Design and testing of portable laser-based viscometer

E Yusibani1,4, I R Sasmita2, L Ardiah1, E Yufita1, M S Surbakti1 and Rahmi3

1 Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Kopelma Darussalam, Banda Aceh 23111, Indonesia
2 IRSLAB, Cigadung Raya Tengah rd., Cigadung Bandung, 40191, Indonesia
3 Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Kopelma Darussalam, Banda Aceh 23111, Indonesia

E-mail: e_yusibani@unsyiah.ac.id

Abstract. Viscosity is one of a physical parameter of a fluid. Viscosity shows a coefficient of resistance in the fluid to reduce the speed of the fluid in a system. In the present study, design and testing has been carried out on a portable laser-based viscometer with the falling sphere method. The main mechanical system consists of two components: an acrylic tube with an inner diameter of 2.335 cm with a length of 28 cm, and a glass sphere diameter of 11.58 mm with the density of 2521 kg·m⁻³. Two lasers with a wavelength of 650 nm are used to determine the traveling time of a sphere in a range of 11 cm in the sample. Two photodiodes are used to capture the light signal and then forwarded it to the Arduino Uno R3 microcontroller to calculate the falling velocity of the sphere and the viscosity of the sample then displayed into a LCD (2×16). Reproducibility of the viscosity measurement data was confirmed with the standard deviation varied from 0.08 to 1.9 mPas. The sensitivity and the precision of the present design increased with the viscosity value.

1. Introduction

Viscosity is one of an important mechanical property of fluids. Viscosity is defined as the internal fluid's resistance to flow. Measuring viscosity can be done by several methods, such as the capillary tube method [1][2], rotating cylindrical method [3], oscillating disk method [4], straight vibrating wire method [5], curved vibration wire method [6], torsionally vibrating crystal [7] and the falling body method. In the latest method, the objects that is fall into the sample can be a sphere [8][9] or a solid/hollow cylinders [10]. The falling sphere method is one of the earliest, simplest and easiest methods. The basic principle of this method is to measure the falling velocity of the sphere into a sample. This method was first described by George Stokes in 1845 and known as The Stokes Law as described in equation (1) [11].

\[ F_f = 6\pi \eta r_s v \]  

(1)

where \( \eta \) is a dynamic viscosity (Pa·s), \( r_s \) is the radius of the sphere (m), and \( v \) is the falling velocity of the sphere (m·s⁻¹). Based on the equation (1), Stokes's law states that the greater the friction force, the greater the viscosity value. The Stoke law is valid with very small Reynolds numbers (<200), in steady...

---

4 To whom any correspondence should be addressed.
state and infinite medium. In a falling sphere method, a solid sphere which has a density \( \rho_s \) and a radius of \( r_s \) is dropped without an initial velocity into the fluid which has a density of \( \rho_f \), where \( \rho_s > \rho_f \).

It is known that the sphere first gets gravitational acceleration, but for a moment after moving far enough the sphere will travel at a constant speed \( v \). This constant speed results in the presence of another force in the sphere, which is buoyant force so that Newton Law II applies. Thus, there are three forces that influence the sphere in the fluid, namely Archimedes force, Stokes force, and gravity, so the equation (2) is applies.

\[
6\pi \eta r_s v + m_f g = m_s g
\]

where \( m_f \) is the mass of the fluid (kg), \( m_s \) is the mass of the sphere (kg) and \( g \) is the local acceleration of the sphere (m·s\(^{-2}\)). If we defined mass as density multiply by the volume \( V \) then equation (2) becomes equations (3) and (4).

\[
6\pi \eta r_s v = (\rho_s - \rho_f)gV
\]

\[
\eta = \frac{2g r_s^2 (\rho_s - \rho_f)}{9v}
\]

Based on the above equations, the physical parameters that must be measured are the densities of the sphere and sample fluid, the radius and the velocity of the sphere. In a simple terms, we can measure the velocity of the sphere by measuring its traveling time and distance in the fluid. Many ways have been developed to calculate traveling time by sensors.

