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The Impact of Diesel/LPG Dual Fuel on Performance and Emissions in a Single Cylinder Diesel Generator

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Abstract: Compared to other engines of the same size, diesel engines are more economical in addition to their ability to generate high power. For this reason, they are widely used in many fields such as industry, agriculture, transportation, electricity generation. The increasing environmental concerns and diminishing oil resources led researchers to improve fuel consumption and emissions. In this context, the usage of Liquefied Petroleum Gas (LPG) fuel in diesel engines is one of the important research subjects that has been keeping up to date. This paper investigates the effects of LPG direct injection towards the end of air inlet period on engine emissions and performance characteristics. A four-stroke, air cooled, single cylinder diesel engine was modified to direct injection of LPG for diesel/LPG dual fuel operation. An Electronic Control Unit (ECU) was designed and used to adjust LPG injection timing and duration. LPG injection rates were selected as 30%, 50% and 70% on a mass base. The test engine was operated at 3000 rpm constant engine speed under varying load conditions. Throughout the experiments, it was observed that smoke density significantly reduced on the dual-fuel operation, compared to the pure diesel operation. Carbon Monoxide (CO) and Hydrocarbon (HC) emissions decreased by 30% and 20%, respectively. Brake Specific Fuel Consumption (BSFC) decreased by 8%. Nitrogen Oxide (NO_x) emissions increased by 6% while effective efficiency increased up to 1.25%.

Keywords: diesel engine; LPG direct injection; diesel/LPG dual fuel; performance; emissions

1. Introduction

Because of the rapidly increasing human population around the world, mechanization and energy requirements have increased in many fields such as transportation, agriculture, electric generation and heavy industry. The diesel engine has a very high utilization rate in those fields due to producing high power at low cost when compared with other engine types in the same size range. Depending on the widespread use of diesel engines, the essential research titles related to the diesel engines are improving the performance and reducing the harmful emissions while the fuel consumption is decreasing. Because of exhausting lifetimes of fossil fuels and tightening emissions standards around the world, developing eco-friendly fuels and fuel systems for diesel engines has been keeping up its importance. In diesel engines, there are many studies to improve engine performance and reduce harmful emissions by using alternative fuels [1–4].

The primary fuel used in diesel engines is diesel as well as many liquid or gaseous fuels are used as alternative fuels. Biodiesel produced from various sources such as vegetable oil, animal fat, waste plastics and waste cooking oils, Tire Derived Fuel (TDF) obtained from waste tires, and various alcohol mixtures are preferred alternative liquid fuels [5–13]. In addition to the liquid fuels, the gas fuels such as hydrogen, Compressed Natural Gas (CNG), Diesel Methyl Ester (DME), biogas and LPG can be used in diesel engines [14–19]. Liquefied Petroleum Gas (LPG) and CNG have currently easiest accessibility and usability among the gas fuels.

LPG fuel can be used as gas or liquid phase in diesel engines. In the gas phase, it is fumigated in the air intake and the LPG-air mixture is formed in the intake manifold [19–22]. When LPG is the liquid phase, it mixes with diesel fuel under higher pressure than 0.5 MPa. Liquefied LPG is mixed with diesel fuel and pressurized by the high-pressure pump. The high-pressure pump delivers diesel/LPG blends to the injector [23–26]. The liquid phase LPG is injected either as LPG-diesel mixture by a single injector or separately by a second injector [27].

In diesel engines operating with LPG in the gas phase, the vapored LPG is taken into the cylinder with the intake air and LPG-air mixture is compressed like in a conventional diesel engine. The LPG-air mixture does not auto-ignite because of its high self-ignition temperature. A small amount of diesel fuel called pilot is injected for ignition of LPG-air mixture. The pilot diesel fuel, which is injected by the conventional diesel injection equipment, normally contributes only a small fraction of the engine output power [28]. LPG usage in the gas phase has been extensively studied. It leads to better engine performance, low particulate and smoke emissions [20,28,29].

Ciniviz [19] investigated the effect of diesel/LPG dual fuel in diesel engine on performance and emissions. They designed gas adjustment valve system in order to deliver the LPG with 30% rate to the intake manifold. Experimental results showed that the engine power, engine torque, and specific fuel consumption were improved with dual fuel run. As a result, the dual fuel operation when compared with the single operation, engine moment and power were increased 5.8%, and NO_x emission and k factor were decreased 5.9% and 1/9 respectively. Additionally, they showed that CO_2 emissions were lower than single fuel mode because CO emissions could not be converted to CO_2 in dual fuel mode.

Alam et al. [20] studied the performance and emissions of a direct injection diesel engine operated on 100% butane LPG. They added di-tertiary-butyl peroxide (DTBP) and aliphatic hydrocarbon (AHC) to the LPG fuel in order to enhance the cetane number. A stable diesel engine operation in wide engine load range was possible with the cetane improved LPG. A few different LPG blended fuels were obtained by changing the concentration of DTBP and AHC. According to experimental results, LPG and only AHC blended fuels increased the NO_x emission compared to diesel fuel operation. Experimental result showed that the thermal efficiency of LPG powered diesel engine was comparable to pure diesel fuel operation. In terms of exhaust emissions, the NO_x and smoke could be considerably reduced with using the various blend of LPG, DTBP, and AHC.

