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Measurement of Motor Vehicle Emissions Based on Low-cost Sensors

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Abstract

One of Indonesia's primary causes of air pollution is the significant level of human activity, particularly the continued use of fossil-fuel-powered vehicles. The incomplete combustion of fossil fuels can lead to gas and particle pollutants forming, impacting the environment. However, the instruments utilized for detecting environmental pollutants are relatively expensive. Therefore, motor vehicle emission tests use low-cost sensors with parameters such as CO, CO_2, NO_2, $PM_{2.5}$, temperature, and RH. The flow rate measures the emission gas flow extracted from a vehicle's exhaust into the testing chamber and then released into the air for disposal. The flow rate utilized in these tests ranges from 12 to 15 lpm. The tests are conducted over 10 minutes to ensure accuracy, obtaining average readings for the measured parameters. For the measurement results using a low-cost sensor, the average value for CO is 383.891 ppm, NO_2 is 10.7237 ppm, CO_2 is 5,254 ppm, $PM_{2.5}$ is 50.25 µg/m^3, temperature and RH is 28.9 °C and 76%. The official test results obtained a CO value of 1,200 ppm, CO_2 of 140,000 ppm, and a temperature of 80 °C. This difference is because the reading range of low-cost sensors is relatively small but has a stable data trend.

Keywords: emission; flow rate; low-cost sensor; measurement; vehicle.

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1. Introduction

Indonesia, a large country with the world's fourth- most populous population, encounters various challenges, one of which is air pollution stemming from the extensive human activity that heavily relies on fossil-fueled vehicles. A notable example is the capital city, Jakarta, encompassing an area of 4,384 square kilometers (1,693 square miles) and housing a population of approximately 10,770,487 residents [1]. In 2018, Statistics Indonesia reported that Jakarta had around 18.7 million vehicles, including motorcycles, passenger cars, buses, and trucks [2]. The escalating number of vehicles has increased fuel consumption. The heightened use of fossil fuels in the manufacturing sector and transportation poses a threat to the environment, giving rise to air pollution emissions that could adversely affect human health [3]. Several cross-sectional studies have stated a strong connection between poor air quality and the incidence of asthma [4–6]. One of those studies about the urban population demonstrated that the correlation between asthma morbidity and air pollution was more potent in children than adolescents and adults [4]. In another study, it was explained that long-term exposure to pollutants such as high concentrations of Particulate Matter (PM) increased the prevalence of chronic obstructive pulmonary disease (COPD) and lung cancer in adults [7].

Several types of air pollution are produced by using fossil energy, such as PM_{10}, $PM_{2.5}$, Carbon Dioxide (CO_2), Carbon Monoxide (CO), Sulfur Dioxide (SO_2), and Nitrogen Oxides (NO_x) [8–10] Vehicle exhaust gas is produced by the combustion residue in a motor vehicle's combustion chamber.

Various pollutants in this gas can detrimentally affect air quality and human health. The findings of these studies are presented individually for the key parameters essential in calculating emissions, such as pollutant concentrations, exhaust flow, and cycle work. Furthermore, developing inexpensive sensors has enabled the measurement of gaseous exhaust emissions from light-duty vehicles [11].

The government, motor vehicle manufacturers, and brand holders are trying to reduce the impact of those hazardous substances through the emission test process [12]. Many researches on air pollution have been carried out in Jakarta, one was done by a team from Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) in 2016 - 2017. In that research, the result of an average of the measurements of the tests that were conducted from 7 days before to 7 days after Eid Al-Fitr, for the concentration of $PM_{2.5}$ has a range of 36.41 $\mu g/m^3$ up to 65.92 $\mu g/m^3$ and 3.66 $\mu g/m^3$ up to 59.16 $\mu g/m^3$ [13]. The research results indicate that Jakarta's air quality has a high $PM_{2.5}$ pollutant level. Therefore, follow-up actions are necessary for dealing with air pollution in Jakarta.

