PAPER

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A simple liquid density measuring instrument based on Hooke's law and hydrostatic pressure

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Abstract

Physics learning cannot be separated from the existence of physics measuring instruments, but their existence in schools are very limited. Therefore, creativity and innovation are needed to develop physics measuring instruments that are easily accessible by schools. This research aims to design and construct a liquid density measuring instrument by applying Hooke's law and hydrostatic pressure. The method used in this research is a quantitative descriptive method with the stages of designing, constructing, developing, and testing the measuring instrument. The design and construction of the measuring instrument in this study is carried out using tools and materials that are simple and easily obtained, such as a glass pipe, PVC pipe, rulers, springs, and wooden table. The liquids used to test the instrument are cooking oil, lubricant, and water. The measurement results of the liquid density using the measuring instrument are in accordance to the known value or the standard.

1. Introduction

Physics is a science that seeks to understand the patterns of nature that may be beautifully describe in mathematical formulations. Mathematics is a language to communicate physics phenomena that occur in everyday life, so physics studies phenomena that occur in everyday life via mathematical descriptions that can be learned by students [1]. Physics teachers are naturally able to teach physics concepts of various daily phenomena to their students in a way that is fun and easy to understand. In terms of teaching physics, a supporting learning media is needed in the form of measuring instruments and teaching aids [2]. However, physics teachers must provide opportunities for students to use measuring instruments and teaching aids directly hence adding to their learning experience.

Measuring instruments and aids that have been circulating so far are mostly factory-made that are difficult to obtain by schools in the suburbs [3]. With the advances in technology, information, and communication, this should no longer be a significant problem. However, the availability of measuring instruments that cannot be directly accessed can be dealt with by developing or innovating self custom-made instruments using inexpensive, easy, and simple tools and materials [4, 5]. Through various developments in measuring instruments of physics quantities, we may provide comparisons between measuring instruments. In addition, we can also provide a variety of choices for students and teachers to use measuring instruments that are simple, inexpensive, and easy to use.

Measuring is conducted by comparing an unknown (physics) quantity with the standard or known quantity of the same kind or dimension. In carrying out a measurement, students require a measuring instrument used to assist the measurement process. This makes the measuring process easier in order to obtain accurate and precise results. Furthermore, various innovations in physics measuring instruments by scientists or researchers can be utilized in educational activities in the form of teaching aids [6]. Teaching aids are one of the learning media that is often used by teachers to convey physics concepts and help make it easier for students to learn physics concepts [7]. Therefore, the existence of measuring instruments in the form of physics teaching aids is very important. However, measuring instruments that are widely available and often found in schools only measure the principal physics quantities, such as length and mass, which are measured using a ruler and a balance, respectively. Moreover, measuring instruments for measuring derived physics quantities are rarely found in schools [8].

It is important to measure the density of liquids. Density is an important characteristic possessed by a substance [9, 10]. Therefore, based on the variety of liquids that we encounter in our daily life and the rarity of measuring instruments to measure the density of liquids, it is necessary to innovate and develop liquid density measuring instruments that may not only be used by the general public, but also used in physics learning activities.

The liquid density measurement can be conducted using the Archimedes principle [11] and assisted by a photodiode sensor [12], but requires tools and materials that are expensive and difficult to obtain by schools. Hence, it is necessary to innovate or develop a density measuring instrument that uses combination of various physics concepts. The development of a measuring instrument that applies certain physics concepts, such as Hooke's law and hydrostatic pressure, is rarely done by researchers and teachers. The hydrostatic pressure is used because it studies the characteristics of fluids in particular liquids [13]. In addition, the Hooke's law and hydrostatic pressure are also concepts that are still considered difficult by students in high school as evidenced by their learning outcomes, which is still low [14].