Saleh [21] focused on the effect of propane ratio changes in LPG content on emissions and performance in dual-fuel diesel engines. In the study, LPG with various propane contents was delivered to a diesel engine with EGR capability. The best engine efficiency was achieved with a 40% propane ratio. Depending on the LPG content, high butane ratio led to the decreasing of NO_x emissions and high propane content caused the reduction of CO emission as well. In a mixture of 30% butane and 70% propane content, the engine performance remained at the same level as pure diesel fuel. NO_x emissions were reduced about 27% at full load in 70% propane and 30% butane mixture.

Rao et al. [30] conducted a performance evaluation of a diesel/LPG dual fuel engine. 10%, 20%, 30%, 40% and 50% of LPG were sent to intake manifold of the single-cylinder test engine. Experiments were carried out at constant 1500 rpm engine speed at different loads. The 50% LPG fuel ratio could only be used up to 40% of the engine load. In all LPG fuel mixture ratios, the effective efficiency had increased when it was compared with pure diesel fuel. They proved that smoke emission and specific fuel consumption were reduced gradually while the LPG ratio of fuel mixture was increasing.

Ergenç and Koca [31], studied the usage of LPG in the diesel engines experimentally. They used an LPG injector mounted in the intake manifold. The measurements were performed in 10%, 20% and 25% LPG ratios. The maximum improvements in engine power, engine torque, and specific fuel consumption were achieved with 25% LPG ratio. In terms of exhaust emissions, NO_x and HC emissions decreased with all LPG ratios while CO and CO_2 emissions increased.

Lata et al. [32], investigated the influence of hydrogen and LPG addition on the efficiency and emissions of a dual-fuel diesel engine. They showed that the efficiency was increased with the usage of LPG at high loads while HC, NO_x, and smoke emissions were reduced. They observed a serious knocking in the test engine at the 70% LPG ratio. The best engine performance was obtained at 40% LPG ratio.

Mirgal et al. [33] studied on the diesel/LPG dual fuel engine. The gas phase LPG fuel was delivered to the intake manifold of a single-cylinder diesel engine. The experiments were carried out at 50% engine load and constant 1500 rpm engine speed. Experimental results were recorded at 35%, 67%, 73% and 90% LPG fuel ratio approximately. As the LPG fuel ratio increased, NO_x emissions decreased, and HC emissions increased regularly. Additionally, CO emissions increased at first and then decreased slightly. It was seen that there was a slight decrease in the cylinder pressure due to the increase in the LPG fuel ratio.

LPG in the liquid phase is mixed with diesel fuel and delivered to the high-pressure pump when the liquid phase LPG fuel is used in diesel engines. The mixture of liquid LPG and diesel fuel is injected into the cylinder with the diesel injector at high pressure. The liquid phase LPG can change to the gas phase easily when it is injected into the cylinder because of the low boiling point of LPG. The quick evaporation of the LPG in diesel/LPG blend can improve the atomization of the fuel spray. The increase of LPG content in the fuel blend will decrease the cetane number of diesel/LPG blend, and this will lead to the increase of ignition delay. In addition, the latent heat of evaporation and the Lower Heating Value (LHV) of diesel/LPG blend give a slight increase in ignition delay. Addition of the LPG in diesel fuel can accomplish a good spray atomization and contributes the fuel–air mixing process, however, the high proportion of LPG in the blends may induce engine knock or combustion noise [23–26].

Cao et al. [23] studied comparison of the LPG and diesel fuels in diesel engines. The LPG in the liquid phase and diesel fuel were transferred to the high-pressure pump as a mixture. LPG-diesel fuel mixture injected into cylinder between 180 and 260 bar pressure by a common injector. They performed experiments with %100 diesel, %10 and %30 LPG ratios. They observed that engine power and torque remained the same level in used fuel ratios under constant 1800 rpm speed. The best CO, NO_x, and smoke emissions were achieved using %30 LPG ratio. On the other hand, the best HC emission was obtained with %100 diesel fuel.

Qi et al. [24] investigated combustion and emission characteristics of diesel/LPG dual fuel in a compression ignition engine. They mixed diesel fuel and liquid phase LPG with 10%, 20%, 30%, and 40% ratios and injected with a common injector. The tests were carried out at engine speeds of 1500 rpm and 2000 rpm under between 15% and 90% engine loads. In all load and cycling conditions, it was observed that the cylinder pressure decreased while the LPG ratio increased. In terms of emissions, NO_x decreased, and HC increased at both engine speeds and at all loads when the LPG ratio was increased. The main reason is that the cylinder gas temperature is lower for blended fuel operation at the low engine load with the increase of LPG mass flow rate, and the more aromatic hydrocarbons in the LPG content, which are too stable to burn out entirely. On the other hand, a good spray can reduce blended fuel close to the cylinder chamber wall, thus HC emissions greatly reduces. There was not a great change in CO emission with pure diesel fuel operation. Smoke emissions decreased gradually, and best smoke emission was achieved by using 40% LPG ratio.

