

Performance, energy balance, and emission characteristics of a spark ignition engine fueled with gasoline and LPG

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Abstract

Efforts to reduce greenhouse gas emissions continue to encourage the transition from liquid fossil fuels to gaseous fuels, as gaseous fuels are expected to provide cleaner combustion and lower hydrocarbon emissions. This study aimed to evaluate the performance of a spark ignition engine with a carburetor fuel system operated using gasoline and Liquefied Petroleum Gas (LPG), and to analyze its energy balance based on the First Law of Thermodynamics. The energy balance consisted of input energy from air and fuel, useful output energy, and energy losses during combustion. The engine was operated at speeds ranging from 2000 to 5000 rpm. Fuel consumption was measured after the engine consumed 50 mL of gasoline and 50 g of LPG. The results showed that emissions of HC, CO, and CO₂ from LPG were lower than those from gasoline. The useful energy produced by LPG combustion was lower than that of gasoline; however, LPG showed higher thermal efficiency due to lower Specific Fuel Consumption (SFC) and reduced energy losses. The conversion from gasoline to LPG in a carburetor system reduced emissions by approximately 7–73%, whereas the average reduction in an electronic fuel injection system was reported at 11–15%.

Keywords:

Carburetor injection system, hydrocarbon emission, liquefied petroleum gas, fuel economy, energy balance

1 Introduction

Energy diversification continues across various sectors, especially in Indonesia, not only in shifting from fossil fuels to biohydrocarbon fuels, but also in shifting from one type of fossil fuel to another, such as from liquid fuels to gas fuels. As one of the world's oil and gas-producing countries, Indonesia's crude oil availability was recorded at 3.8 billion barrels in 2019, with a Reserve-to-Production (R/P) ratio of 9 years. Meanwhile, in the same year, Indonesia's natural gas reserves were around 77 trillion Cubic Feet (TCF) or equivalent to 14 billion Barrels of Oil Equivalent (BOE), with an R/P ratio of 22 years [1][2]. Based on this information, Indonesia will enter an anomalous period during the Golden Indonesia period, which is predicted to be the year of Indonesia's glory, while at the same time, Indonesia faces an energy

shortage, if, within that time period, no new oil wells are discovered. To overcome the depletion of oil reserves, which will run out faster than gas reserves, converting oil energy to gas fuel is necessary.

The use of gas fuel in gasoline engines has been widely adopted and has undergone numerous studies. One of them was conducted by Zulfan, et al. [3] who used a gasoline-engined electric generator using gas fuel. The results of their research showed that the use of gas fuel in gasoline engines is very visible because the maximum energy produced is the same as the maximum energy in gasoline fuel. A comparison of the performance of gasoline fuel and gas fuel in gasoline engines was studied by Octo, et al. [4]. A converter kit and high-pressure regulator were applied to adopt the use of gas fuel in engines. The results showed that using gas fuel in gasoline engines can significantly improve several technical parameters, including engine surface temperature, exhaust gas temperature, and fuel consumption. Similarly, studies were conducted by Mohammed et al. [5] on a gasoline engine with a manual injection system (carburetor). A steel tube equipped with a regulator and a flow and pressure quantity measuring device when gas fuel is used. The results showed that the use of gas fuel can reduce emissions, HC, CO, CO₂, and NO_x, and increase thermal efficiency by 6.6% compared to gasoline fuel.

In-depth experimental and theoretical studies related to the comparison of the use of natural gas fuel (CNG) and gasoline fuel in internal combustion engines have been conducted by Semin et al. [6]. There are 5 main advantages of using CNG in internal combustion engines, namely: CNG is the only fuel that is cheaper than gasoline or even diesel, produces hydrocarbon emissions compared to fossil fuels, lower greenhouse emissions, its more massive use expands the use of gasoline in various sectors, and its reserves are available for a longer period of time than gasoline. Meanwhile, the primary problem that still needs to be solved for the use of natural gas fuel in internal combustion engines is the AFR, which often changes depending on operating conditions. The effect of using natural gas fuel in gasoline engines has also been studied by Ade Syafrinaldy et al. [7], who applied it to a 1500 cc 4-cylinder gasoline engine with a compression ratio of 9:1. The results show that the combustion efficiency of gasoline fuel is higher than CNG, but CNG is more economical. CNG produces lower CO and CO₂ emissions but emits higher levels of unburned gases such as NO, NO_x, and HC.