A measurement of viscosity using lasers and photodiodes has been done by the previous researcher. The sphere was made from steel with a mass, radius and the traveling distance of 14 g, 7.5 mm, and 12 cm, respectively. The sample measured was edible oil and lubricant. Data is taken analogy in the form of a voltage change through a parallel port by a computer. The results showed that measurements using lasers and photodiodes showed more accurate than manual measurements, the percentage of average error of the viscosity measurement was 2.3% better than manual measurements [12]. Aryanto et al. uses seven photodiodes to capture light signals from a beam blocked by a falling sphere, the specified distance is 5 cm for each photodiode, and the sphere has a diameter of 16.5 mm with a mass weighing of 5.42 g. They use ATmega16 microcontroller to analyse the signal of glycerine sample fluid [13]. Two infrared diode lasers as lighters and a phototransistor have also been used by Warsito et al. to measure the viscosity of glycerine. The main system consists of two components: a glass tubes with a diameter of 4.7 mm, a length of 17 cm, and an iron sphere with a diameter of 1.2 cm, a density of 7643 kg·m\(^{-3}\), the output signal from the comparator is forwards to the AT89C51 microcontroller [14]. The measurement using a sensor to detect travel time in the falling sphere method will increase in measurement accuracy.

Viscosity is widely used as a standard for engineering fluid material, food, health and pharmaceutical products. The application of viscosity in product standardization can be found in the milk industry, the paint industry and the pharmaceutical industry. While the application of viscosity in the health sector, among others, is to determine the viscosity of blood in the body and the viscosity of urine. Therefore, to develop a low cost portable viscometer with high precision is desirable. In this present study, the authors will describe a design and testing an inexpensive portable laser-based viscometer by falling sphere method.

2. Method
To measure velocity is the main difficulty when using falling sphere method. The largest contribution to measurement uncertainty comes from the velocity measurement. The measurement of the sphere’s diameter is also one of the largest contributors to the uncertainty. In the present design, the mass and
diameter of the glass sphere is 2.059 g and 11.58 mm, respectively. The traveling distance was 10 to 16 cm. Samples will be put in an acrylic cylinder with inner diameter of 2.335 cm and the height of about 28 cm, so that the volume of the sample will be as much as 127 cc. The present viscometer consists of two photodiodes and lasers. The laser transmitted a red colour with the wavelength of 650 nm then the light signal will be captured by photodiode. When the sphere was traveling in between, then light from the laser will discontinue and the timer will start to ON, when the ball traveling to the other sensor, then the timer will start to OFF. The results of this time measurement will be calculated as a velocity and finally viscosity by Arduino Uno R3 microcontroller. In the present design, the traveling time and the viscosity values will be displayed in the LCD keypad (2x16). The temperature of the fluid is at 303 K measured by RTD PT100 at atmospheric pressure. A schematic diagram and pictures of the apparatus set up in the present design can be found in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The pictures of portable laser-based viscometer (BJ ViscoEL.01) and the experimental set up with a display of LCD 2x16 pixels.

To calculate viscosity, equation (4) is applied. This equation is only valid if the terminal velocity is reached, and if the sphere falls in an infinity medium without inertial effects. For fall within a cylindrical tube with a radius $r$, the correction of the wall effect ($W$) is given by Faxen [15] as show in equation (5). Considering a traveling distance in the cylindrical container of height $H$ (equation (6)), thus the modification of equation (4) to correct for effects on the velocity of the sphere due to its interaction with container walls ($W$) and ends effect ($E$) is given in equation (7).
The wall correction was empirically derived and is valid for \(0.16 \leq r_s/r \leq 0.32\). Beyond this range, the effects of container walls significantly impair the terminal velocity of the sphere, thus giving rise to a false high viscosity value [16]. Measurement of density of a sample fluid was carried out using a 50 ml piknometer.

In the present measurement, the sphere diameter will be calibrated by measuring pure water viscosity in ambient condition based on references obtained from REFPROP [17]. From the measurements, it was found that the effective diameter of the sphere was decided as much as 6.1 mm, which is about 47% smaller than the actual size. Thus, the effective diameter then will be used to calculate the viscosity. Several liquids, pure and mixture will be measured to evaluate the performance of the apparatus. All of the samples were obtained from Aceh province, Indonesia.

3. Result and discussion
Figure 2 shows the viscosity measurement of pure water by varying the traveling distance (L) of the sphere, i.e. 10, 12, 14 and 16 cm. To estimate traveling time of the sphere, two ways have been done i.e. manually and by the sensor (laser based). Manual means that the traveling time value was obtained by stopwatch (L = 12, 14 and 16 cm) while at L = 10 cm has been done by the sensor. The use of two measurement methods (manually and by sensor) is intended to see how the sensor influences data retrieval. Increasing traveling distance will increase the accuracy; however reproducibility of the measurement data done by sensor is better. The average standard deviation of five measurements is as much as 2 to 45% manually (● ▲ ▼) and 0 to 13% by the sensor (■) compared to REFPROP (0.1 MPa, 303 K). It can be seen that the measurement using a sensor to detect traveling time with the present design is increasing the measurement accuracy. Run number for the X-axis means number of experimental data retrieval.