This research focused on the measurement of vehicle emissions. A low-cost sensor is anticipated to aid in the measurement process as a secondary instrument, providing support when the primary instrument is relatively expensive. Low-cost sensor technologies have found broad application in monitoring air quality and assessing exposure. These sensors represent a groundbreaking advancement in air quality monitoring, enabling the widespread deployment of sensors at an affordable price. They have proven effective in monitoring both indoor and outdoor air quality on a community level [14]. Low-cost sensors have been utilized to evaluate $PM_{2.5}$ concentrations in various communities within the Lower Rio Grande Valley (RGV) region [15]. These sensors have been proven instrumental in monitoring outdoor air pollution, offering the advantages of high spatial and temporal resolutions at a cost-effective price [16].

When reference grade measurements are scarce or expensive, these devices become invaluable tools, providing crucial insights into air quality. This is especially advantageous in low and middle-income countries. [17]. Creating a sustainable and affordable air quality monitoring system requires carefully selecting suitable sensors that align with the specific conditions and planned applications [16].

In air quality studies, low-cost sensors have been increasingly used to demonstrate accuracy using various calibration approaches [18]. At a relatively low price, low-cost sensors can be applied in various places prepared for monitoring air quality and on low-cost sensor-based vehicle emission test equipment. In the future, this tool can be helpful, especially in handling problems to find out exhaust gasses in motor vehicles so that they can control exhaust gas output to comply with standard rules that the government has made. Low-cost sensors are simpler to install, use, and administer than existing air pollution measurement equipment. The sensors may be widely deployed in urban environments due to their autonomous functioning and ease of data retrieval. The benefit of the sensors is that they offer information on the sources of pollution and support more thorough investigations into how air pollution affects a variety of facets of human existence [19].

Research on air quality measurement using low-cost sensors has been conducted, one of which was by Hirawan and Sidik in 2018 [20]. Measurements conducted in this research were to determine the value of exhaust emissions from motor vehicles so that they could find out the value of vehicle exhaust gases from certain types of motor vehicles. This study uses a low-cost sensor to monitor the exhaust emissions from vehicles. These studies provide distinct findings for the essential parameters required for emissions calculation, encompassing pollutant concentrations, exhaust flow, and cycle work. Furthermore, developing low-cost sensors has facilitated the measurement of gaseous exhaust emissions from light-duty vehicles [21]. Many research investigations have been done to evaluate the quantification of emissions produced by motor vehicles. These studies aim to assess various measurement methodologies for exhaust gases, with a specific focus on portable systems and less sophisticated laboratory-grade equipment[22]. Thus, the results of this study can be used as a reference for further research on air pollution resulting from motor vehicle emissions in Indonesia.

2. Research Method

2.1 Measurement tool system

This measuring instrument system is built by integrating Ultra-Low Power Analog Sensor Module (ULPSM) for CO and NO_2 sensor, SKU:SEN0177 as $PM_{2.5}$ sensor, SKU:SEN2019 as CO_2 sensor, and Digital-output Relative Humidity & Temperature Sensor 22 (DHT22) as Temperature (T) and Relative Humidity (RH) sensors with Arduino Uno as a microcontroller. As for the specifications, the CO sensor has a measurement range of 0 - 500 parts per million (ppm) with an accuracy of ±3% of readings [23], the NO_2 sensor with range is 0 - 20 ppm with an accuracy of ±2% of readings [24], for $PM_{2.5}$ the measurement range is 0 - 999 $\mu g/m^3$ [25], for CO_2 the measurement range 400 - 5000 ppm with an accuracy of ± (50 ppm + 5% of reading) [26], for the temperature parameter the measurement range is -40 - 80 °C with an accuracy <± 0.5 °C, and for the RH parameter the measurement range is 0 - 100% with an

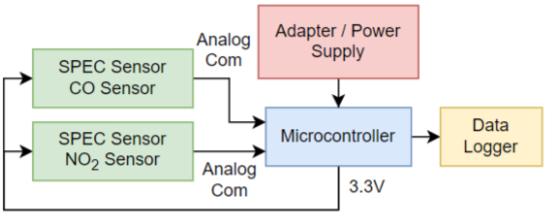

Fig. 1. System with 2 sensors.