Ma et al. [26] studied the effect of diesel and diesel-propane blends on fuel injection timing in a single cylinder compression ignition engine. Propane rate, maximum heat release rate, premixed heat release, maximum cylinder gas temperature and NO_x emissions increased for the same engine speed, engine load, and injection advance while total combustion time, CO, HC, and smoke emissions reduced.

The objective of this study is to observe the effect of diesel/LPG dual fuel, on engine performance and exhaust emissions of a DI small diesel engine at constant engine speed and different loads. For this purpose, a conventional small diesel engine was converted to direct injection diesel/LPG dual fuel engine. The test engine was operated at constant 3000 rpm speed and different engine loads changing from 500 to 1500 W. For each fuel blend and engine load, the impact of LPG direct injection on a single cylinder diesel engine was investigated on engine performance (effective efficiency, fuel consumption, BSFC, EGT) and emissions (NO_x, HC, CO, smoke). Although many studies of LPG/diesel dual fuel have been found in the literature, these studies usually show that LPG is injected into the intake manifold and sent into the cylinder together with the intake air. It is believed that this study could help fill the gap in the literature about the direct injection of LPG on diesel engines.

2. Materials and Methods

2.1. Experimental Fuels

In the experiments, diesel and LPG fuels were used as test fuels. LPG content was 70% propane and 30% butane. The properties of the test fuels are given in Table 1. Diesel fuel meets requirements of EN590 for cetane index, density, and viscosity. The test engine was operated with four different fuel types as D-100 (pure diesel), LPG-30 (%70 diesel + %30 LPG) LPG-50 (%50 diesel + %50 LPG), and LPG-70 (%30 diesel + %70 LPG). The pilot diesel quantity was changed by varying the flow rate of LPG for each load condition at 3000 rpm constant speed. LPG flow rate was adjusted by changing Gasoline Direct Injection (GDI) injector trigger pulse duration via the designed ECU. The starting of GDI injector trigger pulse was set to 250 Crank Angle (CA) towards the end of the intake stroke. Thus, it was prevented that the mixing of evaporated LPG with intake air and reducing the amount of intake air. The width of the trigger pulse of the GDI injector for D-100 fuel was set to zero. In this case, it was ensured that the fuel sent into the cylinder was only diesel fuel. For LPG-30 fuel the duration of the GDI injector trigger pulse was gradually increased starting from 1 ms. The mass flows of the diesel and LPG fuels within a certain time interval were measured for each GDI injector trigger pulse duration. Thus, the fuel sent into the cylinder was set 70% diesel + 30% LPG. The same procedure was repeated for the LPG-50 and LPG-70 fuel ratios respectively. The LPG ratio in total fuel is calculated by using the following equation.

$$LPG_{ratio} = \frac{m_{LPG}}{m_{diesel} + m_{LPG}} * \%100 \quad (1)$$

Table 1. Diesel and Liquefied Petroleum Gas (LPG) fuel properties [34,35].

Fuel	Diesel	LPG
Chemical Structure	$C_{13}H_{28}$	%30 C_3H_8 + %70 C_4H_{10}
Lower heating value (kJ/kg)	42,500	45,908
Autoignition temperature (°C)	240	454
Boiling point (°C)	160–370	−13
Cetane index	52	8
Viscosity-kinematic @ 40 °C	3	0.32
Density (15 °C) (kg/L)	0.83	0.560
Latent heat of evaporation (MJ/kg)	0.260	0.383
Carbon/Hydrogen Ratio (C/H)	~0.47	0.39

2.2. Test Engine

In this study, a single-cylinder diesel generator was used which technical specifications were given in Table 2. The engine used in the generator is a naturally aspirated, air-cooled, single cylinder, direct injection diesel engine.

Table 2. Generator specifications.

Engine Specifications		Alternator Specifications	
Manufacturer	Katana	Manufacturer	Katana
Engine Type	Km 178 Fe	Model	KD 4500 E
Diameter × Stroke	78 × 62	Maximum Power	2.4 kVA
Cylinder Volume	296 cm^3	Power	6.3 kVA
Maximum Output Power	7.6 hp	Phase	1
Continuous Output Power	0.6 hp	Voltage	230 VAC
Engine Speed	3000 rpm	Frequency	50 Hz

2.3. Installation Modifications

The test engine was modified to run diesel/LPG dual fuel. A second injector housing was placed on the diesel engine cylinder head and the Magneti Marelli brand GDI injector was installed. LPG and diesel injector locations are shown in Figure 1. In order to control GDI injector, the angular piston position data which was obtained from an encoder coupled to the crankshaft was used. The ECU controlled the LPG injection timing and duration by evaluating the angular position data. To measure the instantaneous mass consumption of diesel and LPG fuels, electronic scales with precise measuring capability were used. A nitrogen cylinder with 200 bar operating pressure and pressure regulator were used to adjust LPG injection pressure. The liquid phase LPG that accumulates at the bottom of the LPG tank is transmitted to the GDI injector through a high-pressure fuel line. Thus, LPG injection in the liquid phase is provided via GDI injector.