Hooke's law states that if an object increases in length because of a force (F), then the change in length of the object is directly proportional to F. For example, the length of a spring is initially x_0, then the spring is given a load that has a mass of m. The spring is then hung freely or pulled, such that the spring stretches with a change in length of Δx and the length of the spring becomes $x = x_0 + \Delta x$ as shown in figure 1. Furthermore, Hooke's law only applies to a certain limit of elasticity possessed by an object. An elastic limit is the maximum force that can be applied to the object before the object changes shape permanently [15].

Experimental results show that a liquid with density ρ in a container with radius r gives pressure P in all directions. Another important property of a liquid that is at rest with height h is that the force F caused by the pressure of the liquid always acts perpendicular to the surface in contact shown in figure 2. Based on figure 2, the pressure upon the liquid at height h is caused by the weight of the liquid column above it. Thus, P is directly proportional to the ρ and h in the liquid [16]. This is known as the hydrostatic pressure.

In this study, a physics teaching aid in the form of a liquid density measuring instrument is developed by applying Hooke's law and hydrostatic pressure. The objective of the study is to design, construct, develop, and test the measuring instrument with tools and materials that are inexpensive and easily accessible by schools. In addition, this study also discusses the application of the measuring instrument as a result of the development of physics teaching aids in schools.

2. Research method

This is a quantitative descriptive research with the stages of designing, constructing, developing, and testing the liquid density measuring instrument. The first stage is designing the measuring instrument. At this stage, the first step taken is to choose the topics of measuring instrument, Hooke's law, and hydrostatic pressure. The next step is to conduct literature review concerning the measuring instrument, Hooke's law, and hydrostatic pressure. The subsequent step is to design the measuring instrument. The design of the measuring instrument can be shown in figure 3.

The second stage is constructing the liquid density-measuring instrument. Here, the first step is preparing the tools and materials based on the design in figure 3, i.e.: PVC pipe (10 cm in diameter), glass glue, glass pipe (5 cm in diameter), glass saw, rulers, rubber valves, faucet, and cantilever wood. The next step is constructing the measuring instrument as follows: (i) cutting the PVC pipe to a length of 60 cm, (ii) cutting the glass pipe to a length of 40 cm, and (iii) smoothening the two pipes at the edges. The next step is sticking the two ends of the spring with a rubber valve each, then attaching it inside the glass pipe. Subsequently, installing the faucet with a distance of 5 cm from the rubber valve and then connecting the PVC pipe to the glass pipe using the glue as shown in figure 4. Finally, placing the constructed device on the wooden cantilever according to their respective positions.

The third stage is developing the liquid density measuring instrument that has been constructed. This stage is conducted by checking and correcting the deficiencies or errors that are still found in the measuring instrument, such as looking for cracks, untight spaces, or holes that may spill or leak the liquid being measured. The result of the development of the measuring instrument can be shown in figure 4. The final step is to test the liquid density-measuring instrument. Various liquids to be measured are water, cooking oil, and SAE 20 W-50 lubricant.

Furthermore, the working principle of the instrument by applying Hooke's law and hydrostatic pressure can be shown in figure 5. Based on the figure, the liquid to be measured is poured or inserted through the large (PVC) pipe. The liquid flows into the glass (small) pipe with hydrostatic pressure P. Hence, the liquid provides F to the rubber valve, which is connected to a spring that has a cross-sectional area A such that the spring is compressed with an amount of Δx. After that, the height of the liquid h is measured using the ruler mounted near the large pipe. We may also vary h as an independent variable by turning open the faucet and then measure Δx as the dependent variable. Then ρ of the liquid can be determined using a relationship between the hydrostatic pressure and Hooke's law. This starts with the hydrostatic pressure equation shown in equation (1), i.e.:

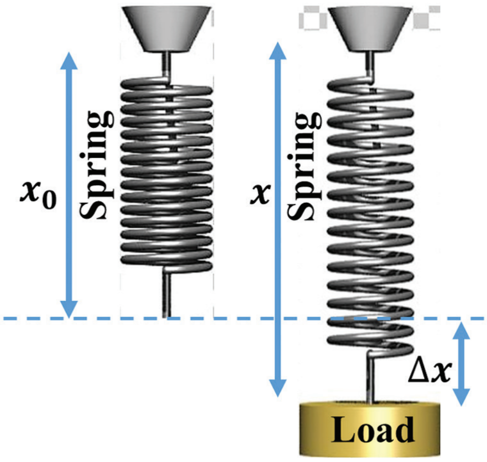

Figure 1. A schematic concept of Hooke's law on a spring.

