Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Development of a gravimetric fuel measurement system for the evaluation of engine performance physical parameters

To cite this article: G C Prada Botia *et al* 2021 *J. Phys.: Conf. Ser.* **2073** 012015

Development of a gravimetric fuel measurement system for the evaluation of engine performance physical parameters

G C Prada Botia[1], **J P Rojas Suárez**[1], **and M S Orjuela Abril**[1]
[1] Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: sofiaorjuela@ufps.edu.co

Abstract. This paper presents the implementation and design features of a gravimetric-based fuel consumption system. The proposed system comprises a gravimetric balance with serial output, a fuel pump, and a control valve that are integrated into a complete engine test bench via Arduino UNO®. The study implements an instrumentation methodology to minimize measurement disturbance and error propagation, which represents a major concern in engine experimental testing. Moreover, an interactive virtual environment is developed to reinforce user interaction via LabView™. Results demonstrated that the proposed measurement system features robust and reliable operation while maintaining negligible disturbance and overall uncertainty ranging from 0.010-0.23 g/s. Additionally, it was evidenced that the measurement system allows the analysis of key parameters to evaluate engine performance. The study of the fuels blends shows that the ethanol content causes a 6.8% increase in brake specific fuel consumption and a 4% decrease in the brake thermal efficiency. Due to the low cost of the developed measurement system can be easily adapted to test bench laboratories to promote a better learning process and in industrial sectors for better energy management.

1. Introduction

Internal combustion engines have paved an essential role in technological development in many countries due to the predominant importance in various sectors such as transportation, power generation, and agriculture, to mention a few [1–3]. Nowadays, different type of alternatives has been proposed for these thermal machines to minimize greenhouse emissions and fuel consumption, while increasing engine performance. For instance, published research is increasingly exploring alternative fuel blends, hydroxy doping, control strategies, engine design, optimization methodologies, waste heat recovery, exhaust gas recirculation, among others [4]. Particularly, fossil-fuel depletion overcomes a major concern worldwide due to the unprecedented consequences to our socio-political and environmental state. Therefore, both researchers and academics are intensively implementing experimental setups to unravel the prospective advantages of different strategies towards fuel consumption minimization [5]. Hence, the relevance of accurate measuring fuel consumption metrics relies on the performance characterization that is governed by the air-fuel mixture in the engine [6]. In this sense, the fuel sensor must be integrated into additional electronic elements to guarantee reliability while providing robust performance and suitable control [7]. The latter intensifies the investment costs while hindering the consolidation of small-scale experimental modules.

There is a plethora of mass and volumetric flow measurement systems in the market that are classified depending on the operation principle [8]. Low-mass flow margin applications generally implement Coriolis-based instruments, which feature accurate predictions at the expense of high acquisition cost

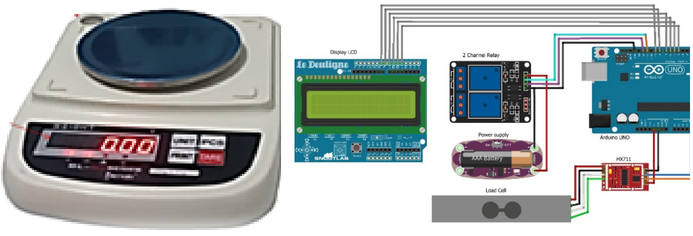
[9]. Therefore, a techno-economic alternative is to implement gravimetric-based measurement, which captures the mass of fuel injected in the engine through a time interval. Despite being a non-expensive alternative, this fuel measurement methodology features robust performance. Indeed, this methodology is in accordance with the API MPMS standards (American Petroleum Institute - Manual of Petroleum Measurement Standard) that serves as a recognized reference to calibrate mass flow meters. The aforementioned advantages make this fuel measuring methodology an ideal candidate for massive implementation in research projects.

The physical phenomena involved in the operation of this component have been extensively studied in the literature. However, there is a knowledge gap regarding practical applications for implementation in experimental modules while describing the overall performance of this component. Thus, the major contribution of this research is to describe the main operational features of a gravimetric fuel instrument. The incorporation of design guidelines to implement a virtual environment for data processing (DAQ) emerges as a differential factor in this research. The foregoing, to facilitate the performance evaluation of internal combustion engines, allow a more complete study in the test benches dedicated to learning and teaching and better energy management in the different industrial sectors that use this type of thermal machine.

