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Evaluation of the Possible Effects of Varying the Volumetric Ratio of Lpg on the Spark Ignition Engine's Performance, Emissions, and Combustion

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Research Article

Abstract

This study investigated the performance, emission reactions, and combustion of liquefied petroleum gas (LPG) at various volumetric ratios with gasoline. The experiments were carried out on a single cylinder spark ignition (SI) engine at different engine loads (500 to 3000 W). In general, the use of LPG has a negative effect on performance and combustion, while making a positive contribution to emissions. The brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) values closest to 100% gasoline were obtained with 25% LPG and were lower by 0.36% and 4.55%, respectively. Conversely, using LPG resulted in lower emissions of carbon dioxide (CO_2), hydrocarbons (HC), and carbon monoxide (CO). The lowest emissions were obtained with the use of 100% LPG as 0.5%, 65 ppm and 9.5%, respectively. Compared to 100% gasoline, 20.63%, 27.78% and 5.19% improvements were achieved. Finally, the cylinder gas pressure value was negatively affected using LPG. Compared to 100% gasoline, the gas pressure value obtained with 75% LPG content fuel was 7.81% lower. It has been concluded that LPG is an environmentally friendly alternative fuel in terms of emissions, and considering the decrease in performance values, 25% LPG can be used successfully in SI engines instead of 100% LPG.

Keywords: Combustion; emission reduction; gasoline; liquefied petroleum gas; spark-ignition engine.

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1. Introduction

Studies on environmentally friendly and clean fuels obtained from renewable sources are accelerating day by day due to the world population, which continues to increase inevitably, the gradual decrease in fossil-based fuels, global warming and increasing air pollution [1–6]. With the developing technology, many alternative fuels are being tried to be used in internal combustion engines [7–9]. There are fuels such as LPG, biodiesel, alcohols, compressed natural gas and hydrogen as an alternative to fossil diesel and gasoline fuels used in internal combustion engines [10–13]. Among these fuels, the usage amount of LPG is almost close to gasoline today [14]. LPG is a fuel derived from petroleum that is obtained by splitting, distilling, or refining natural gas. It is primarily a mixture of hydrocarbons, including butane, propane, and its isomers, which is then liquefied under pressure [15–17]. Without any modifications, internal combustion engines may run on LPG, which is conveniently stored [18–20]. When using high compression ratios, the engine may run without knocking thanks to LPG's higher-octane number than gasoline [21,22]. The calorific value of LPG is better in mass and less volumetrically when compared to that of gasoline. This means that it uses more volumetrically (less by mass) LPG to deliver the same engine power [23,24]. It is very pure, has a low carbon/hydrogen ratio, is not corrosive or harmful, and is free of aromatic hydrocarbons. On the other hand, when LPG is in the gas phase, it mixes more smoothly with air and a much better combustion occurs [25]. Therefore, it emits less harmful exhaust emission to the environment than gasoline and diesel [26,27]. When LPG is used as a fuel, since it is in gaseous state in the combustion chamber, it will not have a dilution effect on the engine oil, so the life of the engine oil is longer, the maintenance costs of the ignition and exhaust system and engine noise are reduced [28, 29]. Additionally, the higher ignition temperature of LPG than gasoline delays the auto-ignition of the fuel and thus makes it more resistant to knocking [30].

There are some previous studies to evaluate the usability of LPG in spark ignition engines and to examine its effects on performance and emissions. The study conducted by Chitragar et al. [23] assessed the harmful gasses and combustion of a four-stroke engine running on hydrogen and LPG. The findings indicated that LPG enhanced emissions because of its increased octane quantity, greater thermal value, and lower carbon content.

