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A Gravimetric Methodology for Measuring Fuel Mass Flow Rate in a No-Load Engine Operating at Various RPMs

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ABSTRACT

The pursuit of performance tests that are both cost-effective and equipped with state-of-the-art technology stands as a vital objective. Among these tests, fuel consumption assessments emerge as crucial parameters in engine and vehicle evaluations. The main aim of this study is to establish a gravimetric methodology for quantifying fuel usage. The objective is to develop a methodology that is both uncomplicated and simple to use, while simultaneously ensuring the instrument's mobility. This study involves experiments on engines using B30 fuel. Recorded data is analyzed and compared with the flow meter. The research focuses on the KUBOTA D722 engine's operation without load across various RPM settings. The comparative results reveal disparities in measurement outcomes, with variations of 0,66 g/s, 0,93 g/s, and 0,31 g/s observed for engine rotation speeds of 1500, 1900, and 2200 RPM, respectively.

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INTRODUCTION

The demand for the use of alternative fuels in diesel engines is showing an increase [1]. Its use encompasses various fields, ranging from the transportation sector to power generation and agriculture [2]–[4]. These sectors often utilize alternative fuels derived from palm oil as biodiesel [5]. The material used to create a biodiesel blend is FAME (fatty acid methyl ester), which is derived from palm oil [6], [7]. This material is known for its environmentally friendly nature, high sustainability, non-toxicity, and sulphur-free properties [8], [9]. This is what makes palm oil a choice as a base material for blending with petroleum as biodiesel. The Indonesian government consistently promotes the progress of higher biodiesel blends.

Fuel consumption is one of the crucial parameters in testing the performance of an engine and a vehicle [10]. There are several methods for measuring fuel consumption. These include gravimetric and volumetric methods, which are the primary methods for determining fluid flow [11]. The gravimetric method involves

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measuring fuel consumption by weighing the fuel before and after the test [12]–[14]. Meanwhile, the volumetric method involves measuring fuel consumption by determining the flow volume of fuel using flowmeter sensors [15]. Researchers have widely conducted these methods on engines with both low and high power [16]. The measurement data provides information on the economic factors in its usage [7]. However, all the tests conducted incur high costs in their implementation.

In this research, a low-cost, simple to use and portable gravimetric method for fuel consumption measurement is developed, using a weighing device consisting of simple components. The weighing device consists of a load cell, with its signal amplified by an HX711 and connected to an Arduino UNO microcontroller. The results of the fuel mass flow rate measurements are then compared with the volumetric method that uses a calibrated flowmeter. This research could help to get an accurate measurement that has low cost and high portability.

MATERIALS AND METHODOLOGY

This research started by designing the equipment for gravimetric. The accuracy, error, and resolution of the sensor are considered important parameters. These parameters affect the result of measurement, uncertainty, and calibration process. The gravimetric should have recording equipment, either online/real-time monitoring or only recording to a memory device and downloading the data after the measurement.

After designing and building the gravimetric flow meter, it should calibrate and calculate the uncertainty. This process tests the validity of the measurements. The results should be below of acceptance value according to certain criteria.

Then to test the performance of the gravimetric flow meter, another standard flow meter was used to compare the results. It was conducted by comparing the results of continuous measurement of gravimetric methods consisting of a load cell connected to Arduino microcontrollers and volumetric methods using KMA AVL flow meters. Measurements are made on an idle engine with no load in situ. The details of each step are explained in the following section.

Engine Specification

This research used a Kubota D722 diesel engine as equipment to compare the flowmeter of both systems. Kubota D722 is a multi-cylinder diesel engine for electricity generators. The technical specifications of the engine are shown in **Table 1**.

The working fluid for this research is commercial diesel fuel. The specifications of the diesel fuel used are biodiesel B30, as indicated in **Table 2.**

Table 1. Technical Specifications of Kubota D722 [17]

No.	Parameter	Unit	Description
1	Design	-	Vertical, water-cooled, 4-stroke diesel
2	Number of Cylinders	-	3
3	Stroke Volume	l	0.719
4	Bore x Stroke	mm	Ø 67 x 68
5	Engine rated speed	rpm	3000
6	Oil Capacity	l	3.4
7	Fuel Tank Capacity	l	3.7

Table 2. Technical Specifications of B30 Fuel [18]

No.	Parameter	Unit	Min	Max
1	Cetane Number	-	51	-
2	Density (at 15°C)	kg/m^3	850	890
3	Viscosity (at 15°C)	cSt	2.3	6.0

Volumetric Method Measurement Instrument (Flowmeter)

In this method, fuel consumption measurement is carried out using a flow meter sensor that operates on the positive displacement principle to obtain fuel consumption data. **Figure 1** shows the movement of the screw for one rotation is proportional to the flow volume per unit of time. These results need to be periodically calibrated using the gravimetric method [19].