2. Methodology

Figure 1(a) displays the electronic weight scale BL-H2 from the manufacturer Bernalo®. The equipment holds a resolution margin of 0.01 g and a load capacity of 1000 g. The weight scale measures the mass of fuel exiting from a beaker recipient through the filling cycle until the minimum set point is reached. Similarly, the equipment starts fuel consumption measurement when the maximum set point is reached.

The system uses a HX711 module that operates as a load cell transmitter to convert the signal from the load cell in grams. The output weight is then stored to calculate the mass differential over time. Accordingly, the specific fuel consumption (g/s) is calculated and delivered to a 0-5 V signal output. It is worth mentioning that once the system achieves the minimum permissible weight for the measurement, the instrument switches to the filling state, thus energizing the pump and opening the valve to fill the baker of the weight scale. Once the container is filled, the scale starts measuring again. Notice that both filling and measuring processes can be interrupted by pressing the emergency switch. Moreover, the integration of the weight scale to the HX711 Module enables serial communication between the weight scale and the Arduino UNO®, which represents the user interface to enable control in the proposed measuring equipment. Figure 1b shows the schematic representation of the system layout. The experiments are performed on a test bench, as illustrated in Figure 2. Moreover, the efficacy of the gravimetric-based fuel measurements is compared with a flowmeter YF-S401 that serves as the baseline for comparison schemes.



(a) (b)

Figure 1. Schematics of the (a) gravimetric fuel meter and (b) Arduino arrange for DAQ.

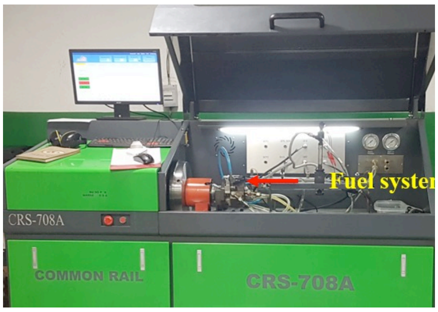


Figure 2. Fuel system test bench.

2.1. Data conditioning system

Data conditioning and system control are powered by Arduino UNO®, which receives the information from the electronic weight scale and transforms it into electrical outputs to facilitate the regulation of the filling cycle by activating/deactivating the solenoid valve and fuel pump.

The operation of the system is configured to identify the minimum set point on the weight scale as the input signal to close the circuit. The latter represents the starting signal for the solenoid valve and pump to operate in the filling cycle. This process is identified by a red signal on the control cabinet panel. Subsequently, the filling process stops until the maximum set point is reached on the weight scale, which de-energizes the electric flow of the fuel system while initiating the measuring cycle identified by a green signal in the control cabinet panel.

2.2. Uncertainty analysis

Experimental measurements are significantly altered by different factors such as environmental conditions, equipment calibration, signal noise, human errors, among others. Therefore, every measurement holds an implicit uncertainty that must be quantified. The study follows the Type A methodology that mainly comprises measurement repetitions to compute statistical calculations related to the overall uncertainty. The best estimate of a series of measurements is calculated according to Equation (1) [10].

$$\bar{q} = \frac{1}{n} \cdot \sum_{i=1}^{n} q_i, \tag{1}$$

where $\bar{q}$ is the average value of the series of measurements, q_i is the individual measurement and n is the number of measurements. Subsequently, the standard deviation (S) is calculated as stated in Equation (2) [10].

$$S = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (q_i - \bar{q})^2}. \tag{2}$$

3. Results

This section presents the core findings of the fuel measuring implementation. First, Figure 3 depicts the schematic representation of the DAQ system developed in LabViewTM that enables organization by recording the output data in an excel datasheet.

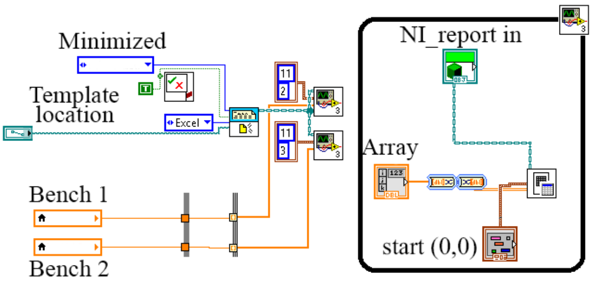


Figure 3. LabViewTM programming scheme for DAQ.