Gas fuel is commonly used not only as a single fuel but also in dual-fuel system engines, as demonstrated by Eshan Singh [8]. In these systems, the Port Fuel Injection (PFI) method introduces methane gas into the combustion chamber, while gasoline is delivered using the Gasoline Direct Injection (GDI) method in spark ignition engines. The results indicate that Nitrogen Oxide (NO_x) emissions remain relatively constant, even as the engine load increases, while carbon monoxide (CO) and Non-Methane Hydrocarbon (NMHC) emissions decrease. This study aims to compare the energy balance of a 110-cc gasoline engine with a conventional gravity injection system when fueled by gasoline and Liquefied Petroleum Gas (LPG).

This research serves as a reference for converting gasoline-powered vehicles to LPG, particularly for two-wheeled motorcycles with conventional injection systems that remain common in Indonesia. Most motorcycles use two-stroke engines, which are more fuel-efficient but produce higher hydrocarbon emissions. Converting from gasoline to LPG will help reduce these emissions and improve fuel economy [9]. Numerous studies have examined the conversion process from gasoline to LPG in spark-ignition engines equipped with electronic injection systems. This conversion did not significantly affect performance or decrease hydrocarbon emissions. However, when applied to engines with mechanical injection systems, it led to a significant reduction in emissions [10].

2 Literature review

The energy balance in a 110-cc carburetor engine is linked to that in the combustion chamber, as illustrated in Fig. 1. The energy

balance equation for the combustion chamber under steady-state conditions is Eq. (1) [11].

$$Q = \sum N_r (\bar{h}_f^o + \bar{h} - \bar{h}^o)_r - \sum N_p (\bar{h}_f^o + \bar{h} - \bar{h}^o)_p \quad (1)$$

It can also be expressed in a different equation form as Eq. (2).

$$\sum [N_r \bar{h}_f^o - N_p \bar{h}_f^o] + \sum N_r (\bar{h} - \bar{h}^o) = \sum N_p (\bar{h} - \bar{h}^o) + Q_{out} \quad (2)$$

where $a = \sum [N_r \bar{h}_f^o - N_p \bar{h}_f^o]$ is the energy of fuel, $b = \sum N_r (\bar{h} - \bar{h}^o)$ is the energy of air, $c = \sum N_p (\bar{h} - \bar{h}^o)$ is the energy of the product.

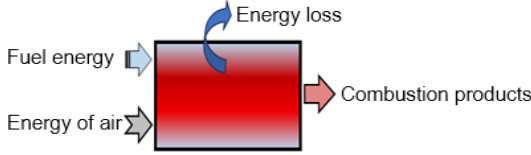
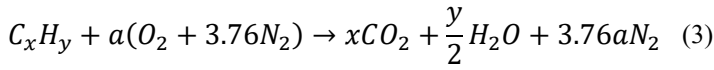


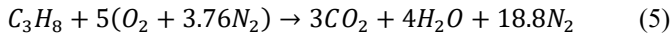
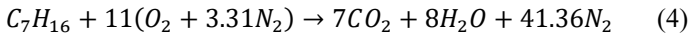
Fig. 1. The energy balance in the cylinder

Volumetric analysis of the substances contained in gasoline and LPG fuels, and the theoretical air-fuel ratio, can be determined by first knowing the combustion reaction equation of each fuel. The general equation for the stoichiometric combustion reaction for hydrocarbon fuels can be obtained from Eq. (3), with the value obtained using Eq. (4) [12].



$$a = x + \frac{y}{4} \quad (4)$$

Therefore, the stoichiometric combustion reactions for gasoline fuel (C_7H_{16}) and LPG (C_3H_8) can be expressed as shown in Eqs. (4) and (5), respectively.