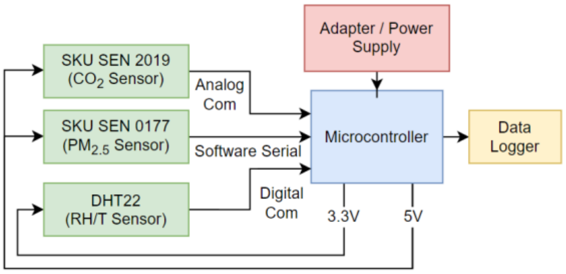

Fig. 2. System with 3 sensors.

accuracy of ± 2% (max ± 5%) of readings [27]. The system is divided into two, CO and NO_2 sensors on the first microcontroller (Fig. 1) and $PM_{2.5}$, CO_2, and DHT22 systems on the second microcontroller (Fig. 2). Voltage of 5V will be directed towards CO, NO_2, $PM_{2.5}$, and CO_2. While a voltage of 3.3V will be utilized for DHT22. These data will then be recorded on the data logger.

The system is located in a chamber with a size of 25×20×15 cm to carry out vehicle emission test measurements. The measuring chamber containing the system can be seen in Fig. 3. The system is equipped with a rubber hose and an air pump to drain gas from the vehicle exhaust into the chamber and throw it into the free air. These conditions are designed so that the emission test equipment is already on the market.

With a chamber like this, the testing can be done quickly. It can be carried out in various places (flexible) because the small shape of the tool makes it easy to carry this (portable), making it practical to carry everywhere. Suppose there is damage or error in one component. The transparent case enhances reparability by facilitating in-depth damage analysis, while the readily accessible components improve its ease of repair. Furthermore, the sensor only necessitates a power source for the device, which can be easily obtained through electricity from various sources.

The objective of this system is to measure the emission of motor vehicle gas exhaust and find out how the measurement results are until the condition of the device is at a steady state and the time it takes for the system to stabilize.

The type of vehicle used is a small MPV Grand Livina 2013 with a capacity of 1500 cc.

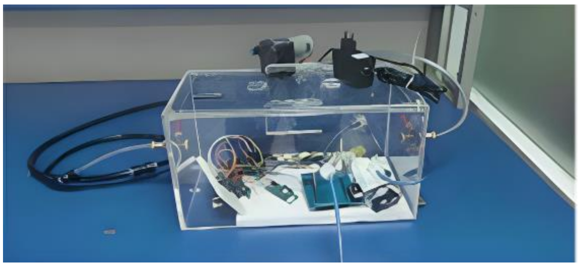

Fig. 3. Vehicle emission testing chamber.

The measurement data is processed and converted to ppm and percentage form units. Convert units to percent aims to compare these results with official emission test kits.

$$C_x(ppm) = \frac{(V_{gas} - V_{gas0})}{M} \tag{1}$$

$$V_{gas0} = V_{ref} + V_{offset} \tag{2}$$

$$\mathrm{M}\left(\frac{V}{ppm}\right) = \text{Sensitivity Code}\left(\frac{nA}{ppm}\right) \times \text{Tia Gain}\left(\frac{kV}{A}\right) \times 10^{-9}\left(\frac{A}{nA}\right) \times 10^{-3}\left(\frac{V}{kV}\right) \tag{3}$$

ppm to percent

$$x(\%) = \frac{x\ (ppm)}{10000} \tag{4}$$

The data is processed and converted to units in ppm and percentage form. Convert units to percent aims to compare these results with official emission test kits. To transform millivolt (mV) into ppm, Eq. 1 is used. This equation involves dividing the difference between the gas volume (V_{gas}) and the initial gas volume (V_{gas0}) by the gas concentration (M). The initial gas volume can be determined by adding the reference volume (V_{ref}) to the offset volume (V_{offset}), as specified in Eq. 2. To calculate the gas concentration, Eq. 3 is applied, which multiplies the Sensitivity Code, a distinctive identifier supplied by the manufacturer, and the TIA gain, denoting the amplifier's trans-impedance gain originating from the sensor. Eq. 4 is then used to convert ppm units to percent.

2.2 Measurement Technique

The measured gas flow rate is prepared before use for the best results. Adjusting the gas flow rate is essential because it will affect the sensor readings and speed up gas disposal in the chamber. Accurate and precise air quality measurements necessitate properly calibrating and verifying the gas flow rate [22].

If it is not disposed of within a specific time, it will interfere with the measurement process. This work conducted the test with a 12-15 L/minute flow rate. The use of this speed is because, at that speed, the gas can flow optimally and quickly into the outside air.