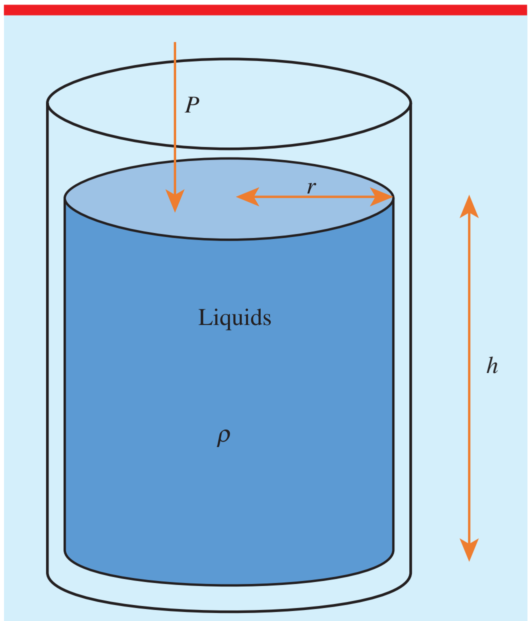

Figure 2. A schematic of hydrostatic pressure on a liquid.

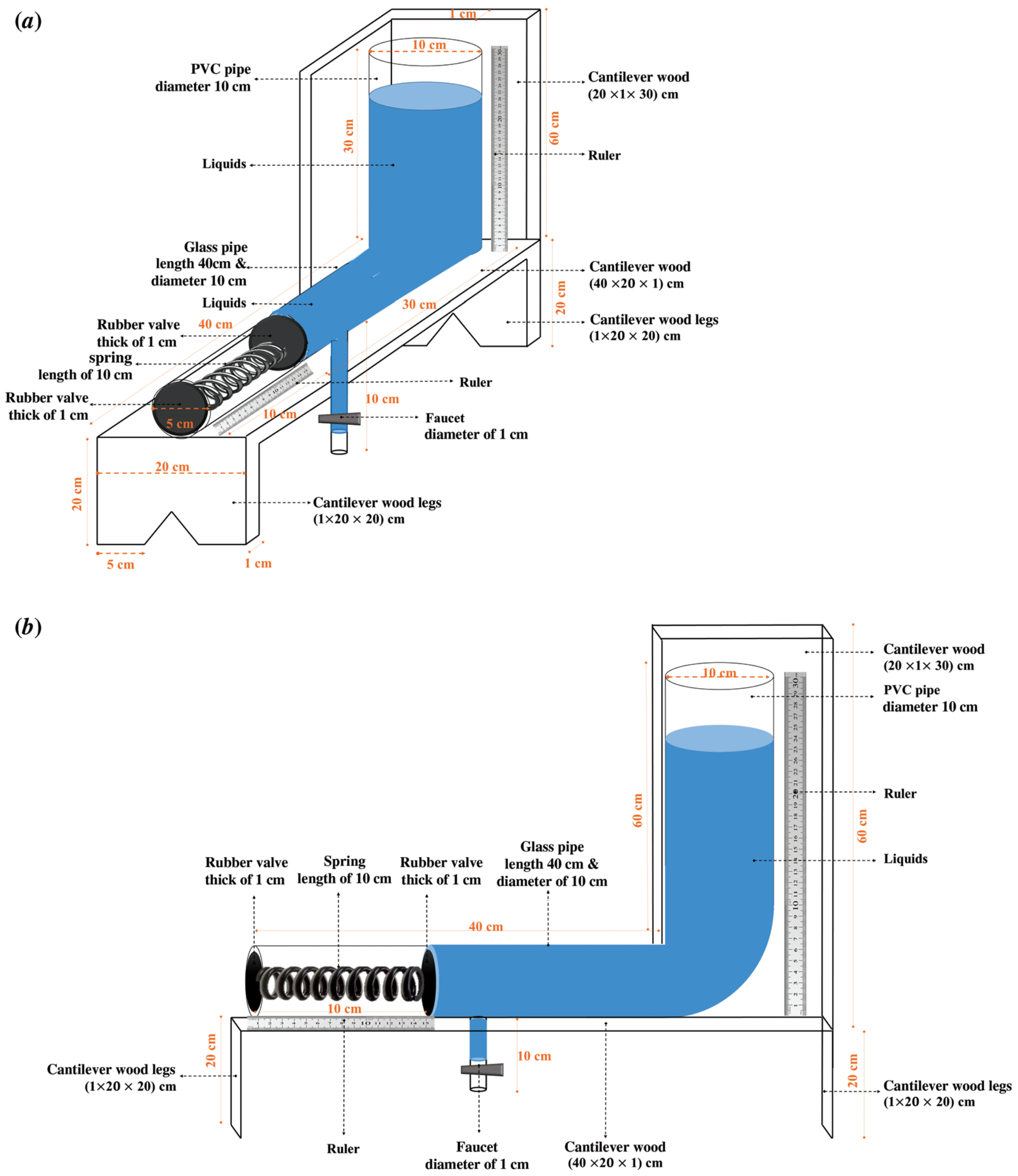

Figure 3. The design of the liquid density measuring instrument, i.e: (a) front and (b) side views.

$$P = P_{\text{hydrostatic}} = \rho g h. \tag{1}$$

Equation (1) is related to the compressive force, i.e.:

$$F = PA. \tag{2}$$

Substituting equation (1) into (2) produces:

$$F = \rho g h A. \tag{3}$$

Hooke's law can be given as follows (without taking into account the direction of the vector):

$$F = k\Delta x. \tag{4}$$

A connection between the hydrostatic pressure and Hooke's law may be obtained by substituting equation (3) into (4), viz.:

$$\rho g h A = k\Delta x,$$

Figure 4. The developed measuring instrument, i.e.: (a) side and (b) front views.

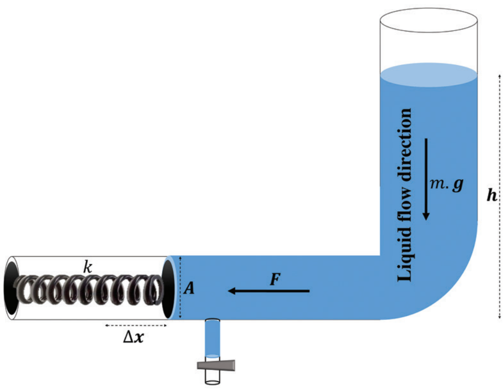

Figure 5. The working principle of the liquid density measuring instrument.

or

$$\rho = \frac{k\Delta x}{ghA}, \tag{5}$$

where g is the acceleration of gravity. Equation (5) is used to measure the density of liquids in this study.

In general, the procedure carried out to measure the density of liquids using this measuring instrument can be explained as follows: (i) arranging tools and materials according to the design in figure 3, (ii) measuring k and A, (iii) pouring the liquid into the large pipe, (iv) measuring Δx and h of the liquids, (v) determining ρ using equation (5), (vi) repeating the measurement of ρ, and (vii) varying h and the type of liquids by opening the faucet. Finally, the density of the liquids obtained from the measurement is compared to the standard or known value, that may be observed in table 1 [17].