Figure 1. LPG and diesel injector locations.

An Opkon brand PRI 50 model incremental optic rotary encoder coupled to the crankshaft was used for determining the angular piston position. As shown in Figure 2, the encoder has three output channels, A, B, and Z. Channel B leads Channel A by 90 degrees phase shift. Channel Z produces a pulse in every full turn of the encoder. A and B channels are used for rotation direction and position information while Z channels are used for rpm measurement. Direction sensing is determined by generating separate pulse trains for CW and CCW direction. A pulse train is generated by checking for falling edges on A or B pulses when other pulses are high. For position measurement, one pulse train adds to a count register and the other subtracts from a count register. Thus, a precise position detection was ensured, and the LPG injector was controlled with an appropriate timing. The GDI injector was triggered either by the injection of LPG into the cylinder or just after that ignition of the diesel fuel injected into the cylinder.

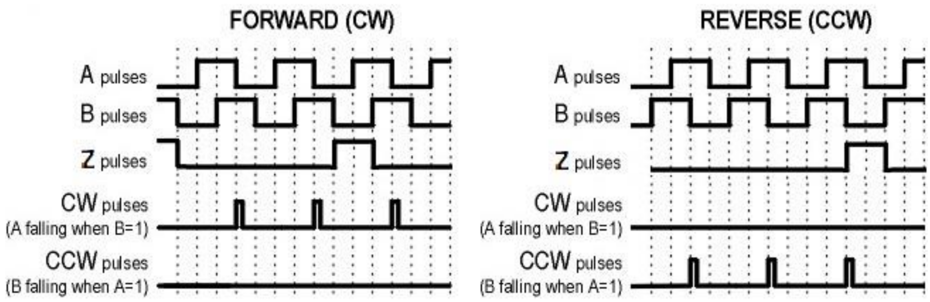

Figure 2. Encoder output signals.

2.4. Test Procedure

The schematic view of the experimental setup is shown in Figure 3. A lamp load unit was built that had 500, 750, 1000, 1250 and 1500 W lamps in order to determine engine performance and emissions under different load states at constant 3000 rpm.

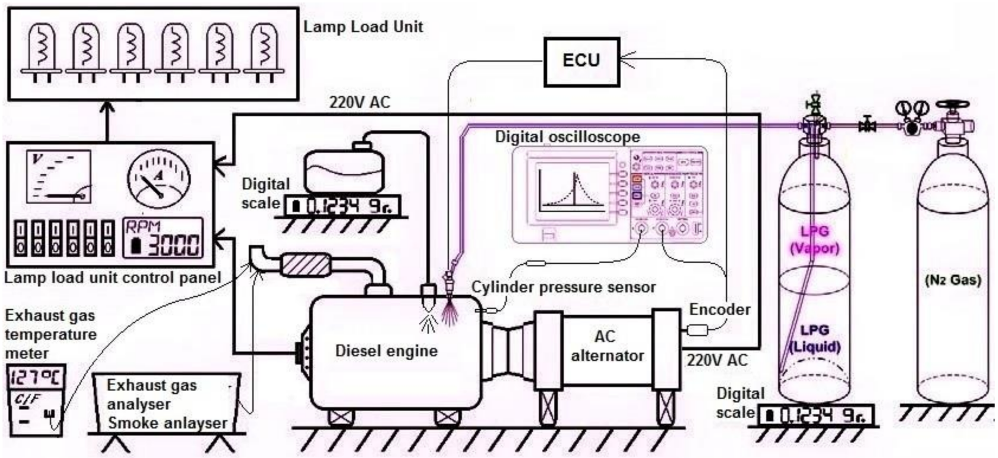

Figure 3. Schematic view of the experimental setup.

The technical specifications of SPIN ITALO PLUS exhaust emission device are given in Table 3. The exhaust emission analyzer can measure CO (% vol) with 0.001 sensibility, HC (ppm), NO_x (ppm) and opacity (%) values. The exhaust gas analyzer device measurement method is based on laser absorption spectroscopy technology, which determines the gas concentration and temperature from the optical absorption at a specific wavelength. The instantaneous exhaust gas concentration and temperature are obtained by the analysis of laser light falling on the measurement sensor after passing through the exhaust gas. A K-type thermocouple with a temperature indicator was mounted to the exhaust pipe for measurement of the Exhaust Gas Temperature (EGT).

