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Data Acquisition System for a Falling-Sphere Viscometer

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ABSTRACT

A commonly used apparatus in undergraduate physics laboratory environment is the falling sphere viscometer or Stokes viscometer. Currently, the whole process of determining the viscosity of a given liquid has to be done manually by the undergraduates and hence the measuring process is found to be rather laborious. The research work described in this report provides an automated method for obtaining and analyzing data using available electronics and computer software reducing accuracy issues and time duration and, thereby making the measurement process more user-friendly. The modified device consists of two main sections, detection of the sphere and the measurement of time and data transfer. The detection of the sphere is done using the principle of electromagnetic induction using the TDA0161 proximity detector with relevant circuitry and inductor coils. Time measurement is done using the PIC 16F877A microcontroller and data is transferred to the PC via MAX232 IC used for serial communication with a computer. Viscosity of the liquid is found by analyzing the obtained data on the PC using the mathematical software MATLAB. The developed viscometer is found to more appropriate to be used for viscosity measurements of liquids with higher viscosity. The obtained viscosity value of 0.096 $kgm^{-1}s^{-1}$ for SAE40 engine oil is found to be in agreement with the manufacture specified value of 0.094 $kgm^{-1}s^{-1}$within experimental uncertainties.

1. INTRODUCTION

Viscosity is described as the resistance of a fluid to flow, caused by its internal friction. Thus, viscosity in physical terms is a fluid property that relates the shear stress in a fluid to the angular rate of deformation. This provides us an indication of the resistance to shear within a fluid. Viscosity can be expressed in two distinct forms, which are the *dynamic* or *absolute viscosity* and *kinematic viscosity*. Dynamic viscosity is described according to the viscous response of a system to its shear stress. Kinematic viscosity requires knowledge of density of the liquid at a given temperature and pressure.

The measurement of viscosity is important in many areas including industry and academic institutions. Instruments used to measure viscosity are called *viscometer*s. According to Leblanc [1] the basic principle of all viscometers is to provide as simple flow kinematics as possible, in order to determine the shear strain rate accurately, easily, and independent of the fluid type. Thus, the flow should preferably be isometric. The shearing stress is then determined and finally the viscosity is found via a simple relationship. Thus, viscometers are classified, depending on how the flow is initiated or maintained. Viscometers can be broadly classified into seven categories. These are capillary viscometers, orifice viscometers, high temperature high shear rate viscometers, rotational viscometers, falling sphere (ball) viscometers, vibrational viscometers and ultrasonic viscometers.

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Of these, the most common and simplest method of determining the viscosity of an unknown fluid is to use the falling sphere viscometeror better known as the Stokes viscometer (Fig. 1). This type of viscometer is popular among academics and it consists of a cylindrical tube of glass or plastic containing the fluid and a smooth sphere which is allowed to fall under gravity through the viscous fluid.

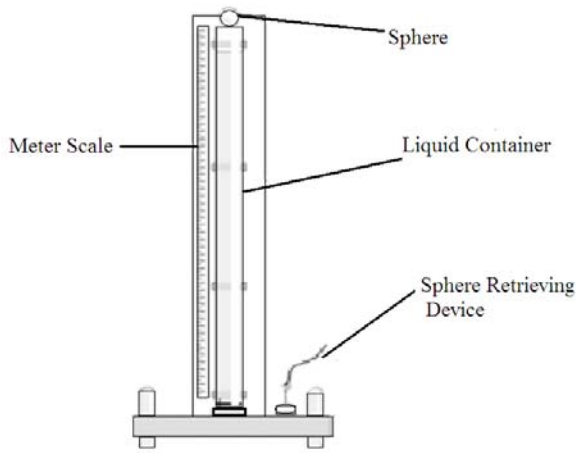

Fig. 1: A falling sphere viscometer available in an undergraduate physics laboratory.

The present method of measuring viscosity of an unknown liquid using the falling sphere viscometer involves manual measurement and calculation of every parameter including the time-of-fall values, thus, reducing the accuracy of the results due to various experimental errors. This report describes how the viscometer could be modified to reduce possible errors involved in time measurements and thereby improve the accuracy of viscosity values obtained from it in physics laboratory environment. With such modifications, the viscometer will certainly be more user-friendly and interesting for undergraduates who use it in one of their laboratory experiments.

1.2 Literature review

Several researches have been carried out to increase the precision of the falling sphereviscometer. These can be classified according to the methods used. For example, in 1982 Flude and Daborn [2] used a laser technique with the *Doppler Effect*. In their work the velocity of sphere is continuously measured as it falls into a cylinder filled with oil.