The device needs to undergo a 20-minute

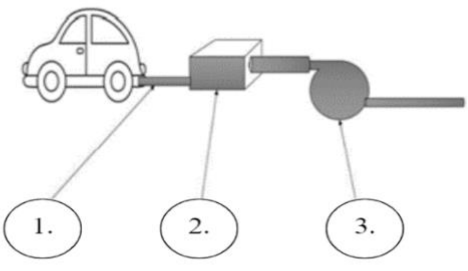

Fig. 4. Flow design for testing.

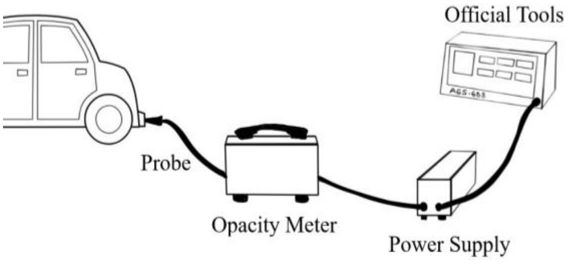

Fig. 5. Schematic Illustration of Measurement Using Official Tools.

calibration process to achieve accurate measurements. The results show that the measurement is in a constant/steady state at 10 minutes. As a result, it was determined that approximately 10 minutes were needed to obtain an effective measurement of motorized vehicle emission assessments.

The first circle in Fig. 4 represents the flow used to conduct measurements, which begins with starting the vehicle's engine and pumping in the measuring chamber for five minutes. The measuring hose is then connected to the vehicle's exhaust. After that, wait 10 minutes for the measurement to determine the vehicle's emission value shown in circle 2. After obtaining the vehicle emission value, the data undergoes processing and is graphically represented. Once the value stabilizes at the initial sensor measurement, the chamber is cleansed by extracting residual emissions using an air pump, applying alcohol, and wiping with a dry tissue. The next step is to clean up the residue shown in Circle 3. The purpose is to clean up the remnants of vehicle emission residues that are still left in the chamber so that the value in the subsequent measurement is not affected by the residue from the previous measurement. Afterward, the measurement results were examined to evaluate the system's performance and the measurement's accuracy. These results were compared with the performance of mass emission measuring instruments used by agencies/companies to test motor vehicle emissions.

2.3 Measurement using Official Tools

As official tools to measure gas emissions, this research used AGS-688 from Brain Bee, which has a range of 0-9.99% CO and 0-50% CO_2. The measurement was made by connecting a 12 V power supply to an official tool and a smoke opacity meter (OPA 300). A 30-cm-long copper rod inserted into the exhaust gas outlet of the vehicle is used as a measuring device mounted on a probe or gas sensor for display. The hose connects the probes and displays together. The tests were conducted using an initial sample and a chemically activated adsorbent to determine CO and CO_2 emission levels with changes. CO, CO_2, and Hydrocarbon (HC) exhaust gases are examples of exhaust gases that can be studied. The machine must be warmed up for 20 minutes before measurement, and the gauge must be at zero (calibrated) condition. Inserting the probe into the muffler allows measurement of CO emission levels, and the LCD gauge displays exhaust emission level values in CO and CO_2 gas units. The schematic illustration of measurement using official tools is shown in Fig. 5.

3. Result and Discussion

3.1 Flow rate used for measuring vehicle emissions

The measured gas flow rate is prepared beforehand to obtain the best vehicle emission test measurement results. A flow rate pump is also required because the exhaust gas will flow into a chamber containing various gas sensors for measuring motor vehicle emissions. The gas flow rate setting is essential because it affects the results of the sensor reading and speeds up the exhaust of the gas in the chamber to the free air. If not removed under certain conditions, it adversely affects measuring vehicle emissions.

The measurement is performed three times using the same device within a consistent interval. Using a high flow rate, the data extracted from Fig. 6 demonstrates a striking similarity in the observed trends across the three measurements. In contrast to Fig. 7, with a moderate flow rate, and Fig. 8, with a low flow rate, it can be seen that the two have quite different trends. As a result, this search chose a high flow rate. This approach is implemented because the high flow rate ensures optimal gas flow without accumulation within the chamber. This leads to a swift, direct gas discharge into the outside air.