Table 3. Exhaust gas analyzer and opacimeter technical specifications.

Measured Parameter	Measuring Method	Measuring Range	Accuracy
CO (%, v/v)	NDIR	0~9.99	0.01
HC (ppm)	NDIR	0~2500	1
NO_x (ppm)	CLD	0~2000	1
Opacity (%)	NDIR	0~99	±2
Operating temperature (°C)		5–40	
Operating Voltage (Vdc)		12	

The digital scales having 1 mg sensitive and a digital chronometer were used to measure both the diesel and LPG fuels flow by weight difference in a constant period. The specific fuel consumption was calculated. The calculated mass fuel consumption is compared to the engine power and the brake specific fuel consumption was found. The Brake Specific Fuel Consumption (BSFC) is estimated in g/(kW h) by using Equation (2).

$$\mathrm{BSFC} = \frac{\mathrm{mf_{diesel}} + \mathrm{mf_{LPG}}}{\mathrm{P_e}} \tag{2}$$

The effective efficiency was calculated with Equation (3) by considering the lower heating value and mass flow rate of both fuels diesel and LPG.

$$\eta = \frac{\mathrm{P_e}}{(\mathrm{mf} * \mathrm{LHV})_{\mathrm{diesel}} + (\mathrm{mf} * \mathrm{LHV})_{\mathrm{LPG}}} \tag{3}$$

Before the data collection, the test engine was run until it reached engine operating temperature of 90 °C with experimental fuels. Experiments were conducted on stable operation modes by loading with lamp load unit. For each fuel blends (D-100, LPG-30, LPG-50, and LPG-70) used in experiments, engine performance and emissions were measured and recorded according to entire load conditions. Experimental measurements were repeated for three times for each operation point and obtained results were averaged. In the experiments, effective efficiency, EGT, fuel consumption, BSFC, and exhaust emissions (NO_x, Smoke, HC, CO) were measured.

3. Results and Discussion

The effect of experiment fuels on the effective efficiency depends on the engine load is shown in Figure 4. The highest effective efficient was achieved about 28.34% using LPG-70 fuel at 1250 W engine load. The ignition delay, uncontrolled combustion, and post-combustion phases were occurred in a short time because of better atomization of the LPG fuel in the cylinder. The lower heating value and C/H ratio of LPG lead to higher flame temperature and effective combustion. In addition, LPG direct injection does not affect intake air and maximum air charging results in the air intake stroke. This phenomenon led to decreasing the fuel consumption and increasing the effective efficiency overall LPG fuel ratios. Effective efficiency results are in concordance with other studies [21,22,36,37].

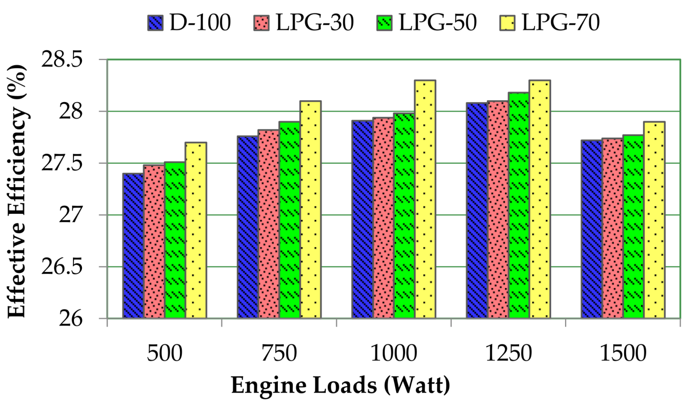

Figure 4. Effect of engine loads change on effective efficiency.

The changes in EGT depends on the engine load are shown in Figure 5. In the experiments, the amount of consumed fuel and EGT increased continuously through the increase of engine load. In addition, EGT presented incremental behavior for all fuel types. However, as the engine load increased, the increase in the LPG ratio reflected more on the EGT. At the lower engine loads ignition delay period of diesel fuel increases and also, fine ignition and combustion of LPG do not occur due to low temperature and pressure inside the combustion chamber. However, at the higher engine loads ignition delay period of diesel fuel decreases and also pressure and the temperature inside the cylinder become higher, an increase in EGT occurs due to this fine ignition and combustion of LPG. In addition, the low C/H ratio of LPG, high combustion rate, and better fuel atomization than diesel fuel have improved combustion process. These similar results were also observed by other researchers [21,34–38].

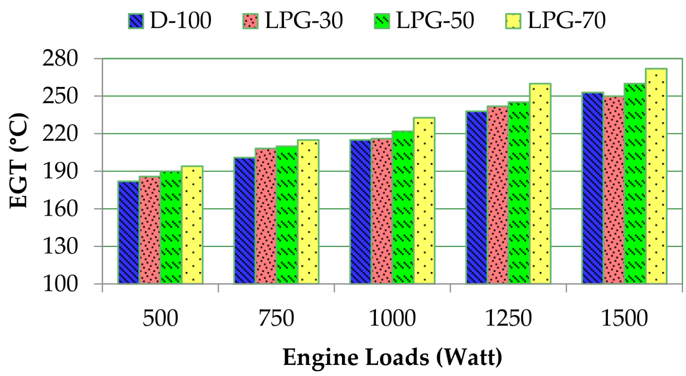

Figure 5. Effect of engine loads change on Exhaust Gas Temperature (EGT).