In 1973 Mcginn et al [3] developed a falling sphere viscometer which utilizes the induction technique though with limited capabilities. In 1988 Tran-Son-Tay et al [4] developed a system of acoustic measurement based on the Doppler effect of an ultrasonic wave returned by the falling particle.
Apart from this,optical methods have also been used for detection purposes. Optical method of sphere detection involves the detection of the sphere using optical sensors or cameras. A computer-interfaced falling ball viscometerdeveloped by J. Wang et al [5] in 1993 uses an optical technique to detect the falling sphere. Arigo et. al. [6] tracked the falling sphere

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using a fixed camera. The high precision falling- sphere viscometer constructed by M. Brizard et al [7] in 2004 also employed a light scanning camera to detect the sphere and to calculate its velocity.A viscometer timer using a low-cost electronic stop watch was constructed by R. J. Gardner and P. C. Senanayake [8]. Although there have been different detection techniques used by different researchers, the measurement of the fall-time of the sphere through the liquid column is the most important aspect of a viscometer.

2. THEORY

The basic law of fluid mechanics that governs the method of measuring viscosity of a fluid is the *Stokes' law* [9]. This law is a mathematical description of the force required to move a sphere through a steady, viscous fluid at a specific velocity. Thus, the Stokes' law is written as $F_d = 6\pi\eta r v$, where F_d is the drag force of the fluid resisting the acceleration due to gravity on a sphere, η is the viscosity of the fluid, v is the velocity of the sphere relative to the fluid and r is the radius of the sphere. Then, once a sphere falling through a column of liquid attains a constant (terminal) velocity, by equating the resultant of the forces due to buoyancy and drag with the force resulting from the gravitational attraction, one can arrive at the relationship

$$\eta = \frac{2r^2(\rho_s - \rho_f)g}{9v_t}, \qquad \text{.. (2.1)}$$

where ρ_s is the density of the material of the sphere, ρ_f is the density of the fluid and v_t is the terminal velocity of the sphere. Equation (2.1) is used to calculate the viscosity of a liquid for an ideal situation and needs to be corrected for practical viscometers as shown by a number of researchers. According to Vishwanath et al [10], the main error in this type of viscometer is due to the so-called *wall effect* which is influence of the wall of the tube of finite diameter on the motion of the sphere. For a sphere falling in a cylinder of finite length, according to Vishwanath, the Faxen expression appears to provide the best results. Faxen showed that the viscosity calculated from the relationship in Equation (2.1) should be corrected as,

$$\eta_t = \eta_m\left[1 - 2.104\frac{r}{R} + 2.09\left(\frac{r}{R}\right)^3 - 0.95\left(\frac{r}{R}\right)^5\right], \qquad \text{........................... (2.2)}$$

where η_m is the calculated value of the viscosity using Equation (2.1), R is the radius of the cylinder and η_t is the corrected ('true') value of the viscosity.

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3. DESIGN AND CONSTRUCTION

3.1 Detection of the sphere

For the work of this research, a viscometer constructed using an acrylic (Perspex) tube with an inner diameter of 7.6 cm, an outer diameter of 8.1 cm and height of 114 cm was used. The sphere detection technique is based on the principle of electromagnetic induction. In this, a variable magnetic field is created by producing a variable current through an inductor coil made of coated copper wire (26 SWG). Thus, the current has to be supplied through an oscillator circuit. The oscillator circuit is constructed using the TDA0161 proximity detector IC [11]. These monolithic integrated circuits are designed for metallic body detection employing inductor coils and operate by sensing variations in high frequency Eddy current losses. Using an externally-tuned circuit, they act as oscillators. The output signal level is altered by an approaching metallic object. Each of inductor coils has a mean diameter of 8.1 cm, a mean thickness of 0.7 cm and 34 turns (Fig 2).

Figure 2: A constructed inductor coil for the purpose of metal detection

After the metal object is detected using the TDA0161 IC, the resultant signal is received as an output from a switching circuit constructed with the BC547 transistor. An LED is used as a visual aid to know whether the metal object has been detected (Fig. 3(a)).

Time measurement is the most important part of the data acquisition process of the viscometer. The main component used in the construction of the time measuring device is the PIC 16F877A microcontroller [12]. The time measurement is done using the Timer 1 module of the microcontroller. The collected data is transferred to the PC via the MAX232 IC used for serial communication (Fig. 3(b)).