According to the authors, using LPG reduces harmful pollutants such CO_2, HC, and nitrogen oxides when compared to gasoline. In another study, Usman et al. [31] tested gasoline, LPG, and LPG/hydroxy gas mixtures at various engine speeds in a spark ignition engine and compared them in terms of performance and emissions. Authors stated that the best results in terms of performance and emissions were obtained with LPG/hydroxy gas mixtures. On average, authors noted that the brake power improved by 7% and the BSFC reduced by 15%. In addition, the authors reported that when compared to LPG, CO, CO_2, and HC emissions dropped by 21%, 9%, and 21.8%, respectively. In another study, Çinar et al. [32] converted a spark-ignition engine to run on LPG and examined the impacts of using LPG at various valve openings and engine speeds. In general, authors stated that with the utilization of LPG, torque and power values decreased and BSFC increased. However, the authors claimed that while nitrogen oxide emissions increased with LPG use, HC and CO emissions decreased. Baek et al. [33] analyzed the injection and combustion process and examined the change in exhaust emissions to understand engine control strategies according to propane content. It has been stated by the authors that propane increases the maximum combustion pressure by improving the ignition timing thanks to its high-octane number. On the other hand, the authors concluded that NO_x, CO and CO_2 emissions increased with the increase in propane. On another study, Dinesh et al. [34] studied the effect of LPG fueling under variable compression ratio in a methanol-fueled SI engine. The authors stated that power and BTE increased with increasing LPG ratio. It was also stated that CO increased, and HC decreased with the addition of LPG. Additionally, it was stated by the authors that the addition of LPG constantly increases NO_x and CO_2.

The primary aim and innovation of this study is the use of LPG at different volumetric ratios. Even though there are many surveys on the utilization of LPG in spark ignition engines, these investigations generally focus on the use of 100% LPG. In this survey, it is targeted to define the best LPG ratio in terms of performance, combustion, and emissions by using LPG at different volumetric ratios.

2. Materials and Methods

2.1. Test procedure

In this experimental research, it was aimed to investigate the impacts of LPG usage on spark ignition engine outputs at different engine loads. The cylinder head of the engine was ground, and the compression ratio was raised to 9.12:1, where the experiments were conducted since LPG's high-octane number permits it to be utilized at a greater compression ratio. Experimental fuels formed with five different proportions of LPG (0, 25, 50, 75 and 100%) were tested on a Honda GX390 4-stroke, single-cylinder, and air-cooled spark ignition engine at six different engine loads (500, 1000, 1500, 2000, 2500 and 3000 W). The electrical controller provided the proportionate modification of the fuel measurements needed for ideal combustion and determined the engine's air mass flow rate using the manifold absolute pressure sensor. LPG from the injector was then mixed proportionately with gasoline. Water cooling safety has been placed between two flow meters to put out any fire that might start from any kind of fire or in the case that the valves blowback. Figure 1 shows the experimental system's architecture, and Table 1 and Table 2 list the characteristics of the engine and fuels that were employed in the testing. Table 3 shows the sensitivity and measurement ranges of the emission device.

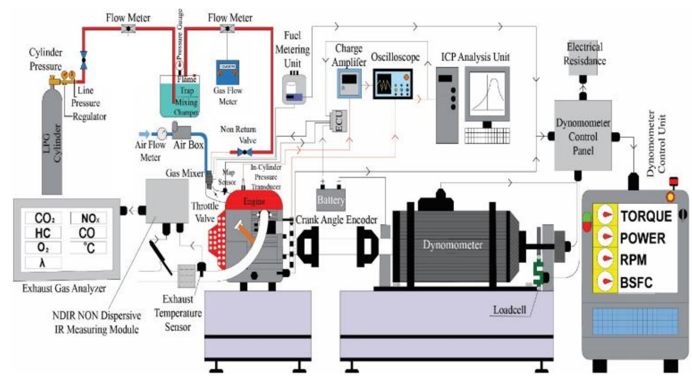

Fig. 1. Schematic of the experimental system.

Table 1. Some main assets of test fuels.