The effect of engine loads change on the amount of the fuel consumption is given in Figure 6. The fuel consumption was reduced by means of occurring better combustion because the lower heat value of LPG is higher than diesel fuel about 8%. This situation may be explained by increasing of the LPG flow rate increases the heat release because of the overall equivalence ratio and the combustion is inclined to be more complete, leading to high in-cylinder pressures and increased power output. The fuel consumption results are in concordance with those of other researchers [21,30,32,37,39].

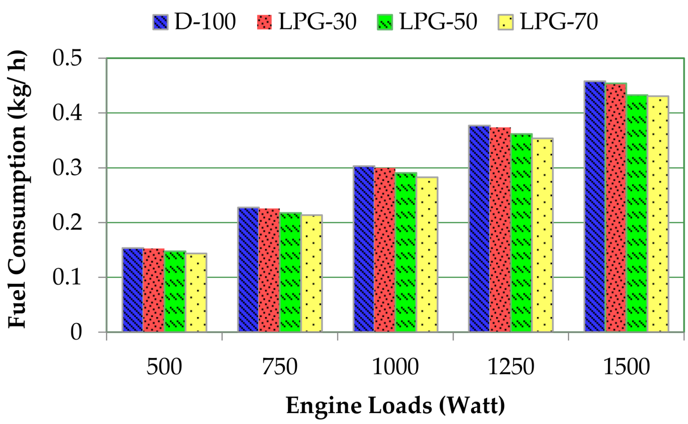

Figure 6. Effect of engine loads change on fuel consumption.

The BSFC for experiment fuels is given as a function of engine loads in Figure 7. The lowest BSFC was achieved using LPG-70 fuel at 1000-Watt engine load. When the BSFC was compared in terms of D-100 and LPG-70, it was seen that BSFC demonstrated reducing behavior by about 6%. Thus, the BSFC decreased because of the lower heat value of LPG was higher than pure diesel. Similar results were reported in other studies [21,30,40–42].

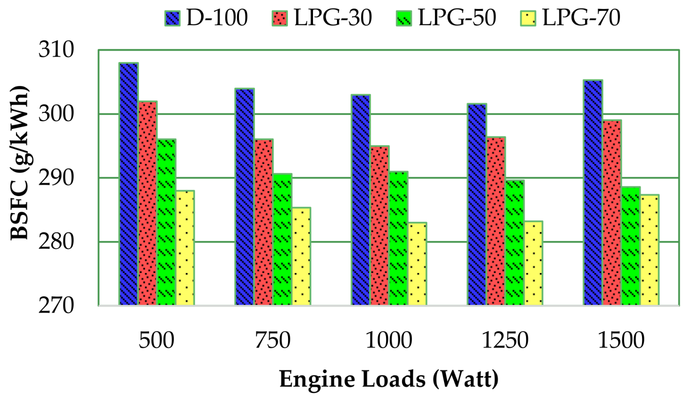

Figure 7. Variation of Brake Specific Fuel Consumption (BSFC) depending on engine loads.

The NO_x emission is given as a function of engine load in Figure 8. Although better combustion in the cylinder and increasing effective efficiency is desired in the automotive industry, they cause to rise NO_x emission directly. It is well known that NO_x emissions are the result of nitrogen reacts with oxygen at the high temperature in the cylinder. The cylinder peak pressure, the maximum heat release rate, the maximum cylinder mean gas temperature, the proportion of the premixed heat release, and NOx emission increase while increasing the propane proportion in the fuel blends [42,43]. As the load is increased, the richer mixture results in higher temperatures which in turn results in higher NO_x emissions. Due to locally rich combustion, NO_x emissions of the diesel engine are less sensitive to temperature increases resulting from increasing load [31–33]. For the diesel/LPG dual fuel engine, the maximum pressure is always higher than pure diesel fuel operation, due to the combustion and extra heat released from gaseous fuel [1]. The higher LPG ratio in dual fuel operation leads to two effects. First, the premixed combustion and the speed of flame propagation increases but the mixing-controlled combustion for the liquid fuel reduces. Second, the reduced amount of pilot injection causes the smaller size of the ignition sources, therefore increases the path that the flame needs to propagate to consume all the premixed mixture in the chamber [44]. This may be postulated to higher ignition delay of the liquid fuel and/or the lower self-ignition temperature of the gaseous fuel. The LPG fuel has lower cetane number and this can increase the ignition delay period of the fuel compared to pure diesel. In addition, the LPG has a high self-ignition temperature compared to diesel fuel. Therefore, it is expected that diesel/LPG blend would exhibit a longer delay for pure diesel fuel to ignite and the lower self-ignition temperature of LPG can increase the rate of pressure rise during the combustion. Thus, NO_x will increase due to the excessive change in pressure per unit CA and the increase of maximum temperature of the cycle.