The metal detector device needs a calibration before use and this is done by using its in-built variable resistors. The 10 kΩ variable resistor is used for coarse tuning, while the 1 kΩ variable resistor is used for fine tuning. In this process, the 10 kΩ resistor is kept in the zero resistance position and the 1 kΩ resistor in the full resistance position. Then, the 10 kΩ resistor is turned clockwise (to increase resistance) until the green LED is turned off. At this point, the 1 kΩ resistor is turned counter clockwise until the LED is just about to light. Then, the reset button is pressed to adjust the 1 kΩ resistor to its optimal detection position.

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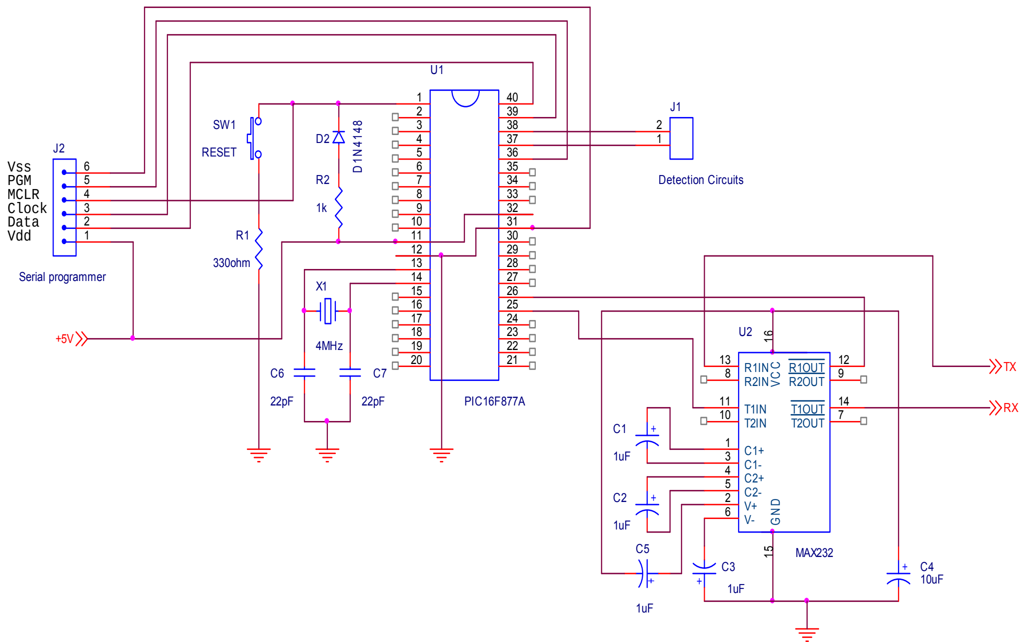
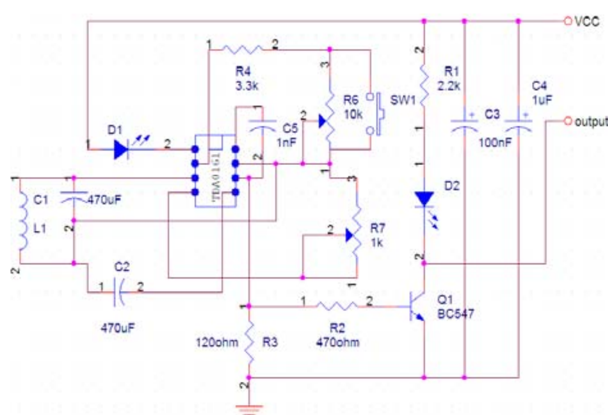


(a)



(b)

Fig. 3: (a) The timing and serial communication circuit. (b) Schematic diagram of the metal detector circuit.

3.2 Liquid and spheres

The *Reynolds criterion* or *Reynolds number* given by

$$R_e = \frac{v_f\, d}{\eta_k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

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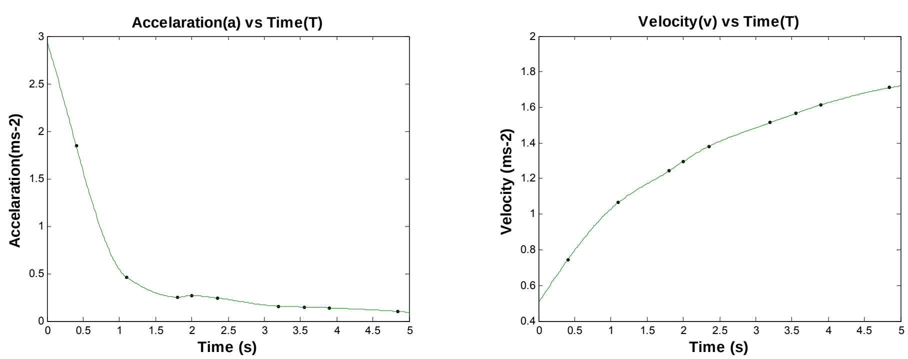
where v_f is the velocity of the flow, d is the diameter of the sphere and η_k is the kinematic viscosity of the medium, is used to determine the characteristics of different flow regimes of a fluid. Depending on the Reynolds criterion, if a medium flows around an object such as when a sphere is dropped into a liquid, the flow can be either a *laminar flow* $(R_e < 2300)$ or a *turbulent flow*. Thus, SAE40 engine oil was chosen for testing purpose of the viscometer.