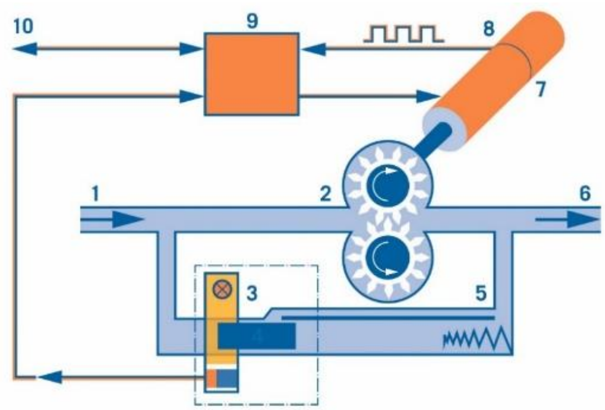

Figure 1. Diagram of flow meter measurement [20]

The AVL KMA Mobile comprises a gear meter (2), pressure differential sensor (3), control electronics (9), servo driver (4), and interface (10). The electronic controller and servo driver regulate the pressure differential across the gear meter to zero, establishing a direct proportionality between the gear meter speed and the flow. Fuel is introduced from (1) via the gear motor and exits through (6). (5) serves as a by-pass and a space for the measuring coil, producing varying magnetic resistance. These resistances undergo evaluation by the subsequent control electronics. The resulting output voltage (8) acts as the reference value for the subsequent speed control of the servo drive.

$$Qv = \frac{f}{k} \quad (1)$$

$$Qm = Qv * \rho \quad (2)$$

Equation (1) and (2) are for calculating the volume flow rate and mass flow rate respectively. Where Qv is the volume flow rate of the fluid in cm^3/s, f is number of screw rotations or frequency in Hz, and k for correction factor for volume of each pulse in pulse/l. K-factor was obtained from the calibration process. To get the mass flow rate or Qm (g/s) is multiplied the volume flow rate by fuel density, ρ, in g/cm^3.

A standard instrument commonly used for testing measurements is the volumetric flowmeter in this study.

Table 3. Technical Specifications of AVL KMA Mobile [20]

No.	KMA Mobile	
1	Type	AVL KMA Mobile
2	Measurement Range	0,16 – 75 liter/hour
3	Resolution	3 400 – 840 pulse/cm^3
4	Measurement Uncertainty of Volume/Mass	≤ 0,1% (according to DIN 1319)
5	Density	1 g/dm^3
6	Response Time	<125 ms (according to ISO 16183)
7	Inlet Pressure	0,3 – 5 bar

Gravimetric Method Measurement Instrument (load cell)

Measurement using the gravimetric method is performed with a weighing instrument consisting of a load cell sensor commonly available in the market with a capacity of 40 kg, a resolution of 1/15000 g, a rated output of 2 mV/V, non-linear characteristics of 0.02% F.S, and creep characteristics for 30 minutes at 0.0016% F.S. The ADC module (analog to digital conversion) HX711 has a 24-bit accuracy and a differential output of 40 mV. The Arduino Uno microprocessor has 14 input/output pins using optical technology, 6 Pulse Width Modulation (PWM) outputs, and 6 analog inputs. It operates with a 16 MHz crystal oscillator and is programmed in the C++ language. In the fuel weight measurement, data is continuously recorded from the beginning to the end of the testing process at a data acquisition rate of 10 data points per second. The measurement results are calculated as the average difference in fuel weight per second. [12]–[14].

$$\dot{m} = \left|\frac{m_2 - m_1}{\Delta t}\right| \quad (3)$$

Equation (3) is the formula to get the mass flow rate, $\dot{m}$, in gravimetric measurement. m_1 and m_2 are initial and final mass in g, respectively, and Δt is total time in s.

Design

This process involves the use of a 40 kg capacity load cell, equipped with the HX711 signal amplifier, and an Arduino Uno microcontroller. The data generated by the microcontroller is transmitted to the data processor through the Integrated Development Environment (IDE) software. **Figure 2** shows the configuration of the gravimetric.