Table 1 displays the recorded data from the DAQ system of the test bench in free output consumption mode. The output results of the gravimetric-based meter have been denoted in run numbers, whereas the output data obtained from the flowmeter is identified in series numbers. According to the results, both the gravimetric-based and flowmeter components feature similar calculations, which supports the efficacy the data deviation reaches a maximum value of 0.23%, which can be associated with vibrations induced by fuel flowing through the tubes [11]. Calibration imprecisions in the electronic weight scale can be mentioned as another contributor. Figure 4 shows the overall results obtained from the comparison of both instruments.

Based on Figure 4, the data deviation of the flowmeter presents an increasing trend as the fuel flow rises, which can be associated with the magnification of error propagation at this regime due to adverse velocity gradients and turbulent interactions that affects the final measure [12]. In a similar manner, the disturbance of the gravimetric-based system increases proportionally as the fuel flow escalates. The latter results from the intensification of electronic noise that mitigate the accurate prediction of fuel consumption over time. However, the uncertainty is significantly low, which supports the reliability of the proposed system.

On the other hand, Figure 5 displays the engine's fuel consumption using the gravimetric meter for a flow range of 0.3-0.6 LPM. According to the result of Figure 5, the initial stage presents measurement disturbance as the fuel consumption varies between 2-6%. However, after 5 seconds, the fuel consumption features a constant tendency which demonstrates stability within the calculations. This pattern is consistent with other measuring instruments that reported instabilities and unpredictability within the start-up of the engine testing [8,13].

Table 1. Output results of the fuel measuring system.

	Time (s)	1	2	3	4	5	6	7	8	S	$\bar{q}$
Free output consumption (Gravimetric meter)	Run 1 (g)	9.11	8.88	8.75	8.83	9.07	8.98	9.07	9.18	± 0.16	9.01
	Run 2 (g)	13.16	12.96	13.04	12.66	12.87	12.75	12.82	12.9	± 0.16	12.85
	Run 3 (g)	15.18	15.26	14.8	14.76	14.67	14.75	14.95	15.26	± 0.23	14.96
Free output consumption (flow meter)	Series 1 (g)	9.13	9.35	9.12	9.06	9.18	9.08	9.12	9.31	± 0.10	9.17
	Series 2 (g)	12.99	13.11	13.05	13.29	13.15	13.24	12.93	12.67	± 0.19	13.01
	Series 3 (g)	15.30	15.13	14.94	15.13	15.03	15.02	14.98	14.94	± 0.12	15.02

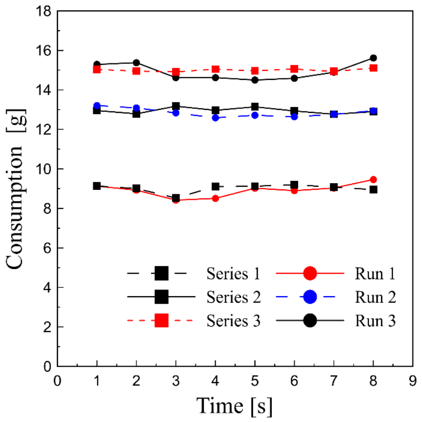


Figure 4. Comparison scheme from fuel measuring systems.

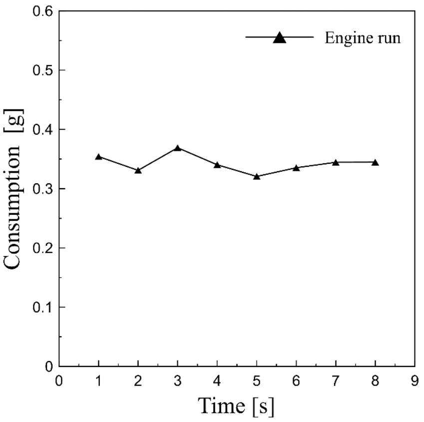


Figure 5. Engine run fuel consumption measuring.

The development of the fuel measurement system allows the evaluation of relevant engine performance parameters, such as the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE), which are defined by Equation (3) and Equation (4).

$$\mathrm{BSFC}\ \left(\frac{\mathrm{Kg}}{\mathrm{KW\cdot h}}\right) = \frac{\dot{\mathrm{m}}_{\mathrm{f}}(\mathrm{Kg/s})}{\dot{\mathrm{W}}_{\mathrm{engine}}\ (\mathrm{KW})} \times 3600, \tag{3}$$

$$\mathrm{BTE}\ (\%) = \frac{\dot{\mathrm{W}}_{\mathrm{engine}}\ (\mathrm{KW})}{\dot{\mathrm{m}}_{\mathrm{f}}(\mathrm{Kg/s})\cdot \mathrm{CV}(\mathrm{KJ/Kg})} \times 3600, \tag{4}$$

where $\dot{\mathrm{m}}_{\mathrm{f}}$ is the fuel flow, $\dot{\mathrm{W}}_{\mathrm{engine}}$ is the engine power and CV is the lower calorific Value. The composition of the fuel blends analyzed is indicated in Table 2. The experimental tests cover different levels of torque and rotational speed of the engine. In total, nine operating conditions were defined, which are shown in Table 3.