Based on the reaction equation above, the mole fraction and molecular weight of each element in the fuel, air, and combustion product gas for gasoline and LPG combustion can be determined, as written in Table 1 and Table 2, while the molecular weight of each element is calculated using Eq. (6).

$$BM = Yix\overline{BM} \quad (6)$$

Eqs. (4) and (5) are used to calculate the energy content of each material substance involved in the reaction, specifically the fuel, combustion air, and the products as combustion gases. The energy quantity depends on the mole fraction of each material in the reaction equation. The values for these fractions are provided in Tables A-22 and A-23 of Michael J. Moran's book [13], which are based on the temperature of each substance. According to Eq. (3), the stoichiometric air-fuel ratio for the combustion of hydrocarbon fuel is expressed as shown in Eq. (7) [14].

$$AFR_{stoic} = \frac{(m_{air})}{(m_{fuel})_{stoic}} = \frac{4.76a}{1} \frac{MW_{air}}{MW_{fuel}} \quad (7)$$

Both the air-fuel ratios for gasoline and LPG fuels are represented in Eqs. (9) and (10).

$$AFR_{stoic-gasoline} = \frac{4.76(11) 28.84}{1} \frac{1}{100} = 15.1 \quad (9)$$

$$AFR_{stoic-LPG} = \frac{4,76(5) 28,84}{1} \frac{1}{44} = 15,6 \quad (10)$$

3 Research methodology

The test engine utilized in this study was a single-cylinder spark-ignition engine equipped with a carburetor fuel system, as detailed in Table 1. Therefore, the schematic diagram of the engine test is described in Fig. 2. This engine can run on two types of fuel: gasoline and LPG. For LPG, a gas fuel converter was employed, whereas a carburetor was used for gasoline. The test was conducted at engine speeds ranging from 2000 to 5000 RPM. At each RPM, the time taken for fuel consumption was recorded after using 50 mL of gasoline and 50 g of LPG. Two measuring tools were utilized: a measuring cup for the gasoline and a digital scale for the LPG. The test was conducted three times for each engine speed, and the average value was used to calculate engine performance. The calorific values of gasoline and LPG (propane) were 45 MJ/kg and 48.2 MJ/kg, respectively. Other properties of both fuels are presented in Table 2.

Table 1. Specification of the test engine

Parameter	Value
Displacement (cc)	109.1
Bore (mm)	53.3
Stroke (mm)	48.4
Compression ratio	9.5:1
Injection system	Carburetor
Transmission system	Chain (4 speed)
Maximum power (PS)	7.7 @7000 RPM
Maximum torque (N.m)	7.95 @5500 RPM

Table 2. Fuel properties

Property	Gasoline	LPG (Propane)
Chemical formula	C_7H_{16}	C_3H_8
Lower heating value (MJ/kg)	45	48.2
Density (kg/m ³)	770	2.0
Flame speed (m/s)	0.57	0.84
Research octane number	90	110

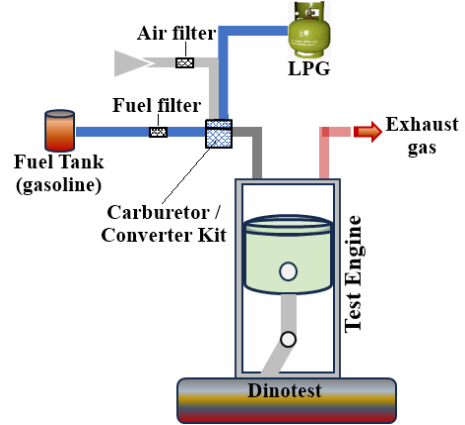


Fig. 2. Schematic of the experimental setup

The energy analysis conducted in this study aims to evaluate the energy content of fuel and air, as well as the combustion product gases containing various compounds from each material. The carburetor engine operates by using gravity to draw fuel and air into the cylinder, which leads us to assume a pressure of 1 atmosphere and a temperature of 32°C. Additionally, the temperature of the combustion products, comprising CO_2 , H_2O , and N_2 , is measured at the exhaust manifold.

4 Results and discussion

4.1 The engine performance

This research produced several significant findings concerning the performance and emissions of single-cylinder spark-ignition engines. These findings were analyzed through various parameters obtained from both observation and data analysis. Fig. 3 illustrates the trends in brake power and torque for gasoline- and LPG-fueled engines. Notably, the torque trends differ considerably from the brake power trends for both fuel types. Engine brake power typically increases as engine speed rises, and gasoline engines generally produce more power than LPG engines. In contrast, engine torque

tends to decrease with increasing engine speed, with gasoline engines also generating more torque than LPG engines. The rise in engine brake power at higher speeds is primarily due to increased fuel consumption.