![Figure 2. A viscosity measurement of water by the present design compared to REFPROP.](image-url)
Several viscosity measurements (>15) are taken along the acrylic cylinder for various pure and mixture samples. Traveling distance \((L)\) of the measurement is deciding as much as 11 cm. Figure 3 shows traveling time and velocity of pure liquid (lubricant oil SAE40, palm oil, patchouli oil (A from Aceh Selatan, B from Gayo Lues and C from Aceh Besar), kerosene) measures by the present design apparatus. Lubricant oil give the highest traveling time value of about 50 ms while kerosene for the short time of around 20 ms. The falling velocities calculated respectively to the traveling time is up to 6 m/s. Kerosene has bigger value relatively to the others and followed by patchouli oil, palm oil and finally lubricant oil. Reproducibility of the measurement is confirmed with the standard deviation of viscosity value varied from 0.3 to 1.8 mPas.

Figure 3. Traveling time and velocity of the various pure samples in the present measurement by sensor.

Figure 4-6 show a traveling time and velocity measurement of lubricant oil SAE40, palm oil and kerosene, respectively, which is mix by patchouli oil C with the composition of 100:0; 75:25; 50:50; 25:75 and 0:100 (v/v). The reproducibility and the sensitivity of the present design apparatus are good especially for a relatively high viscosity. The precision of the present design is decreased at traveling time around 20 ms. This short time measurement give a scatter value of the velocity, however the tendency still recordable as can be seen in Figure 6.

Figure 4. Traveling time and velocity for mixture of lubricant oil SAE40+Patchouli C in the present measurement by sensor.
To calculate viscosity, the correction derived by Faxen was applied. The W/E value in the present design is as much as 0.49. The result of the all viscosity measurement can be seen in Figure 7 and Table 1. The table contains the results of density and viscosity measurements by the present viscometer from several samples compared to the available references. The sample consists of pure and mixture fluid to show the sensitivity, precision and accuracy of the present design. It is clearly observed that the sensitivity and the precision of the present design are good. The discrepancy is noticeable when patchouli oil C and kerosene is mixture by increasing volume of 25% of the sample. However, the accuracy of the present design still needs to be improved.
The 9th AIC 2019 on Sciences & Engineering (9thAIC-SE)  IOP Publishing
IOP Conf. Series: Materials Science and Engineering 796 (2020) 012027  doi:10.1088/1757-899X/796/1/012027

Figure 7. Overall measurement of viscosity with the present design (Note: LO:Lubricant Oil SAE40; PO:Palm Oil; PC:Patchouli Oil C; KR:Kerosene).

Table 1. Density and viscosity measurements of the present design for several samples.

| Sample                        | Density, $\rho$ (kgm$^{-3}$) | Viscosity, $\eta$ (mPas) | References $\rho$ (kgm$^{-3}$); $\eta$ (mPas) |
|-------------------------------|-------------------------------|--------------------------|-----------------------------------------------|
| Patchouli oil A              | 942                           | 38.9 ± 1.4               | 946.6; 9.2933 (313K) [18]                     |
| Patchouli oil B              | 934                           | 35.3 ± 1.9               |                                               |
| Patchouli oil C              | 925                           | 35.1 ± 1.7               |                                               |
| Palm oil                     | 895                           | 57.5 ± 0.3               | 899.6; 40.78 (CPO, 313K) [18]                 |
| Palm oil (75%) + Patchouli oil C (25%) | 903                          | 50.3 ± 0.9              | 877.13; 4.71 (edible oil, room T) [19]         |
| Palm oil (50%) + Patchouli oil C (50%) | 913                          | 42.1 ± 0.6              | 973; 0.78 (edible oil, 302K) [20]             |
| Palm oil (25%) + Patchouli oil C (50%) | 918                          | 39.3 ± 0.6              |                                               |
| Lubricant oil SAE40          | 848                           | 70.5 ± 0.4               | 898 (288 K); 13.14 (373K) [21]                 |
| Lubricant oil SAE40 + Patchouli oil C (25%) | 868                          | 52.7 ± 0.5              | 900; 270 (298K) [22]                           |
| Lubricant oil SAE40 + Patchouli oil C (50%) | 886                          | 44.0 ± 0.5              |                                               |
| Lubricant oil SAE40 + Patchouli oil C (50%) | 908                          | 32.3 ± 1.4              |                                               |
| Kerosene                     | 785                           | 28.1 ± 0.9               | ns; 1.64 (300 K) [23]                         |
| Kerosene (25%) + Patchouli oil C (25%) | 884                          | 35.1 ± 1.7              |                                               |
| Kerosene (50%) + Patchouli oil C (50%) | 851                          | 31.0 ± 1.0              |                                               |
| Kerosene (75%) + Patchouli oil C (50%) | 827                          | 29.0 ± 2.9              |                                               |