Table 2. Composition of test blends.

Nomenclature	Composition (%) Diesel (D)	Palm biodiesel (PB)	Ethanol (E)
D100	100	-	-
D95PB5	95	5	-
D93PB5E2	93	5	2
D91PB5E4	91	5	4

Table 3. Operation modes.

Operation mode	Brake torque (Nm)	Engine speed (rpm)
1	3.5	3200
2		3600
3		4000
4	5	3200
5		3600
6		4000
7	6.5	3200
8		3600
9		4000

The BSFC and BTE results for the test fuels under the different engine operating conditions are shown in Figure 6 and Figure 7. The results in Figure 6 show that fuel consumption increases with the addition of ethanol in the palm biodiesel blend. On average, the D93PB5E2 and DPB5E4 fuels describe an increase in BSFC of 4.7% and 8.9% compared to D95PB5, respectively. This is mainly attributed to the greater presence of oxygen present in ethanol, which causes a reduction in the calorific value of the fuel. Similar results are reported in the literature for other percentages of ethanol in biodiesel [14].

Figure 7 indicates that the BTE of the engine is reduced by the presence of ethanol in the fuel, which is directly related to the higher fuel consumption described in Figure 6. In the particular case of the fuel blends D100, D95PB5, D93PB5E2, and D91PB5E4 obtained a maximum BTE of 33%, 32%, 31%, and 30.5%, respectively. On average, a 2.2% and 5.8% decrease in BTE was observed for the D93PB5E2 and D91PB5E4 blends compared to D95PB5, respectively. Similar findings are reported in the literature [15].

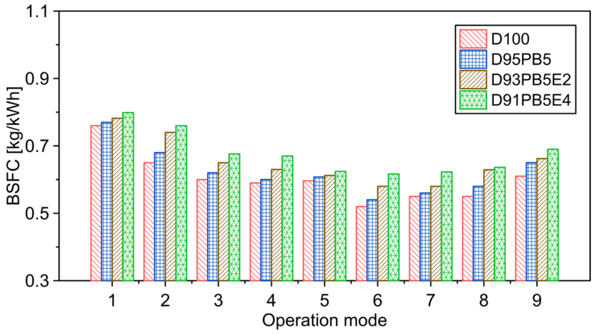


Figure 6. Brake specific fuel consumption.

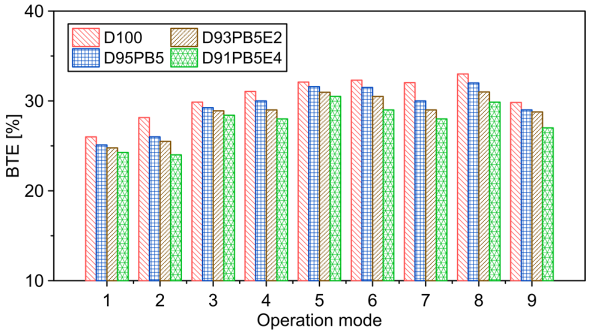


Figure 7. Brake thermal efficiency.

4. Conclusions

The present study outlines the main characteristics of the implementation of a gravimetric-based fuel measuring system. A complete characterization of the uncertainty analysis and design guidelines were discussed to embrace the massive penetration in experimental testing of internal combustion engines. The consolidation of a virtual interface in LabView TM to obtain and store the output data represents a unique factor from this research. Results indicated that the Arduino® code presents robust performance while processing the output signals from the HX711 load cell transmitter to convert it into fuel flow rate data. The proposed methodology enables control of the filling process in the gravimetric system by establishing maximum and minimum set points in the electronic weight scale.

The implementation of a DAQ system using the software LabVIEW™ promotes user interaction and further enables data processing every second in datasheets which facilitates the post-data treatment. On the other hand, the study proved that the gravimetric-based measuring systems present accurate predictions when compared to a commercial flowmeter YF-S401 with a relative error between 0.76 - 1.73%, which represents a confidence value of more than 95%. The overall uncertainty obtained within the calculations reaches ± 0.010 g/s for the engine consumption and ± 0.23 g/s for the maximum flow rate. The major factor for uncertainty and error propagation can be directly associated with residual vibrations, turbulent interactions, signal noise, among others, that reduce the accuracy of the fuel measuring system at a moderate level.