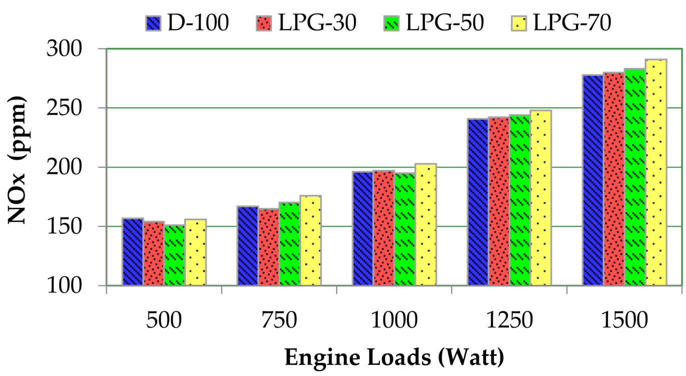

Figure 8. Variation of NO_x emission depending on engine loads.

In the case of diesel/LPG dual fuel operation, the injected more diesel fuel ratio generates bigger initial flame and this produces smoother combustion of the gaseous fuel when the load is increased. The increasing of gaseous fuel ratio which is admitted into the cylinder causes the fuel to burn at higher rates. The oxygen in the excess air taken into the cylinder at the air intake stroke combines with nitrogen due to the high burnt gas temperature and occurs increased NO_x emissions.

In the experiments, NO_x emission increased as both the engine load and the proportion of LPG were increased. This situation has occurred because LPG exhibited a better combustion reaction and higher temperature at the end of combustion than D-100. These results are in concordance with other studies [21,26,38,41,42].

Smoke emission values of the test engine are shown in Figure 9. LPG is a cleaner fuel than diesel fuel because LPG has lower carbon content and can be mixed with air homogeneously. In addition, increasing the LPG fuel ratio and the combustion temperature in the cylinder led to a decrease in smoke emission effectively. Additionally, because of LPG fuel has a lower C/H ratio than diesel fuel, it exhibits lower smoke emissions. For this reason, the diesel/LPG dual fuel operation reduces the smoke emission at all engine load conditions as compared to pure diesel operation. Diesel/LPG dual fuel keep the engine clean and smoke-free. Smoke emissions are in concordance with other studies [24,30,34,41–43,45,46].

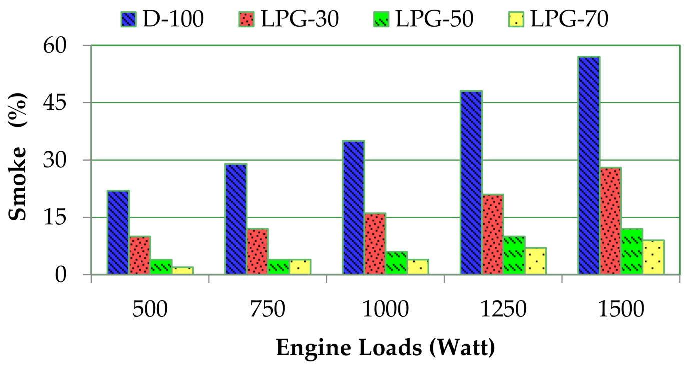

Figure 9. Variation of smoke emission depending on engine loads.

The measured HC emission values depend on engine load ratios are given in Figure 10. HC emissions using different LPG ratio decreased by means of getting better combustion reaction with diesel pilot fuel and performing more effective combustion reaction with the help of LPG. The essential factors of forming HC emissions are lower combustion temperature in the extremely poor mixture, insufficient oxygen and limited reaction time in the excessively rich mixture. The direct injection of LPG has better air charging performance and this phenomenon led to decrease unburned fuel as well. In the experimental setup, using of extremely poor and excessively rich mixtures were prevented by ECU while LPG in the liquid phase was injecting into the cylinder. Thus, HC emissions of diesel/LPG operation were reduced about 20% when it was compared with D-100 fuel. Similar results were obtained by other studies [24,26,36,46].

The measured CO emission values as a function of engine load are shown in Figure 11. In general, CO_2 emissions were produced because of full combustion of a large amount of fuel in the cylinder. On the other hand, CO emissions occurred when the remained fuel from full combustion was burned inadequately. HC emissions were formed by the non-combustible portion of the fuel. The reasons of forming CO and HC emissions are very similar. The direct injection of LPG fuel into the cylinder under high pressure by an injector caused to reach better atomization level of the LPG compared to the diesel fuel. Thus, improvement of the combustion reaction using LPG fuel provided reducing CO emissions. The better combustion and higher calorific value of the LPG improve the flame propagation and oxidation reactions that reduce the HC and CO emissions slightly. Moreover, the lower C/H ratio of LPG deceases HC and CO emissions. CO emission decreased using LPG-70 fuel about 30% than D-100 fuel. These results are in concordance with other studies [21,23,26,40].

