



Enhanced Performance and Reduced Pollution of Bi-Fuel Engine with Liquefied Petroleum Gas Injection System, an Application in Motorcycles

Quach Hoai Nam¹ and Nguyen Thanh Tuan^{1,*}

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ABSTRACT

LPG fuel has many advantages as an alternative fuel for internal combustion engines. Based on the LPG - gasoline bi-fuel engine already available on motorcycles, in the research, installing sensors and designing a second ECU to control more fuel injection time and automatically adjust the injection time according to respective injection pressure. Test results when the motorcycle is operated with three independent fuel supply systems, gasoline with the carburetor, gaseous LPG with mixer type, and liquid LPG injection system in the intake manifold. The results show that the engine power with a fuel injection system significantly increases power. The measured power value in the experimental modes is approximately equal to the engine power when running on gasoline. Comparing the emission parameters, LPG discharged into the environment with a lower concentration of harmful substances than gasoline, significantly reduced compared to the mixer type system.

1. INTRODUCTION

Nowadays, with the increasing number of vehicles, pollution problems and concerns about energy supply in every country. Traditional energy is not the right choice in the future because they will face increasingly scarce supply, and especially the problem of pollution from vehicle emissions [1].

In the last decade, to reduce the use of fossil fuels (gasoline and diesel), research activities related to using of a variety of alternative fuels for internal combustion engines have shown progressive results. However, it remains a challenge to expand to older vehicles. In Southeast Asia, there are many studies related to engines using biofuels and vegetable oils, which is a challenge when the land is concentrated for crop production, ensuring food for people. In Vietnam, the program of using Compress Natural Gas (CNG) fuel for the bus fleet has been used for about ten years but still only encapsulated in one bus company with a fixed route. In order to have more vehicles, it is necessary to build a fuel supply infrastructure and a government policy in the form of price and tax incentives [2], [3].

Electric cars and electric motorcycles are reasonable solutions. However, the disadvantage is that the battery charging time is extended, the route is short, and the cost of owning an electric vehicle is also high. Therefore, switching to LPG becomes a viable option in the medium term, at least in the next 15-20 years. Comparing the popularity and

convenience, Liquefied Petroleum Gas (LPG) can be bought easily everywhere because many households now use LPG for cooking. Moreover, LPG is now considered a low-cost fuel compared to other fuels [4]-[6].

When using LPG for vehicles, most researchers give positive results that the amount of harmful gas after combustion from LPG fueled engines is lower than gasoline engines, with research results in experimentation and simulation. The concentration of toxic substances has a decreasing rate depending on the published results. However, when compared to gasoline, engines running on LPG will be reduced 10-20% NO_x, CO will decrease by 15-25% [7]-[10], and HC will be reduced by 10-30% [9], [11]-[14] to the environment.

However, the engine power when using LPG will be lower than gasoline, especially LPG fuel injected into the combustion chamber in the gas phase. As known, LPG exists in a high-pressure tank in the liquid phase. LPG evaporates quickly because the vaporization temperature is very low at minus 42°C [15], [16]. When entering the combustion chamber, it will occupy a larger volume than gasoline when the same mass. Thus, injecting LPG in the gas phase as a mixer system is not beneficial to the engine's power. A liquid-phase LPG injection system must do the solution to optimize the engine power. When studying LPG, the performance parameters are often compared with when the engine runs on gasoline. Engine power when using LPG

¹Faculty of Transportation Engineering, Nha Trang University, 02 - Nguyen Dinh Chieu, Khanh Hoa Province, Vietnam.

*Corresponding author: Nguyen Thanh Tuan; Phone: +84-916162280; E-mail: nguyenthantuan@ntu.edu.vn.

is reduced. The most significant reduction can be up to 20% compared to gasoline-powered engines [17]-[21].

A study by Blažek and Mareš [22] on liquid and vapor, LPG fuel systems at the end of intake stroke showed that. When injecting liquid LPG, the LPG temperature ($T_{BDC/LPG/liquid}$) at the end of the intake process in the cylinder is 52°C, while injecting LPG in the vapor phase, this temperature ($T_{BDC/LPG/gas}$) will be 82°C. In a gasoline fuel system, the gasoline temperature ($T_{BDC/Gasoline}$) will be loader is 62°C. The reason is in the liquid phase because LPG collects heat to evaporate. It will reduce the temperature of the fuel and air mixture in the cylinder compared to the gaseous LPG injection.