Qualities	Gasoline	LPG
Chemical Composition	C_8H_{18}-C_7H_{16}	$C_{3.7}H_{9.4}$
Density at 15°C (g/cm^3)	0.74	0.53
Lower calorific value (kJ/kg)	43550	46100
Heat of vaporization (kJ/kg)	330	-
Flame Speed (cm/s)	45	32
Research octane number	91	105

Table 2. Specifications of the Honda GX390 engine.

Engine Specifications	
Brand	Honda GX390
Type	Air cooled, 4-strokes, single cylinder spark ignition engine
Cylinder volume	389 cm^3
Maximum output power	8.7 kW (at 3600 rpm)
Maximum torque	26.5 Nm (at 2500 rpm)
Initial Ratio of Compression	8.0:1

Table 3. Measurement sensitivity and range of the emission device

Emission	Range	Accuracy
CO	0-10.0 % vol.	0.001%
NO_x	0-5000	1 ppm
HC	0-10.000 ppm vol.	1 ppm
CO_2	0-20.0 % vol.	0.001%

Every test was run three times in this experimental investigation, and the results were averaged. In addition, uncertainty analysis was performed for the reliability of the results.

$$Uncertainty = square\ root\ of\ \left[(U_{BSFC})^2 + (U_{BTE})^2 + (U_{CO})^2 + (U_{CO_2})^2 + (U_{HC})^2 + (U_{cylinder\ pressure})^2 + (U_{load})^2\right] \quad (1)$$

$$= square\ root\ of\ [(1.05)^2 + (1.23)^2 + (2.16)^2 + (2.91)^2 + (1.44)^2 + (1.32)^2 + (2.09)^2] = \pm 4.892\ \% \quad (2)$$

3. Results and Discussion

Figure 2 illustrates how HC and CO emissions alter in response to variations in the LPG proportion and engine load. While the highest HC and CO emission levels were found with 100% gasoline in all loads, the minimal values were achieved with 100% LPG. Because to the rising LPG ratio, HC and CO emissions have decreased in direct proportion. In addition, the expanded engine load led to a steady reduction of HC emissions in all test fuels. On the other hand, while CO emission reduced linearly in all test fuels up to 2500 W engine load, it grew again after 2500 W engine load. While the lowest HC emission values were obtained with 3000 W engine load, HC emission was obtained as 90 ppm with 100% gasoline fuel, while it was obtained as 65 ppm with a decrease of 27.78% with 100% LPG fuel. On the other hand, while the lowest CO emissions were achieved with 100% gasoline fuel at 2500 W load, CO emission was obtained as 0.63%, with 100% LPG fuel it was achieved as 0.5% with a 20.64% reduction. The cause for the decrease in CO and HC emissions by the usage of LPG can be explained by the fact that the carbon-hydrogen proportion of LPG is lesser than that of gasoline, and that the gaseous state of LPG improves the combustion process by forming a more homogeneous mixture compared to gasoline. The change in HC and CO emissions according to the engine load can be explained by the fact that the in-cylinder temperature that increases owing to the increased engine load contributes to the complete combustion process. The raise in CO emissions again after the nominal engine load can be explained by the decreasing combustion temperature with the decrease in the amount of air-fuel mixture as the volumetric efficiency decreases at high engine load [16]. Figure 3 illustrates the variation in CO_2 based on engine load and various LPG ratios. As the engine load increased, CO_2 emissions—a byproduct of full combustion—rose for all fuels. On the other hand, CO_2 emissions decreased contingent on the LPG proportion. The smallest CO_2 emission level was achieved by 100% LPG at 500 W load as 9.5%, and a 5.19% reduction was achieved compared to 100% gasoline. Since LPG is a fuel type with low carbon content, CO_2 emissions have decreased. In addition, CO_2 emissions increased for all fuels as the in-cylinder combustion rate increased with increasing engine load. Duy et al. [35] found similar results that HC, CO and CO_2 decreased with LPG use.