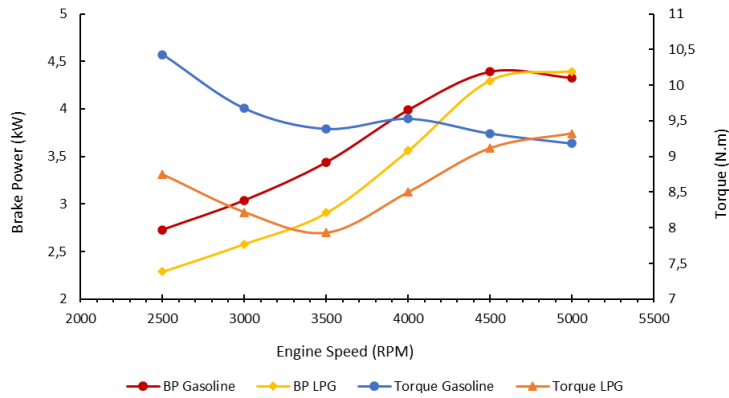


Fig. 3. Power and torque trends of the engine

The brake power of a gasoline engine is significantly higher than that of an LPG engine. This is because gasoline produces more energy, approximately 5.58 kW, while LPG yields only about 5.06 kW. As a result, the torque produced by an LPG engine or gas engine is lower than that of a gasoline engine [15, 16]. As engine speed increases, engine torque typically decreases. One reason for this reduction is the diminishing supply of air and fuel to the combustion chamber, which leads to a decrease in the engine's volumetric efficiency [17].

Fig. 4 and Fig. 5 show the fuel consumption and Specific Fuel Consumption (SFC) of a 110-cc spark-ignition engine fueled by gasoline and LPG. Fig. 4 illustrates that the time required to consume 50 mL of gasoline and 50 grams of LPG per minute decreases with increasing engine speed. This is because high engine speeds require an increased fuel supply, it's mean that the time needed to use up 50 mL (gasoline) or 50 gr (LPG) is shorter with increasing engine speed.

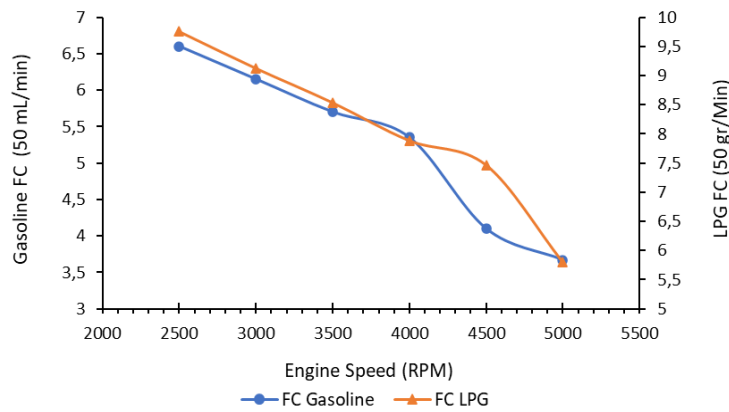


Fig. 4. Trends of fuel consumption of the test engine

Meanwhile, Fig. 5 demonstrates the mass flow rate of fuel to generate mechanical energy on the shaft per hour, commonly referred to as SFC. The figure shows that LPG's SFC is higher than that of gasoline, especially at low engine speed. However, LPG's SFC will be significantly lower than that of gasoline at engine speeds exceeding 4,000 rpm. This phenomenon occurs because the mixing of air and LPG fuel is significantly better than that of air and gasoline, as engine speed increases. Additionally, the density of LPG gas is much lower than that of gasoline (approximately 2.0 kg/m³ compared to about 770 kg/m³). This lower density allows for easier mixing with air, leading to a more efficient combustion process [18].

Fig. 6 illustrates the emissions of carbon monoxide (CO) and carbon dioxide (CO₂) from engines operating on gasoline and LPG fuels across different engine speeds. Emissions of both CO and CO₂ remain relatively stable as engine speed changes. Notably, the CO₂ emissions from LPG fuel are significantly lower than those from gasoline fuel. LPG gas blends with air more easily than gasoline, which helps reduce carbon monoxide emissions [19]. Additionally,

the production of CO₂ emissions from LPG is slightly lower than that from gasoline. It is easier to achieve a homogeneous mixture of LPG gas and air than that of gasoline and air because the distance between LPG gas molecules is greater than that of gasoline. As a result, LPG combustion produces less CO₂, which is the main byproduct of complete combustion [20][21]