With these temperature values, to further explain the decrease in the power of the LPG engine. It is possible to compare the engine power of LPG in liquid, vapor, and gasoline by brake mean effective pressure value. With the assumption of an engine in full load mode, the fuel equivalence ratio equals 1, the fuel in the two cases gasoline and LPG are fully charged, and other assumptions are the same. Brake mean effective pressure when using two types of fuel is shown by the formula below.

$$\frac{BMEP_{LPG}}{BMEP_{Gasoline}} = \frac{(AFR_{Gasoline} \cdot R_{air} + R_{Gasoline}) \cdot LHV_{LPG} \cdot T_{BDC/LPG}}{(AFR_{LPG} \cdot R_{air} + R_{LPG}) \cdot LHV_{Gasoline} \cdot T_{BDC/LPG}} \quad (1)$$

Substituting the temperature value and property values of gasoline, LPG, and air-fuel into formula (1) will have the brake mean effective pressure ratio when using the gaseous LPG system and the pressure when the engine uses gasoline.

$$\frac{BMEP_{LPG/gas}}{BMEP_{Gasoline}} = 0.925 \quad (2)$$

Similarly, the engine's brake means effective pressure ratio when using liquid LPG to the engine pressure when using gasoline is equal to the following value.

$$\frac{BMEP_{LPG/liquid}}{BMEP_{Gasoline}} = 0.995 \quad (3)$$

The results have shown that when using a liquid LPG injection system, the engine power can completely approximate the value of the engine when running on gasoline. Meanwhile, if using a gaseous LPG fuel supply system, the system uses a reducer and vaporizer. Engine power will be reduced by 7.5%, as calculated in formula (2). Symbols and values of the above parameters are shown in Table 1.

For research on small single-cylinder engines in motorcycles, these vehicles remain quite popular in Southeast Asian countries such as Malaysia, Indonesia, Thailand, the Philippines, and Vietnam [23]-[26], as well as typical South Asian regions like India. The LPG fuel supply system is quite common. The fuel conversion kits available for installation in motorcycle engines are mainly LPG mixer systems or electronic fuel injection, but LPG is injected as a gas phase [16],[23]-[27], because the fuel system still uses a

pressure reducer/vaporizer. As analyzed above, with these LPG fuel systems, engine power is significantly reduced. The diverse number of motorcycles requires research and application tailored to each specific motorcycle type, along with optimization of engine power.

Table 1. Symbols and values of parameters in formulas (1), (2) and (3)

Name	Symbol	Value
brake mean effective pressure of working cycle with LPG engine	$BMEP_{LPG}$	-
brake mean effective pressure of working cycle with gasoline engine.	$BMEP_{Gasoline}$	-
stoichiometric air-fuel ratio of gasoline	$AFR_{Gasoline}$	14.5 kg/kg
stoichiometric air-fuel ratio of LPG.	AFR_{LPG}	15.6 kg/kg
individual gas constant of air.	R_{air}	287 J/kg K
individual gas constant of gasoline	$R_{Gasoline}$	76 J/kg K
individual individual gas constant of LPG.	R_{LPG}	168 J/kg K
gasoline lower heating value.	$LHV_{Gasoline}$	43.5 MJ/kg
LPG lower heating value	LHV_{LPG}	46.1 MJ/kg

In this study, based on the available LPG–gasoline bi-fuel engine on the motorcycle (with mixer LPG system type), we designed a new fuel supply system with liquid LPG injection on the intake manifold. By directly comparing three types of fuel supply systems on the same motorcycle engine, the advantages of LPG injection systems on a specific motorcycle engine are experimentally clarified. Moreover, this solution leverages the fuel injection system already available on the corresponding motorcycle engine, reducing design and manufacturing costs while providing an effective liquid LPG injection system that increases engine power and reduces environmental pollution compared to the mixer LPG system and gasoline-powered engines.

2. METHODS AND MATERIALS

2.1 Fuel system and experimental motorcycle

The LPG fuel used in this study is a blend of 50% propane and 50% butane, which is the appropriate fuel ratio for the engine when evaluating the effect of propane on engine emissions [17], [28], [29]. LPG is compressed in a tank with a mass of 3 kg. In the fuel LPG supply system to the engine, including a safety valve, a manual valve that opens and closes with an automatic solenoid. The engine used in the

study is the Honda Wave motorcycle engine, which is a popular motorcycle in some markets in Southeast Asia and Vietnam. This motorcycle has operated a distance of 55,000 km, cylinder capacity 97 cc, maximum power of 5.2 kW at 7500 rpm, maximum torque of 6.2 Nm at 5500 rpm, a compression ratio of 9.1. Currently, the motorcycle uses both LPG and gasoline fuel. When running on gasoline, the fuel supply system uses a carburetor. When running on LPG, a mixer LPG fuel system with a vaporizer is used.