The developed fuel measurement system allows the analysis of relevant parameters to evaluate the performance of the engine under different fuel blends. Analysis of the blends D100, D95PB5, D93PB5E2, and D91PB5E4 shows that increasing the ethanol concentration causes a 6.8% increase in BSFC and a 4% decrease in brake thermal efficiency compared to palm oil biodiesel. Low investment and maintenance costs outweigh the particular advantages of gravimetry-based fuel metering systems, making it easy to consolidate a small and medium-scale budget engine test bed. In the future, it is proposed to increase the capacity of the measurement system for a complete characterization of the engine while maintaining a low economic cost and easy installation. In this way, it seeks to improve the educational learning capacity in test benches laboratories and facilitate energy decision-making in industrial sectors.

References

[1] Hernández-Comas B, Maestre-Cambronel D, Pardo-García C, Fonseca-Vigoya M D S, Pabón-León J 2021 Influence of compression rings on the dynamic characteristics and sealing capacity of the combustion chamber in diesel engines *Lubricants* **9(3)** 25

[2] Orozco T, Herrera M, Duarte Forero J 2019 CFD Study of heat exchangers applied in brayton cycles: a case study in supercritical condition using carbon dioxide as working fluid *Int. Rev. Model. Simulations* **12(2)** 72

[3] Consuegra F, Bula A, Guillín W, Sánchez J, Duarte Forero J 2019 Instantaneous in-cylinder volume considering deformation and clearance due to lubricating film in reciprocating internal combustion engines *Energies* **12(8)** 1437

[4] Patel R L, Sankhavara C D 2017 Biodiesel production from Karanja oil and its use in diesel engine: A review *Renew. Sustain. Energy Rev.* **71** 464

[5] Costa J F, Almeida M F, Alvim-Ferraz M C M, Dias J M 2013 Biodiesel production using oil from fish canning industry wastes *Energy Convers. Manag.* **74** 17

[6] Duarte J, Amador G, Garcia J, Fontalvo A, Vasquez Padilla R, Sanjuan M, Gonzalez Quiroga A 2014 Auto-ignition control in turbocharged internal combustion engines operating with gaseous fuels *Energy* **71** 137

[7] Ismail T M, Ramzy K, Abelwhab M N, Elnaghi B E, Abd El-Salam M, Ismail M I 2018 Performance of hybrid compression ignition engine using hydroxy (HHO) from dry cell *Energy Convers. Manag.* **155** 287

[8] Adefila K, Yan Y, Sun L, Wang T 2017 Flow measurement of CO_2 in a binary gaseous mixture using an averaging pitot tube and coriolis mass flowmeters *Int. J. Greenh. Gas Control* **63** 289

[9] Nazeri M, Maroto-Valer M M, Jukes E 2016 Performance of Coriolis flowmeters in CO_2 pipelines with pre-combustion, post-combustion and oxyfuel gas mixtures in carbon capture and storage *Int. J. Greenh. Gas Control* **54** 297

[10] Mendoza-Casseres D, Valencia-Ochoa G, Duarte-Forero J 2021 Experimental assessment of combustion performance in low-displacement stationary engines operating with biodiesel blends and hydroxy *Therm. Sci. Eng. Prog.* **23** 100883

[11] Chudina M 2003 Noise as an indicator of cavitation in a centrifugal pump *Acoust. Phys.* **49(4)** 463

[12] Beji T, Ebrahimzadeh S, Maragkos G, Merci B 2018 Numerical modelling of the interaction between water sprays and hot air jets - Part II: Two-phase flow simulations *Fire Saf. J.* **96** 143

[13] O'Banion T 2013 Coriolis: the direct approach to mass flow measurement *Chem. Eng. Prog.* **109(3)** 41

[14] Das D, Kumar A, Yadav A 2018 Evaluation of performance, emission and combustion characteristics of a CI engine fueled with karanja biodiesel and diethyl ether blends *Biofuels* **9(1)** 89

[15] Janakiraman S, Lakshmanan T, Raghu P 2021 Experimental investigative analysis of ternary (diesel + biodiesel + bio-ethanol) fuel blended with metal-doped titanium oxide nanoadditives tested on a diesel engine *Energy* **235** 121148