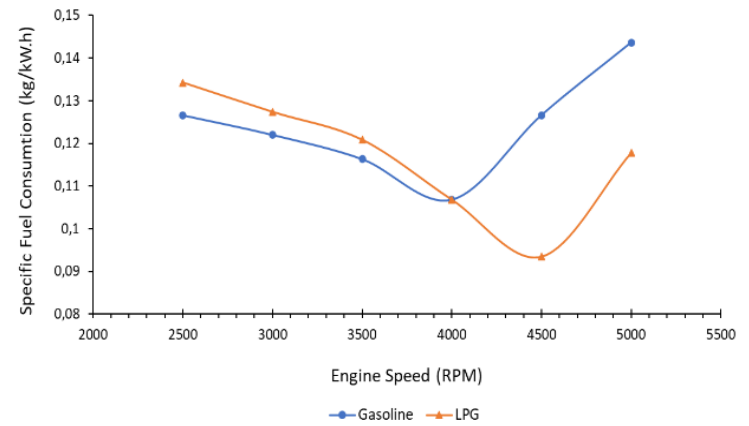


Fig. 5. Trend of the SFC of the engine

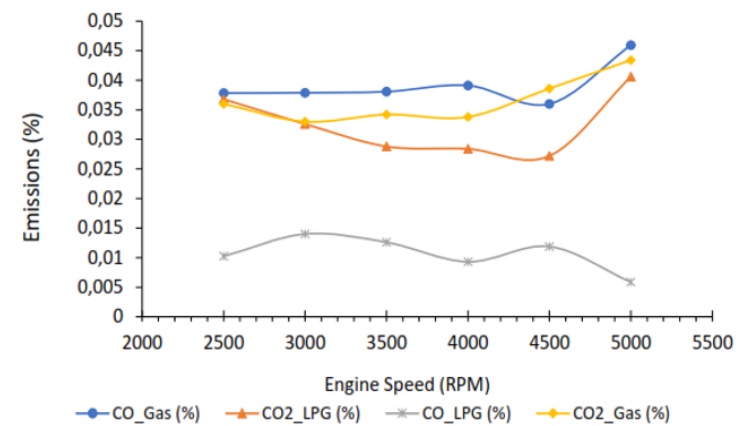


Fig. 6. CO and CO₂ emissions of the engine

Fig. 7 shows hydrocarbon (HC) emissions from a 110-cc single-cylinder spark-ignition engine powered by gasoline and LPG. The figure illustrates that HC emissions from gasoline tend to increase with increasing engine speed. This is because fuel supply to the combustion chamber increases with increasing engine speed, increasing the potential for combustion failure.

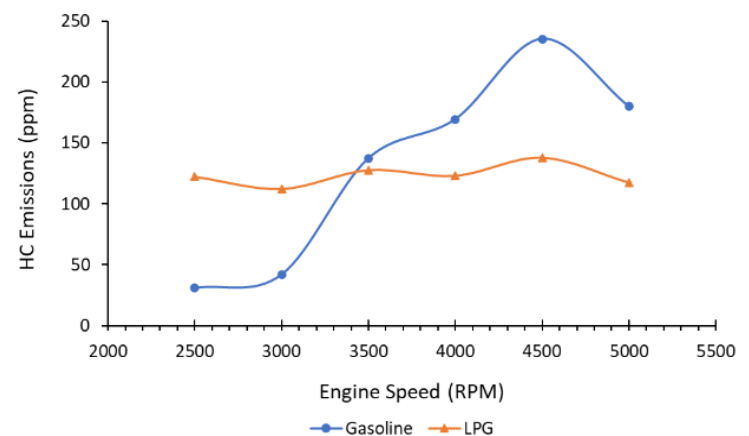


Fig. 7. HC emission production of the engine

Meanwhile, HC emissions from LPG fuel tend to be steady at 123 ppm, which is much lower than the average HC emissions from gasoline, which are 133 ppm. High HC production is caused by many factors, including ignition timing, fuel, and fuel systems, which can lead to combustion failure [22]. A fuel mixture that is too rich also causes incomplete combustion, which triggers high HC emissions. In this case, LPG fuel is more easily atomized than gasoline, allowing it to form a homogeneous mixture with air and produce perfect combustion [23].