3.2 Optimal Time Testing

To ensure the ideal period to measure steady-state vehicle measurements and values, a preliminary time measurement of approximately 20 minutes is conducted before the measuring device is utilized to measure emissions in motorized cars. According to the data, the measurement is already in a steady or constant condition by the tenth minute. So, this study concludes that for the measurement of motor vehicle

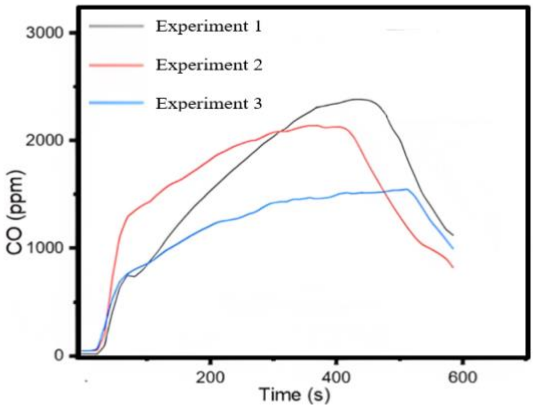

Fig. 6. High-speed flow rate.

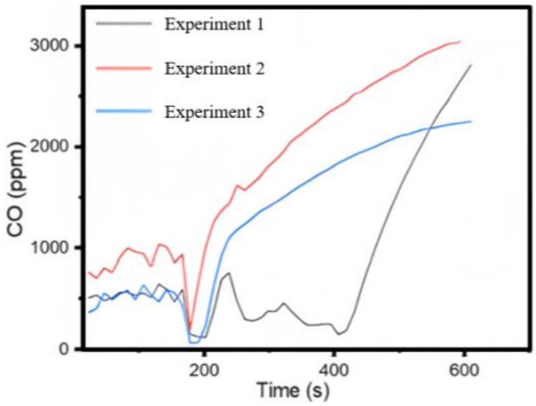

Fig. 7. Medium speed flow rate.

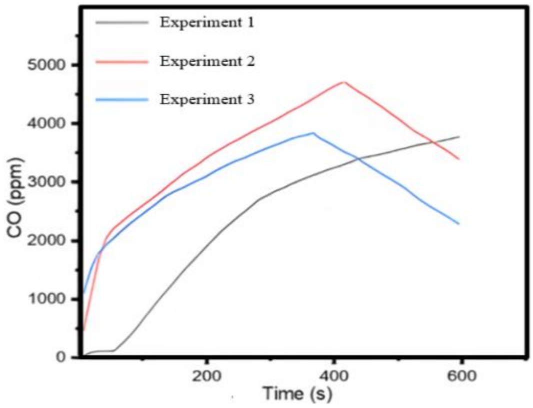

Fig. 8. Low-speed flow rate.

emissions, the time to get the final result of how the condition is measured is about 10 minutes of testing time.

In Fig. 9, the concentration of NO_2 at a steady state after 10 minutes of measurement time is about 11 ppm. According to Fig. 10, the CO concentration value is 365 ppm. Additionally, Fig. 11 displays the RH concentration data, around 73%. According to Fig. 12, the value of $PM_{2.5}$ measurement findings at a steady state is 53 µg/m^3. The CO_2 and temperature measurements are presented in Fig. 13 and Fig. 14. The concentration of CO_2 is 5,200 ppm, and the temperature is 28.9°C.

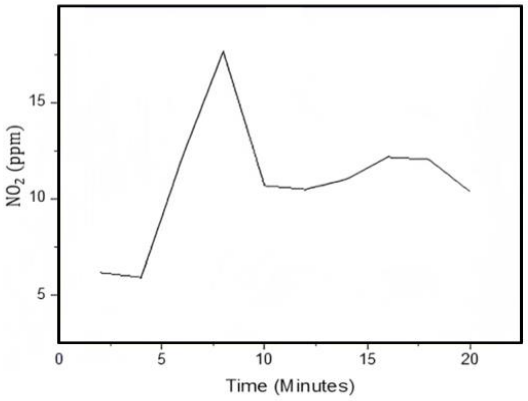

Fig. 9. NO_2 measurement for 20 minutes.