The data from the measurement are analyzed on average, i.e.:

$$\overline{\rho} = \frac{\sum_{i=1}^{n} \rho_i}{n}, \tag{6}$$

where $\overline{\rho}$ is the average liquid density (g cm^{-3}) and $\sum_{i=1}^{n} \rho_i$ is the total density of the liquid from $i = 1$ to $i = n$th measurements. In addition, the precision and accuracy of the liquid density measurements are determined using standard deviation and relative uncertainty, viz.:

$$\Delta\rho = \sqrt{\frac{\sum_{i=1}^{n} (\rho_i - \overline{\rho})^2}{n-1}}, \tag{7}$$

where $\Delta\rho$ is the standard deviation, and

$$\mathrm{RU} = \left(\frac{|X - Y|}{Y}\right) \times 100\%, \tag{8}$$

where RU is the relative uncertainty (%), X is the liquid density measured using the instrument and Y is the density of the liquid in table 1.

3. Results and discussion

The results of the density measurement using the measuring instrument can be observed in table 2. It can be observed that the results of the density measurement obtained from the measuring instrument are in accordance to the standards or known values (table 1). This shows that the measuring instrument is valid for measuring the density of liquids. However, the density of the three liquids measured using the measuring instrument still gives different results compared to the known values. One way to analyze this difference is to look at the accuracy of each density of the three measured liquids, i.e.: 99.68%, 99.71%, and 99.69% for water, SAE 20W-50 lubricant, and cooking oil, respectively. It can be observed that the lowest relative uncertainty is obtained for SAE 20W-50 lubricant, which is 0.29%, which shows that 99.71% of the density measured using the measuring instrument is in accordance with the standard value. This shows that the accuracy of measuring the density using the measuring instrument is best obtained when measuring the density of lubricants. This is because at the time of measurement, the lubricant does not seep in the rubber valve, does not inundate the spring, and more viscous than water and cooking oil.

In addition, the precision of the liquid density measuring instrument is shown from the average standard deviation in the rightmost column of table 2. Based on the table, it can be observed that the precision of the measuring instrument is around 1.5% to 2.2%. This may be compared to the previous precision results in [11, 12], which are 0.1% and 2.4% to 4.7%, respectively. It may be observed that the precision of this measuring instrument is better than [12] but worse compared to [11]. Although the precision of this measuring instrument is less than in [11], we still argue that this instrument is still worth of constructing. The justification is that the physical concepts and experimental procedures of the instruments are different, i.e.: [11] uses the Archimedes law ([12] uses the same law added with photodiode sensor), whereas this instrument uses a combination of Hooke's law and hydrostatic pressure. These differences create different dynamics in the measurement activities, especially when used by students, and hence making students to perform higher order thinking skills (HOTS) to compare and analyse various instruments measuring the same physical quantity.

This measuring instrument can also be used as an aid in physics learning activities for students, especially in the topics of Hooke's law and hydrostatic pressure. Students can apply the concepts of Hooke's law and hydrostatic pressure via this instrument because this instrument is convenient as it does not require large volumes of the liquids and only uses a small spring. This is supported by [18, 19] that measuring instruments or physics aids used in physics experiments can improve students' understanding of physics concepts and science process skills. Therefore, in the learning process, after a physics teacher explains the concepts of density, Hooke's law, and hydrostatic pressure, the measuring instrument can be used as a demonstration tool for students to practice their understanding of the aformenetioned concepts. In addition, the teacher may also give assignments to students to measure the density of various liquids with the procedures given in the previous section and compare the results with the standards shown in table 1. The teacher can then ask the students to make their own version of table 2 and discuss the measurement procedure and results. Finally, the teacher can use this measuring instrument as a model to explain the application of Hooke's law and hydrostatic pressure in daily utilities, such as vehicle pistons and shock breakers. We argue that the working principle of the measuring instrument is similar to the working principle of pistons and shock breakers, especially in the spring compression due to liquid pressure. Thus, it is hoped that by using this measuring instrument students can understand the Hooke's law and hydrostatic pressure.

Table 1. A list of density of liquids.

