R. M. Kasim. *A Meta-analytic Review of Studies of the Effectiveness of Small-Group Learning Methods on Statistics Achievement.* Journal of Statistics Education. Volume 22, Number 1. 2014.