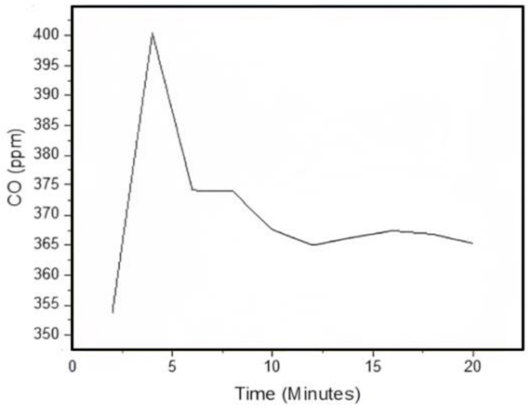

Fig. 10. CO measurement for 20 minutes.

3.3 Motor Vehicle Emission Test for 10 Minutes

In the low-cost sensor-based motor vehicle emission test, the measurements were conducted four times to determine the correlation value of each test for the CO, NO_2, $PM_{2.5}$, CO_2, temperature, and RH sensors (Fig. 15 – Fig. 20). For the CO sensor, the average value of the test at the 10th minute is 383.89 ppm with a standard deviation of 17.12. For the NO_2 sensor, the average value at the 10th minute is 10.72 ppm with a standard deviation of 3.21. For the CO_2 sensor, the average value of the test at the 10th minute is 5,254 ppm with a standard deviation of 14.72. The $PM_{2.5}$ sensor's average value is 50.25 µg/m^3 with a standard deviation 2.49. For temperature and RH sensors, the average temperature is 28.9 °C, and RH is 76.8%. The given parameters used for testing are shown in Table 1.

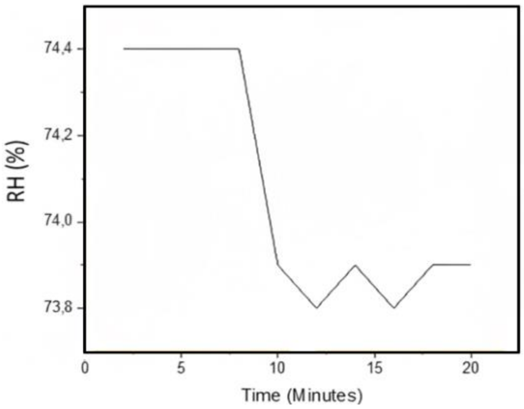

Fig. 11. RH measurement for 20 minutes.

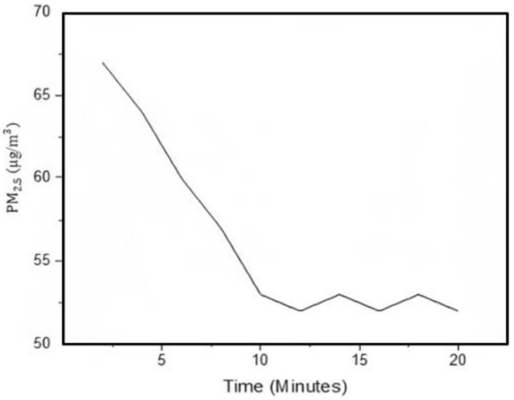

Fig. 12. $PM_{2.5}$ measurement for 20 minutes.

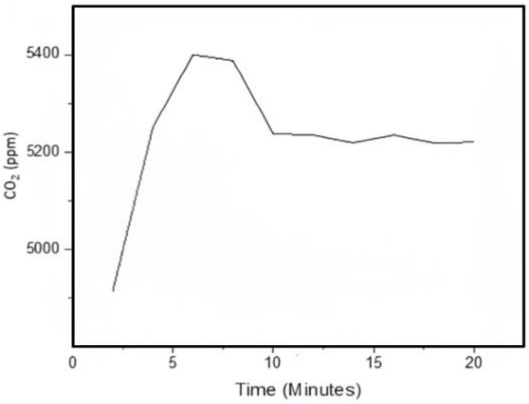

Fig. 13. CO_2 measurement for 20 minutes.