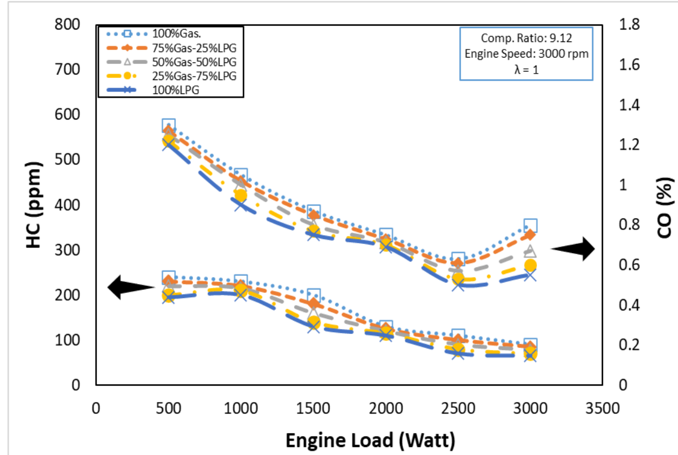

Fig. 2. CO and HC emissions of spark ignition engine with different LPG percentages under various engine load.

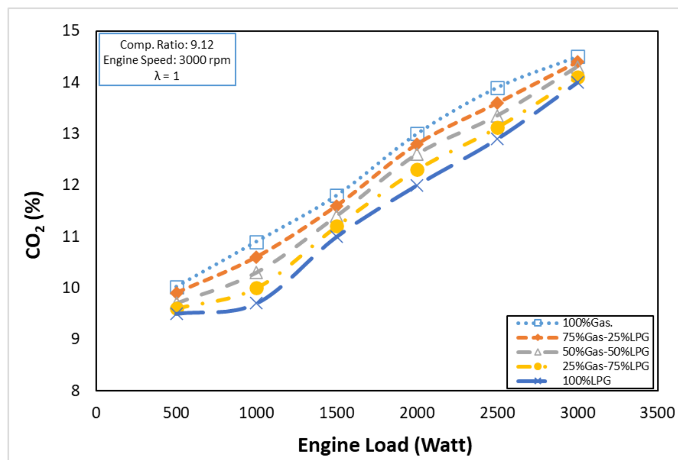

Fig. 3. CO_2 emissions of spark ignition engine with different LPG percentages under various engine load

Internal combustion engines need air and fuel to generate power. The quantity of fuel consumed by the engine is usually calculated as mass flow on the dynamometer. However, this value is not sufficient to determine the efficiency of the engine. Because it is not clear how much mechanical power is obtained from the consumed fuel. For this reason, the amount of fuel consumed instantaneously is proportional to the power obtained at the engine output, and thus BSFC is obtained. The main issues influencing the BSFC are the calorific value and density of the fuel used. Alternative fuel with low calorific value and density must be consumed more to obtain the similar output power obtained from a spark ignition engine with gasoline. It is understood from Figure 4 that BSFC decreased up to 25% LPG ratio, and BSFC increases when LPG ratio exceeds 25%. As shown in Table 1, the lower calorific value of LPG (46100 kJ/kg) is higher than that of gasoline (43550 kJ/kg). Accordingly, BSFC is supposed to decrease with the usage of LPG. As expected, this decrease was realized up to 25% LPG percentage. However, it is seen from Table 1 that the density of LPG (0.53 g / cm^3) is lower than that of gasoline (0.74 g / cm^3). Due to the need for more fuel due to the low density, the BSFC started to increase when the LPG rate exceeded 25%. In addition, BSFC showed a decrease in each fuel with expanding engine load owing to the rise in-cylinder temperature and decrease in incomplete combustion loss with increasing engine load. With the increase of engine load to 3000 W, the amount of fuel consumed began to increase with the decrease in engine power and torque due to increased inertia forces and friction. The smallest BSFC of 420 g/kWh was attained using a 25% LPG content fuel and a 2500 W load. Compared to 100% gasoline at the same load, there was a 4.55% reduction. Chaichan et al. [36] reported that BSFC increased with the use of LPG compared to gasoline.