Here it should be mentioned that, when selecting spheres with different diameters, one has to consider the wall effect exerted by the wall of the tube on falling spheres. As shown by Equation (2.2), in order to reduce this effect to ~ 20% level, for a tube having an internal diameter of ~ 8 cm, the diameter of a sphere should be less than 8 mm. Although spheres of smaller diameter are preferable to have, as they give: (1) a smaller wall effect and (2) a longer time-of-fall, the coil's limited metal detection capability prevents us from using spheres having a diameter less than 6 mm. The device was tested for spheres with three different diameters of 9.47 mm, 7.94 mm and 7.15 mm. The mass of each sphere was 3.52 g, 2.06 g and 1.50 g respectively.

4. RESULTS AND DISCUSSION

The data analyzed in this section correspond to the time-of-fall values obtained for SAE 40 engine oil. The values of the minimum viscosity and the density of SAE 40 engine oil as specified by the manufacturer at room temperature (27 °C) are 0.094 $kgm^{-1} s^{-1}$ [13] and 865 kg m^{-3} [14] respectively. Using the data obtained for the three spheres, acceleration vs. time and velocity vs. time graphs can be drawn (see Fig. 4) and, using Equations 2.1 and 2.2, the viscosity coefficients can be calculated (see Table 1).



(a) (b)

Fig. 4: (a) Graph of acceleration plotted vs. time for sphere with $r = 3.97$ mm. (b) Graph of velocity plotted vs. time for the sphere with $r = 3.97$ mm.

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Table 1: Table of results

Sphere Radius, r (mm)	Density, ρ_s (kg m^{-3})	Measured terminal velocity, v_t (m s^{-1})	Measured value of viscosity, η_m (kg m^{-1}s^{-1})	Corrected value of viscosity, η_t (kg m^{-1}s^{-1})
4.735	7923.3	2.0	0.172 ± 0.001	0.128 ± 0.001
3.97	7859.7	1.73	0.139 ± 0.001	0.109 ± 0.001
3.575	7859.7	1.63	0.119 ± 0.001	0.096 ± 0.001

Thus, from Table 1 it can be inferred that the smallest sphere yielded the most accurate results.

The necessity of using metal balls for the detection purpose gives the spheres a higher mass (or density) than glass spheres of equal size. As a result, a metal sphere moves with a higher velocity and hence makes more difficult for it to reach the terminal velocity after moving through a reasonable height of the liquid column than for a glass sphere of the same size.

Numerous metal detection circuits were constructed and tested. All these early attempts failed due to various practical reasons. One reason for these failures was the incompatibility of the circuits to the constructed tube. Some circuits failed to detect the relatively small metal sphere while others needed two coils for the detection process. Another reason for not choosing these circuits was the size and amount of components needed for construction. These circuits contained many electronic components for current oscillation and metal detection, thus it would have been problematic to assemble these circuits and pin point errors when the device does not function correctly. Thus, a smaller, more easy-to-use and accurate device was required for time measurements.

In this research work, only two metal detection devices (made up of two detection coils) were employed and then, time-of-fall measurements were made by changing their relative positions along the tube for each time measurement. Although this was not the best procedure, the limited capabilities (only a few pins on PIC16F877A are reserved for timer applications) of the timer circuit, the unavailability of proximity detector ICs in the local market and their relatively high cost compelled us to use it. A further improvement would be to use several detection coils along the length of the tube with each having a suitable circuit which can record time values when the sphere passes through each coil thus, eliminating the need to measure time values repeatedly at various heights.

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5. CONCLUSION

It can be concluded that the final outcome of the device, constructed under the above methodology is a success. This device has the capability of providing a more accurate, low time-consuming and a more user-friendly means of measuring viscosity in a laboratory environment. This device with a few modifications mentioned in Section 4 can be used as an alternative setup to the present falling sphere viscometer setup used in the undergraduate laboratory experiment for the measurement of viscosity, as it provides the necessary accuracy and precision required for this experiment [15].

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