Table 1. Testing Parameters

Parameter	Average	Standard Deviation
CO	383.89 ppm	17.12
NO_2	10.72 ppm	3.21
CO_2	5,254 ppm	14.72
$PM_{2.5}$	50.25 μg/m³	2.49

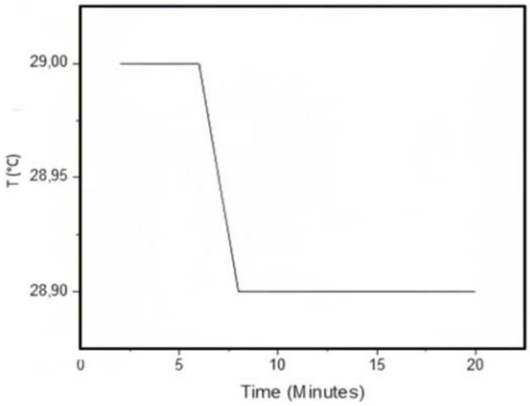

Fig. 14. Temperature measurement for 20 minutes.

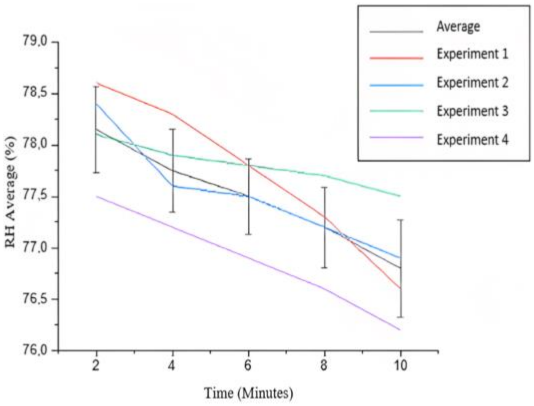

Fig. 15. RH measurement for 10 minutes.

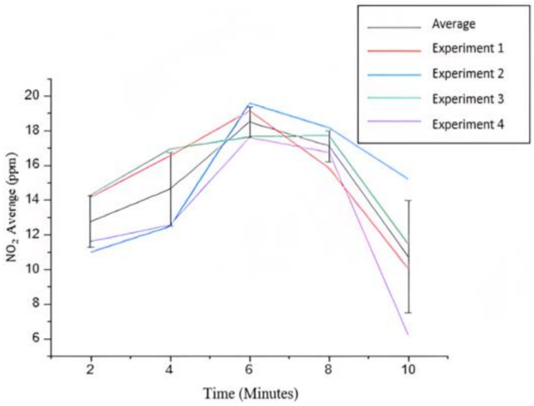

Fig. 16. NO_2 measurement for 10 minutes.

Table. 2. Comparison of Low-Cost Sensor Results and Official Emission Test Results.

Emission Test Results with Low-cost Sensor	Emission Test Results with Official Tools
$PM_{2.5}$: 50.25 μg/m³	-
CO_2: 5,254 ppm	CO_2: 14% (140,000 ppm)
CO: 383.891 ppm	CO: 0.12% (1,200 ppm)
NO_2: 10.7237 ppm	-
Temperature: 28.9 °C	Temperature: 80 °C
RH: 76%	-

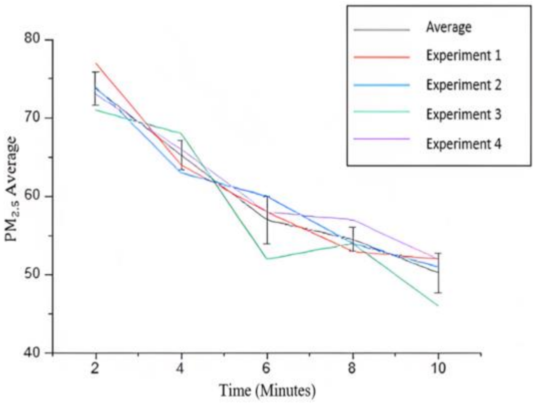

Fig. 17. $PM_{2.5}$ measurement for 10 minutes.

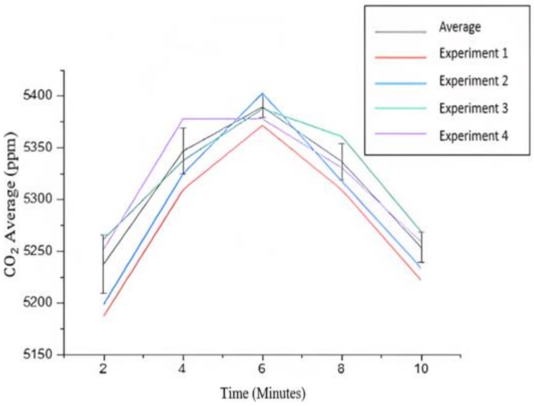

Fig. 18. CO_2 measurement for 10 minutes.