Fig. 8 shows a comparison of the mass flow rates of gasoline and LPG fuels as a function of engine speed. The figure clearly indicates that gasoline fuel consumption is greater than LPG fuel consumption at the same engine speed. The figure also shows a tendency for the mass flow rate to increase with increasing engine speeds, for both gasoline and LPG. The mass flow rate of LPG fuel is lower than that of gasoline to meet the same engine power, one of the reasons being that the RON value of LPG is greater than that of gasoline (~110 vs ~90). The high-octane number can minimize detonation in the combustion chamber so that the perfect combustion process can be achieved and reduce fuel consumption [24]. This is proven by research by Suyabodha [25], who used gasoline RON 95, where it was seen that the fuel consumption rate of gasoline 95 was lower than that of LPG fuel.

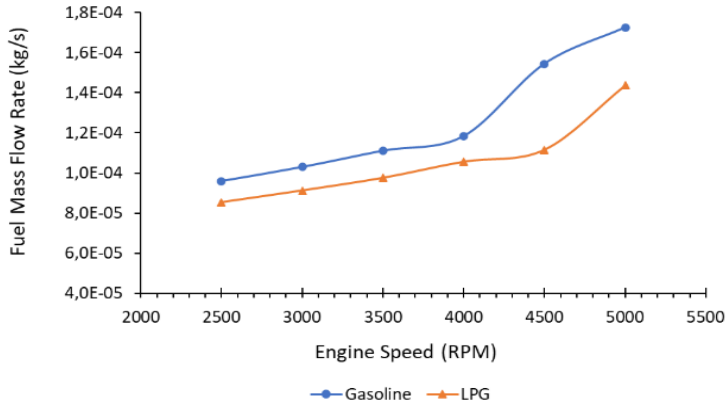


Fig. 8. Mass flow rate of fuel of the engine

4.2 The energy balance

The energy balance in a 110cc carburetor engine is illustrated by Fig. 9 to Fig. 11. Fig. 9 shows the potential fuel energy that is converted into heat energy as the input energy in a spark-ignition engine, whether it is gasoline-fueled or LPG-fueled. The figure demonstrates that the heat produced from the combustion of gasoline and LPG fuel rises as engine speed increases. This occurs because higher engine speeds lead to an increase in cylinder temperature. Additionally, as engine speed increases, the supply of air and fuel to the combustion chamber also increases, resulting in a wider throttle opening. These two factors will enhance the heat energy produced from fuel combustion as input energy [26][27].

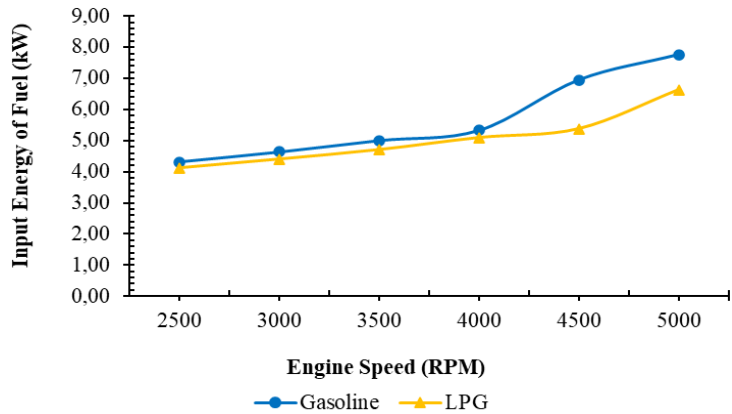


Fig. 9. Input of energy of the engine

Meanwhile, Fig. 10 illustrates the engine's output energy, which is defined as useful energy obtained through brake power. The figure demonstrates that the useful energy produced by gasoline and LPG increases with engine speed. Notably, the output energy from gasoline is higher than that from LPG. This difference occurs because the engine is specifically designed for gasoline, resulting in smaller energy losses compared to LPG, as illustrated in Fig. 11. Additionally, the flow of gasoline fuel per second generates greater input energy (as shown in Fig. 9), which enhances its potential to produce more useful energy [28]. Fig. 11 illustrates that using LPG fuel in a spark ignition engine equipped with a carburetor injection system leads to a steady decrease in energy losses as engine speed

increases. In contrast, using gasoline fuel results in higher energy losses, particularly at high speeds [29][30].