According to Figure 4, where BTE values are revealed contingent on the altering LPG proportion and engine load, it is understood that the BTE decreases with the utilization of LPG. Then again, the increased engine load had a negative impact on BTE in all fuels, especially after from 1500 W load. The decreasing trend of BTE in all fuels after average engine load levels can be explained by increased friction and inertia forces. 100% LPG produced the lowest BTE value, whilst 100% gasoline produced the highest. The greatest BTE value with 100% gasoline was found to be 28% at 1500 W load. At the same load value, the BTE value (27.9%) obtained with fuel containing 25% LPG was found to be almost close to the value obtained with 100% gasoline. The BTE difference between the two fuels was found to be 0.36%. Because LPG enters the cylinder in gaseous form, less air is introduced into the engine, which lowers volumetric efficiency and causes a fall in BTE when LPG is used.

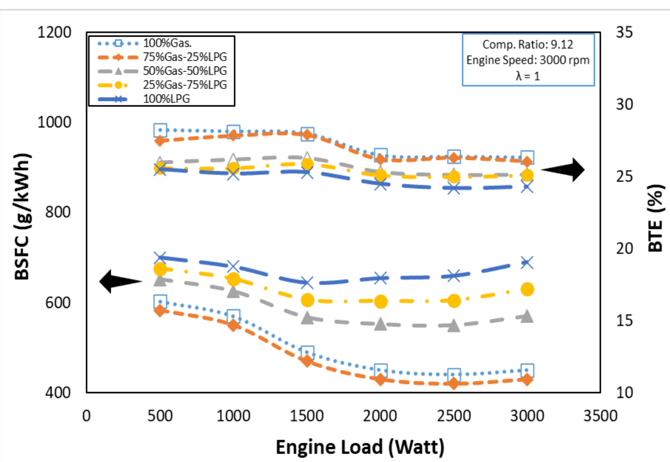

Fig. 4. BSFC and BTE of spark ignition engine with different LPG percentages under various engine load.

Curves showing the distribution of mechanical loads in the cylinder in terms of crank angle (CA) caused by the combustion of fuel are called cylinder gas pressure curves [37]. Figure 5 shows the cylinder gas pressure changes with respect to CA of different test fuels. With the addition of LPG, the cylinder gas pressure values decreased. The highest gas pressure value was obtained as 32 bars with 100% gasoline. Among the fuels containing LPG, the gas pressure value closest to this value was obtained as 29.5 bar with 25% LPG containing fuel. Gas pressure values decreased due to the lower combustion speed of LPG (32 cm/s) compared to gasoline (45 cm/s). Additionally, using LPG causes the air mass of the gaseous fuel in the intake manifold to decrease, which lowers the pressure values during combustion.

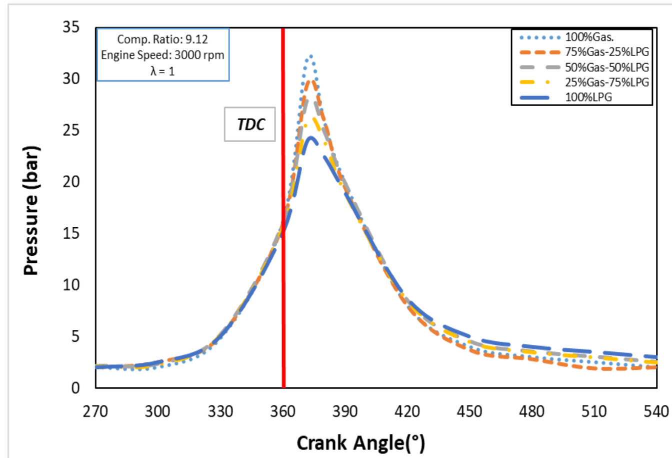

Fig. 5. Cylinder gas pressure of spark ignition engine with different LPG percentages under various engine load.