Type of liquid	Density (g cm^{-3})
Sea water	13.6
Water	1.00
Mercury	1.02
SAE 20 W-50 lubricant	0.88
Cooking oil	0.82
Gasoline	0.79
Kerosene	0.76
Alcohol	0.68

To determine the measurement range of the instrument, we first adjust h from 10 cm to 70 cm. The density of the liquids cannot be measured at $h \leqslant 10$ cm and $h \geqslant 70$ cm. This is because if the liquid is at h of 10 cm, the liquid cannot compress or shorten the spring. Moreover, if h is 70 cm, the liquid compresses the spring too hard that the liquid spills as the rubber valve is separated from the glass pipe. This is a limitation of the measuring instrument, i.e.: it cannot measure the density of liquids for $h \leqslant 10$ cm and $h \geqslant 70$ cm. Therefore, the maximum h of a liquid that may be used is 60 cm and the minimum h is 15 cm. Thus, we obtain the measurement range for the liquid density of 15 cm $\leqslant h \leqslant$ 60 cm.

Equation (5) is the basic formula for calculating the density of a liquid. It is clear that the equation is quite simple because it only depends on h and Δx, provided that k, g, and A are known. Varying h should not effect ρ or in other words different h following Δx) should produce the

Table 2. The results of the liquid densities using the measuring instrument.

k (g s^{-2})	g (cm s^{-2})	A (cm^2)	h (cm)	Δx (cm)	ρ (g cm^{-3})	$\Delta\rho$ (g cm^{-3})	Standards (g cm^{-3})	$\overline{\rho}$ (g cm^{-3})	Average $\Delta\rho$ (g cm^{-3})
Water									
165 960.73	980	19.63	15	1.7	1.001	0.032	1.00	0.997	0.022
			20	2.4	1.053	0.024			
			25	2.7	0.971	0.036			
			30	3.5	0.995	0.016			
			35	4.0	0.991	0.032			
			40	4.6	0.992	0.026			
			45	5.2	0.993	0.016			
			50	5.7	0.991	0.009			
			55	6.3	0.992	0.013			
			60	6.9	0.989	0.016			
Relative uncertainty = 0.32%									
SAE 20W-50 Lubricant									
165 960.73	980	19.63	15	1.5	0.874	0.026	0.88	0.878	0.013
			20	2.0	0.880	0.024			
			25	2.5	0.877	0.019			
			30	3.1	0.880	0.016			
			35	3.5	0.873	0.014			
			40	4.1	0.876	0.012			
			45	4.6	0.878	0.009			
			50	5.1	0.880	0.001			
			55	5.6	0.879	0.001			
			60	6.1	0.877	0.014			
Relative uncertainty = 0.29%									
Cooking oil									
165 960.73	980	19.63	15	1.4	0.817	0.048	0.82	0.818	0.014
			20	1.9	0.820	0.001			
			25	2.3	0.820	0.016			
			30	2.8	0.817	0.016			
			35	3.3	0.819	0.021			
			40	3.8	0.815	0.010			
			45	4.3	0.817	0.011			
			50	4.7	0.818	0.009			
			55	5.2	0.816	0.001			
			60	5.7	0.817	0.012			
Relative uncertainty = 0.31%									

same ρ. The derivation of equation (5) from Hooke's law dan hydrostatic pressure can be used as a mathematical exercise for students.

4. Conclusions

A measuring instrument used to measure the density of liquids by applying the Hooke's law and hydrostatic pressure is designed and constructed using tools and materials that are simple, inexpensive, easily obtainable and accessible by high schools or colleges. The densities of the three liquids, viz.: water, cooking oil, and SAE 20W-50 lubricant are in accordance with the standard values in table 1. In addition, this measuring instrument can be used as an aid in physics learning activities in the topic of fluids in particular the density of liquids and to show basic applications of the Hooke's law and hydrostatic pressure. Students can also be given the task to (i) measure the density of various liquids and (ii) improve this measuring instrument. Thus, further studies in improving the measuring instrument can be done by replacing the spring with other more flexible springs, tightening the rubber valve with the glass pipe so that they do not easily fall off, and elevating the large (PVC) pipe to improve the accuracy of the measuring instrument.

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