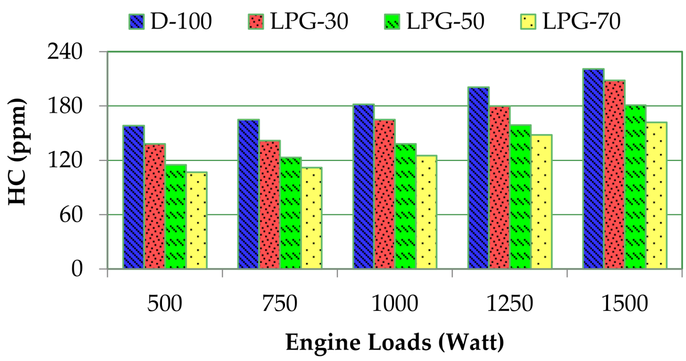

Figure 10. Variation of HC emission depending on engine loads.

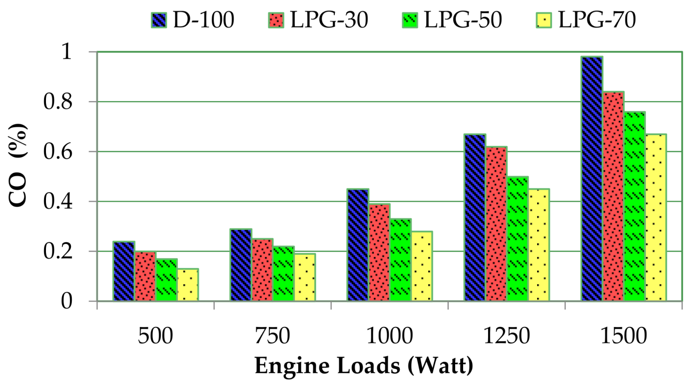

Figure 11. Variation of CO emission depending on engine loads.

4. Conclusions

In this study, the effect of direct injection of LPG into the cylinder on performance and emissions has been investigated experimentally. The tests were performed using different fuel compositions and engine loads at a constant 3000 rpm engine speed. D-100, LPG-30, LPG-50, and LPG-70 fuels were used in the experiments. The test engine was loaded with 500, 750, 1000, 1250 and 1500 W loads through the loading unit. Depending on those parameters, fuel consumption and exhaust emissions were measured. As a result;

The best effective efficiency was reached using LPG-70 fuel. It was increased about 1% than D-100 fuel. The BSFC was reduced linearly depends on the lower heat value which increased with the LPG fuel ratios. The BSFC was decreased as 6% at 1000 W engine load when the LPG-70 fuel was compared with D-100 fuel.

In general, the EGT values for all LPG fuel ratios were higher than D-100 fuel. LPG fuels produced more temperature about 10% than D-100 fuel. NO_x emissions increased about max. 4% when the engine operated with LPG fuels. CO and HC emissions were improved because of the low carbon content of LPG and increasing the in-cylinder temperature. The most emission improvement was gathered for smoke emission. The smoke emission reduced gradually by means of adding LPG content in the fuel mixture. In addition, the increasing pilot diesel fuel ratio caused the increasing smoke emission significantly. The smoke emission decreased as 70% for LPG-50 and 80% for LPG-70 when it was compared with D-100 results.

The dual fuel engine improves fuel economy and exhaust emissions, but it has some disadvantages like a second injector, separate fuel line, electronic and software modifications on fuel injection systems. Additionally, it can be reversed to a pure diesel engine easily when it is necessary.

Author Contributions: All authors designed the experimental setup, analyzed the data, discussed the results and implications and commented on the manuscript at all stages. M.A. and A.I. performed the experiments and wrote the paper. M.B.C. led the development of the paper.

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Nomenclature

BSFC	Brake specific fuel consumption (g/kWh)
CA	Crank Angle
CLD	Chemiluminescence detector
CO	Carbon monoxide
CW	Clock wise
CCW	Counter clock wise
CNG	Compressed natural gas
DME	Diesel Methyl Ester
D-100	Diesel fuel
ECU	Electronic control unit
EGT	Exhaust gas temperature
HC	Hydrocarbon
GDI	Gasoline direct injection
LPG	Liquefied petroleum gas
LPG-30	%30 LPG + %70 Diesel fuel
LPG-50	%50 LPG + % 50 Diesel fuel
LPG-70	%70 LPG + %30 Diesel fuel
NDIR	Non-dispersive infrared
NOx	Nitrogen oxide
PM	Particulate matter
TDF	Tire Derived Fuel
η	Effective efficiency (%)
mf	Fuel consumption per hour (kg/h)
LVH	Lower heating value (kJ/kg)
Pe	Effective engine power (kW)

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