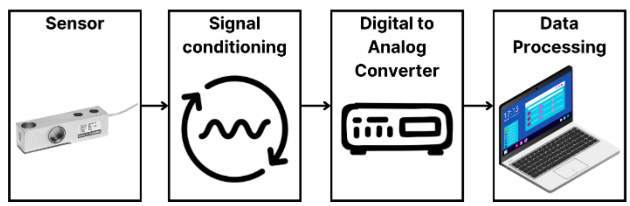

Figure 2. Scale Equipment Configuration

Calibration

The calibration process is conducted by measuring the loadcell equipment with a calibrated weight standard and the calibration process follows the applicable standard [21]. Gravimetric measures the incremental and decremental process until the maximum capacity of the load cell.

The calibration process depends on the capacity of the load cell and the load measured for this research. The calibration conduct repeats several times, at least 3, to get a better result of calibration and accommodate the error between measurements.

Table 4. Uncertainty calculation of load cell

Items	Resource	Uncertainty Formula	Uncertainty Value	Sensitivity (C)	Unit	Standard	Unit
UA	Repeated Observations	S/√n	0,239	1	-	0,239	gr
UB1	Resolution	0,001/√3	0,001	1	-	0,001	gr
UB2	Certification	7/2	0,0035	1	-	0,0035	gr
				U^2L		0,0574	gr
				Combined Uncertainty		0,2396	gr
				Expanded Uncertainty (k=2)		0,4793	gr

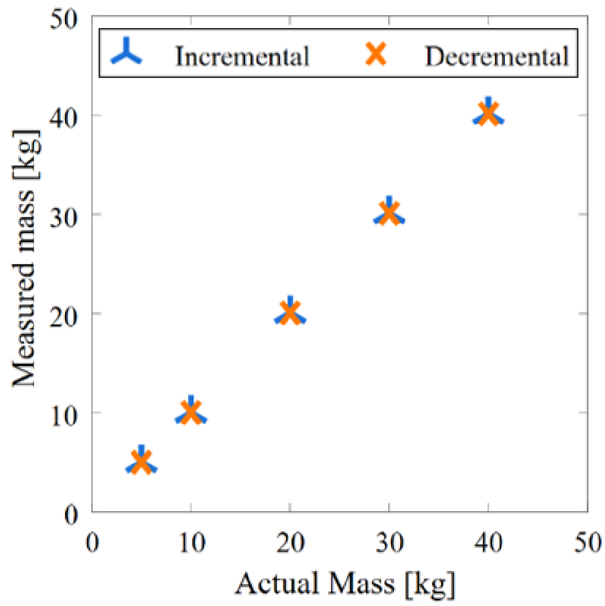

Figure 3. Load cell Calibration Results

Figure 3 shows the calibration process using a calibrated weight standard. The load cell measured well for both incremental and decremental processes. The calibration results show no difference between incremental and decremental measurements. These results present good measurements for the load cell. Meanwhile, the load cell uncertainty value is 0.4793, as shown in **Table 4**.

Table 4 shows the uncertainty calculation of the load cell. There are two types of uncertainty, type A and type B. Type A uncertainty from statistical measurements. Uncertainty from type A is from repeated observation. Meanwhile, type B uncertainty is parameters that are unrelated to the statistical measurements, such as resolution and certification.

Comparative Test

Fuel mass flow rate measurements were conducted on the engine under no load conditions with varying rpm in situ. The findings of the gravimetric method measurements are subsequently compared to those of the volumetric method measurements. Engine testing is performed continuously. **Figure 4** shows the test cycle conducted for this research. The engine operates under no-load conditions at 1500, 1900, and 2200 rpm [22]. The engine operates using B30 biodiesel fuel.

The fuel supply tank is placed on top of the scale, and then the fuel is delivered to the engine through a filter and a flowmeter. The engine is run under no-load conditions at a designated speed. After the condition stabilizes, data is simultaneously recorded using both software, which is AVL Device Control Software (flowmeter) and Arduino IDE (load cell) continuously.