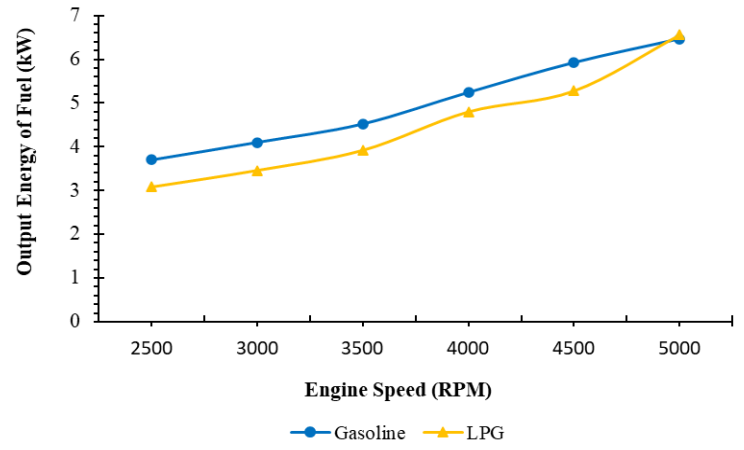


Fig. 10. Output energy of the engine

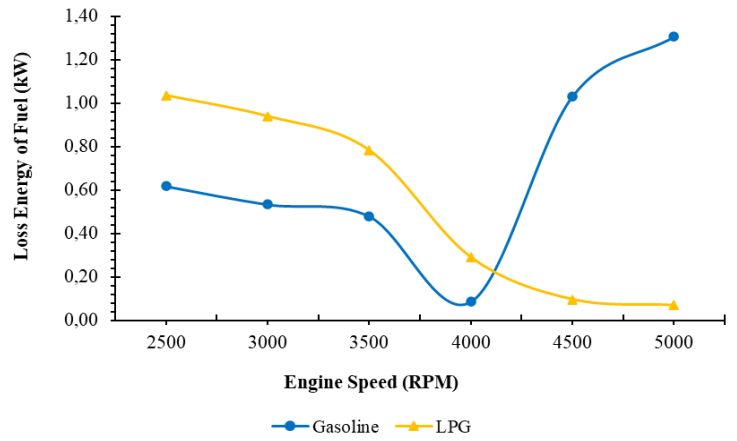


Fig. 11. Energy loss of the engine

Fig. 12 and Fig. 13 are Sankey diagrams showing the energy balance of gasoline and LPG-fueled engines. Both figures indicate that gasoline fuel produces higher combustion parameters than LPG fuel, including input energy, useful energy, and energy losses. However, the LPG-fueled engine produces slightly higher thermal efficiency than the gasoline fuel, namely 87.74% and 87.55%, respectively. Energy input in this study is associated as the fuel energy rate (kg/s) multiplied by the LHV value (MJ/kg) of the fuel.

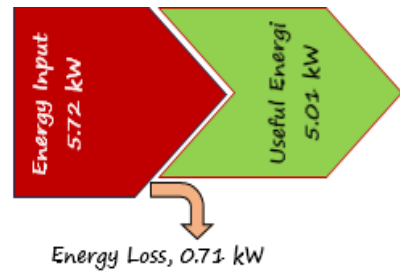


Fig. 12. Sankey diagram of a gasoline engine

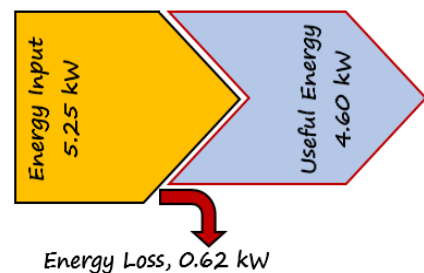


Fig. 13. Sankey diagram of an LPG-fueled engine

5 Conclusions

Based on the results of this study, LPG in carburetor engines reduced energy losses more consistently as engine speed increased, indicating its potential for cleaner and more efficient combustion. The key conclusions are:

1. LPG has the potential to replace gasoline because it produces lower CO, CO₂, and HC emissions by 72.4%, 10.85%, and 7.19%, respectively. These values are lower than those reported for LPG in spark ignition engines with electronic fuel injection systems, which showed emission reductions of approximately 11.54% and 14.40% for CO and CO₂.
2. Engine brake power using gasoline was higher than that using LPG because the energy produced per kilogram of gasoline was greater. This result was influenced by the higher density of liquid fuel, which is approximately 350 times greater than LPG.
3. The SFC of gasoline was on average 4.5% higher than LPG, with values of 0.090 kg/kWh and 0.086 kg/kWh, respectively. The gasoline mass flow rate was also 15.90% higher than LPG.

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