ns: not specified

4. Conclusions
A simple and inexpensive portable laser-based viscometer by a falling sphere method has been designed and tested to measure the dynamic viscosity of liquid at atmospheric pressure and temperature. Lubricant oil SAE40, patchouli oil, palm oil, and kerosene have been measured and
analysed. Not only pure material, but also mixed fluids have been measured with the composition of 100:0; 75:25; 50:50 and 25:75 (v/v) for lubricant oil, palm oil and kerosene with patchouli oil C. Reproducibility of the viscosity measurement is good with the standard deviation varied from 0.3 to 1.9 mPas. The sensitivity of the present apparatus increased with viscosity value. The present deviations with respect to the existing references suggest that with more refinements it may be possible to take viscosity measurements by the present device with an accuracy of less than 5%.

Acknowledgments
This research is funded by Universitas Syiah Kuala, Indonesia (H-Index Project number 1445/UN11/SP/2017) under Kementrian Riset, Teknologi dan Pendidikan tinggi (KEMENRISTEKDIKTI) Indonesia.

References
[1] Yusibani E, Nagahama Y, Shinzato K, Fujii M, Kohno M, Takata Y and Woodfield P L 2011 Int. J Thermophys. 32(6) 1111-1124
[2] May E F, Berg R F and Moldover M R 2007 Int. J Thermophys. 28 (4) 1085
[3] Diller D E 1965 J. Chem. Phys. 42 6
[4] Kestin J and Leidenfrost W 1959 Physica 25 1033
[5] Tough J T, McCormick W D and Dash J G 1964 Rev. Sci. Instrum. 35 13451348
[6] Yusibani E, Woodfield P L, Shinzato K, Takata Y and Kohno M 2013 Exp. Therm. and Fluid Sci. 47 1–5
[7] Mason W P 1947 Trans. ASME 69 359
[8] Brizard M, Megharfi M, Verdier C and Mahé E 2005 Rev. Sci. Instrum. 76 (2) 025109
[9] Tang J X 2016 Rev. Sci. Instrum. 87 054301 doi:10.1063/1.4948314
[10] Rudenko N S and Slyusar V P 1968 Ukrainian Phy. J. 13 656-659
[11] Resnic H, Walker J and Halliday D 1960 Fundamentals of Physic (oxford) Ed. Halliday D
[12] Surtono A and Susanto E 2007 J. Sains MIPA 13(3) 251-256
[13] Aryanto D, Saptaningrum E and Wijayanto 2012 Jurnal Fisika dan Aplikasinya 8(8) 1-5
[14] Warsito, Suciyati S W and Isworo D 2012 Jurnal Natur Indonesia 14(3) 230-235
[15] Faxon H 1923 Astronomi och Fysik 27(17) 1-28
[16] Webster J G 1999 The Measurement, Instrumentation and sensors handbook Leblanc G E et. al. Viscosity Measurement Copyright 2000 (CRC Press, IEEE Press)
[17] REFPROP-Reference Properties- NIST-USA Reference Fluid Thermodynamic and Transport Properties Database (REFPROP v.8)
[18] Atabani A E, Mahlia T M I, Masjuki H H, Badruddin I A, Yussof H W, Chong W T and Lee K T 2013 Energy 58 296-304
[19] Sutiah K, Firdausi K S and Budi W S 2008 Berkala Fisika 11(2) 53-58
[20] Yusibani E, Hazmi N A and Yufita E 2017 Jurnal Teknologi dan Industri Pertanian Indonesia 9(1) 28-32
[21] Anonymous 2009 total motor oil sae (brochure)
[22] Souza R J M and König A 2012 Ano 28 147-161 ISSN 1807-16006
[23] Engineering ToolBox 2008 Dynamic Viscosity of common Liquids. [Online] Available at: https://www.engineeringtoolbox.com/absolute-viscosity-liquids-d_1259.html [Accessed 7 July. 2019]