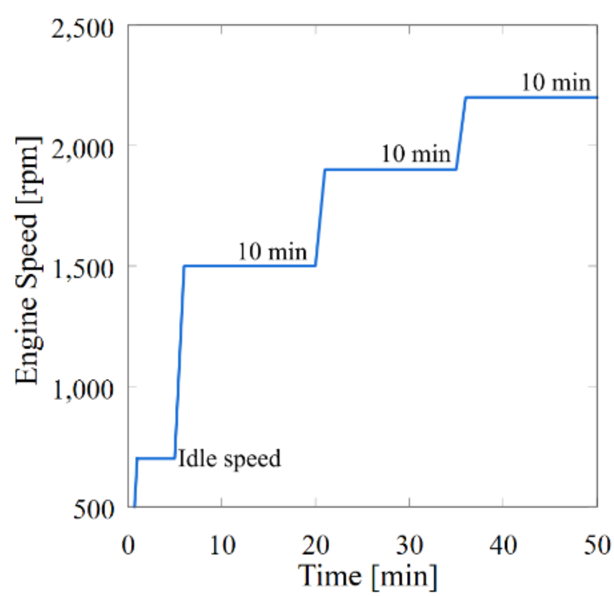

Figure 4. In-situ test cycle

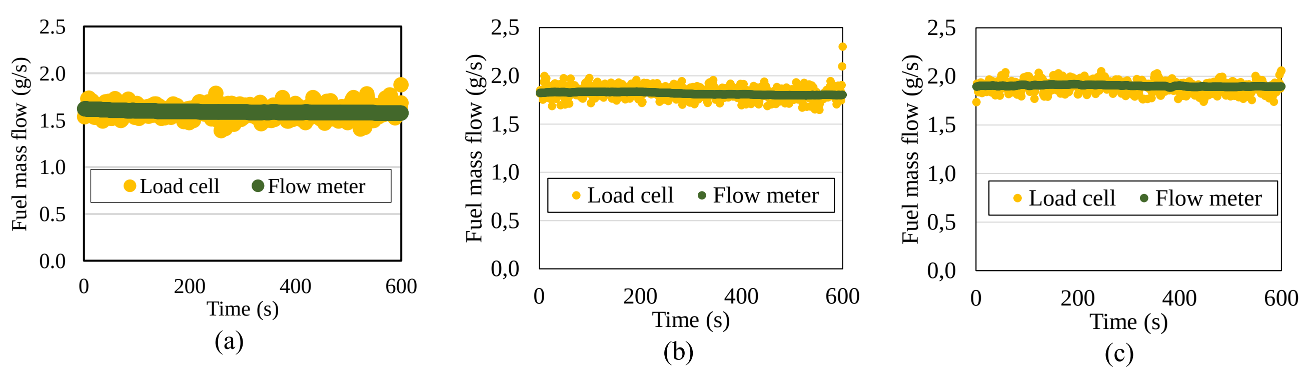

Figure 5. Mass flow rate measurement comparison at (a) 1500 rpm, (b) 1900 rpm, and (c) 2200 rpm

Table 5. The average measurement result of each rpms

No.	RPM	Load cell (g/s)	Flow meter (g/s)	Diff (g/s)	Error %
1	1500	1,599	1,588	0,011	0,72%
2	1900	1,834	1,816	0,018	0,99%
3	2200	1,896	1,902	0,006	0,33%

RESULTS AND DISCUSSION

The Idle Test Result

Figure 5 and **Table 5** show a comparison of the results of measurements in an idle mode in situ between the gravimetric method and the volumetric method in a 10-minute test, the difference in the average fuel flow rate at 1500 rpm is 0.11 g/s, while the difference at 1900 rpm is 0.018 g/s. And at 2200 rpm is 0.006 g/s. At 1900 rpm, the difference between the two methods shows the highest value with a higher gravimetric average value. While at 2200 rpm, the volumetric value is higher than gravimetric.

The data logging speed with the Arduino microprocessor was found to be better. It makes the weighing equipment suitable for transient measurements as it is more responsive than the flow meter. Figure 5 shows that volumetric measurement is more stable, so it needs to be developed further to increase the stability of gravimetric measurements.

This method, which utilizes a gravimetric approach, has been shown to yield more accurate results than previous research [14]. The present study delves into a comprehensive comparison of the gravimetric and Duarte et al. methods, scrutinizing their respective accuracies and underlying principles. The gravimetric method exhibits superior performance, particularly under conditions of high load or high speed. This enhanced accuracy can be attributed to the gravimetric method's extended measurement duration, which facilitates the capture of more precise fuel consumption data.

CONCLUSION

The measurement results of the mass flow rate conducted by the weighing equipment compared to the flow meter show similar results with an error value of less than 1%. On the other hand, it was found that the weighing equipment, aided by the Arduino microprocessor provides a better response. Further research is needed with different engine capacities and test cycles. This study demonstrates that measuring fuel flow rate using weighing equipment is low-cost, simple, and the instrument’s mobility can be used to measure fuel flow rate effectively, although some aspects need improvement to achieve accurate and reliable measurements.

AUTHOR CONTRIBUTIONS

Henry Nolandy, MSK Tony Suryo Utomo, Berkah Fajar Tamtomo Kiono, Respatya Teguh Soewono, and Kurnia Fajar Adhi Sukra contributed equally to this research.

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