Figure 6 shows the variation of volumetric efficiency (VE) with load. VE decreased depending on LPG usage and reached its lowest value in 100% LPG usage. In 25%, 50%, 75% and 100% LPG use, VE decreased by 2.59%, 3.81%, 7.25% and 8.36%, respectively, compared to 100% gasoline use. On the other hand, VE increased with the increase in load. Under full load conditions, the VE rises rapidly due to the full opening of the throttle and the resulting removal of resistance limiting the air flow. It is thought that the low density of LPG and the fact that it consumes more volume than the liquid phase causes the volumetric efficiency to decrease [38]. Gumus [25] found a similar result that VE decreased with the use of LPG compared to gasoline and VE increased with all fuels with load.

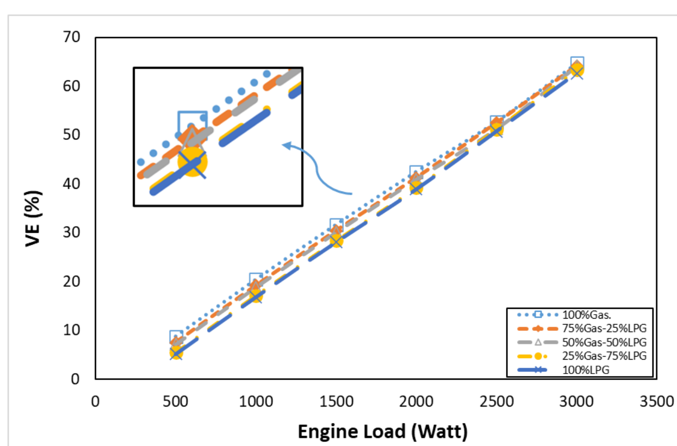

Fig. 6. Volumetric efficiency of spark ignition engine with different LPG percentages under various engine load.

4. Conclusions

The effects of employing LPG at various volumetric ratios on a single-cylinder spark ignition engine's performance, combustion, and emission values were examined experimentally in the current survey. The tests were performed at different engine loads values and constant engine speed, and the main results obtained are given below.

- LPG use reduced BTE. The highest BTE among LPG-containing fuels was 27.9% at 1500 W load, with 25% LPG content. A slight decrease of 0.36% was observed compared to 100% gasoline.
- While BSFC value decreased up to 25% LPG rate, BSFC values started to increase after this rate. With a fuel containing 25% LPG, a BSFC value of 420 g/kWh was obtained at 2500 W load. There was a 4.55% reduction compared to 100% gasoline.
- All type of emissions has decreased because of LPG use. With the utilization of 100% LPG, CO, HC, and CO_2 reduced by 20.63%, 27.78% and 5.19%, respectively, compared to the use of 100% gasoline.
- Fuels containing LPG adversely affected the cylinder gas pressure. The closest value was 29.5 bar with fuel containing 75% LPG, whereas the greatest cylinder gas pressure was 32 bar with 100% gasoline. There was a decrease of approximately 7.81%.

In conclusion, it can be said that LPG is an environmentally friendly alternative fuel due to its low emission level. Given the reduction in performance values associated with LPG use, it can be concluded that the best value for emissions and performance in spark ignition engines is to use 25% LPG rather than 100% LPG. It is believed that carrying out optimization studies to ascertain the ideal LPG ratio in next research will be beneficial for improving performance and emissions.

Nomenclature

BSFC:	brake specific fuel consumption
BTE:	brake thermal efficiency
CA:	crank angle
CO:	carbon monoxide
CO_2:	carbon dioxide
HC:	hydrocarbon
LPG:	liquid petroleum gas
TDC:	top dead center

Conflict of Interest Statement

The authors say they have no competing interests. The authors declare that none of the direct applications of their study have resulted in any financial interest or benefit.

CRediT Author Statement

Suleyman Simsek: Investigation, Methodology,
Samet Uslu: Conceptualization, Writing-original draft, Validation,

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