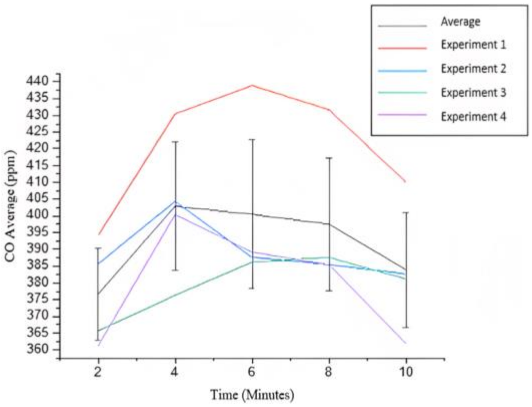

Fig. 19. CO measurement for 10 minutes.

A comparative analysis is conducted between the developed device and commonly used test equipment to assess its performance and accuracy. However, several parameters in the emission test kit are not used in testing motorized vehicle emissions based on low-cost sensors. Certain parameters in the emission test kit are not utilized in testing motorized vehicle emissions using low-cost sensors. Some parameters for gathering equivalent data include comparing the results of emission tests conducted with low-cost sensors and official emission test equipment, namely CO, CO2, and temperature (Table. 2).

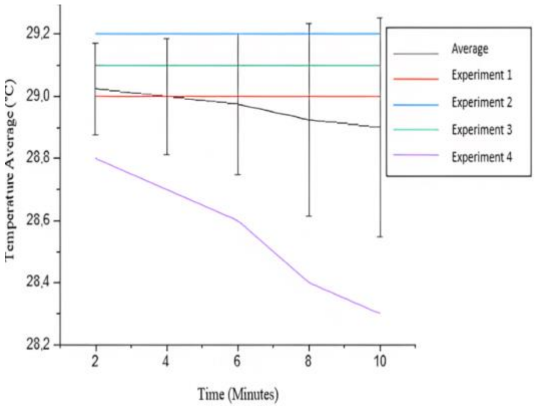

Fig. 20. Temperature measurement for 10 minutes.

The data shows that the CO_2 value in the official emission test is 14% or converted in ppm of 140,000 ppm. Meanwhile, when testing using an emission test kit with a low-cost sensor, a value of 5,254 ppm was obtained. Apart from that, there are also differences in the CO measurement results, where the CO value on the official CO tool is 0.12% or converted in ppm of 140,000 ppm. However, the data obtained in the emission test using a low-cost sensor was 383.891 ppm. Differences in these data can occur because the emission test data using a low-cost sensor has a smaller range than the official tool. For instance, the CO sensor value has a measurement range of 0-500 ppm, and the CO_2 sensor value has a measurement range of 400-5,000 ppm. These values can produce different measurements than test results data obtained using official tools. Based on the DHT22 datasheet, the temperature sensor range is -40 °C - 80 °C. The test results obtained are 28.9 °C. However, the emission test results obtained are 80 °C. This could happen because of the influence of temperature from the environment, which can cause error readings on the sensor, considering that the DHT 22 sensor is very susceptible to ambient temperature.

4. Conclusions

Research on vehicle emission test measuring instruments based on low-cost sensors has been conducted. This study uses the following parameters for testing motor vehicle emissions: CO, CO_2, NO_2, $PM_{2.5}$, temperature, and RH sensors. Based on the measurement results, a 12-15 lpm flow rate is better for testing because it can flow vehicle emission gases from the chamber to the free air and optimize sensor performance. For the measurement results using a low-cost sensor, the average value for CO is 383.891 ppm, NO_2 is 10.7237 ppm, CO_2 is 5,254 ppm, $PM_{2.5}$ is 50.25 $\mu g/m^3$, temperature and RH is 28.9 °C and 76%. The official test results obtained a CO value of 1,200 ppm, CO_2 of 140,000 ppm, and a temperature of 80 °C. These results have a significant difference because the reading range of the low-cost sensor is relatively small but has a steady-state trend of measurement data at the 10th minute. Low-cost sensor data can contribute to research studies and trend analysis over time. Collecting consistent data using low-cost sensors can identify long-term trends and assess the effectiveness of emission measures.

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