To have an additional liquid LPG fuel injection system on the intake manifold. This study used a gasoline fuel injection system of a similar motorcycle engine with the same cylinder capacity to install and convert. Throttle position sensors, engine speed sensors, camshaft sensors, start signal sensors, and the original ECU was installed on this engine. However, the ratio of fuel and air between gasoline and LPG is different; the theoretical amount of air required to burn 1 kg of gasoline completely is 14.5 kg [18]-[20], while LPG is 15.6 kg [12],[14],[30]. LPG needs a longer injection duration than gasoline. In addition, the fuel injection pressure is a fixed value of 3 bar, the LPG nozzle used in this study has 10 holes with a flow rate of 180cc/min; the LPG injection pressure does not use a pump but depends on the opening and closing of the LPG valve. Therefore, in this study, an additional ECU was designed to control the LPG injection duration according to the LPG/air mass ratio and the LPG pressure on the pipeline accordingly. The diagram of the fabricated and installed fuel supply system is shown in Figure 2. In which, the designed second ECU is shown in Figure 1. The formulas used in calculating the injection time to the second ECU control is shown in section Basic Formulas in the second program.

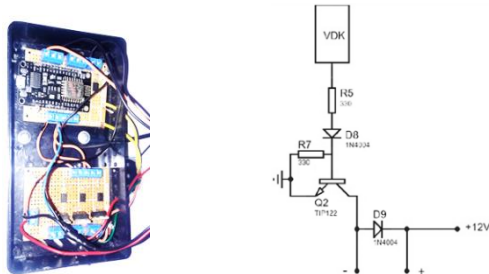


Fig. 1. Second ECU and LPG fuel injection control circuit.

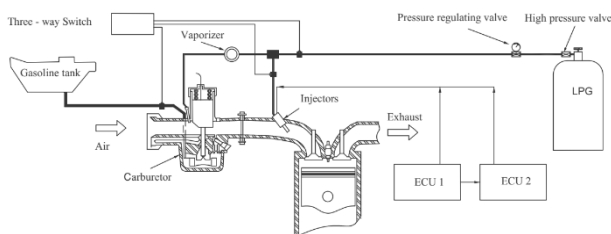


Fig. 2. Diagram of the bi-fuel system.

2.2 Basic Formulas in the second program

LPG mass flow is defined as the amount of fuel that passes through the injector hole in a unit of time. *Mass flow* ($\dot{m}_{LPG}$) depends on the flow coefficient (μ), the area of the needle hole (S), the pressure difference between the inside of the injector and the medium (Δp), and the LPG density (ρ). The following formula determines the fuel injection flow through the injector hole [31]-[33].

$$\dot{m}_{LPG} = \mu \cdot S \cdot \sqrt{2 \cdot \Delta p \cdot \rho} \quad (1)$$

The LPG mass (m_{LPG}) in a working cycle depends on the cylinder volume (V), stoichiometric air-fuel ratio (L), air-fuel equivalent ratio (λ), and volumetric efficiency (η_v). LPG mass for one cycle is calculated according to the formula [34]-[36]:

$$m_{LPG} = \frac{1}{L \cdot \lambda} \cdot \frac{V}{60} \cdot \eta_v \quad (2)$$

Once the LPG fuel mass has been determined for a cycle and the LPG flow through the nozzle hole, the fuel injection duration (t) will be determined when using LPG.

$$m_{LPG} = \dot{m}_{LPG} \cdot t \quad (3)$$

The same calculation will determine the fuel injection time for the gasoline system. From there, it is possible to know the exact injection duration difference between gasoline and LPG to have information for the 2nd ECU to control LPG injection time. However, because LPG is contained in the tank, the LPG pressure depends on the valve opening level and the amount of LPG so that the fuel injection pressure will change. Combination formula (1) and (3) was put in the program for the second ECU to adjust the injection time when the LPG pressure changes automatically.

It is also based on the air-fuel equivalence ratio to adjust accordingly for each operating mode of the engine by formula (4).

$$\lambda = \frac{m_{air}}{L \cdot m_{LPG}} \quad (4)$$

3. EXPERIMENTAL PROCEDURE

After researching, manufacturing, and installing a liquid LPG fuel injection system on the intake manifold, successfully on motorcycle engines, the motorcycle was on the test bench to experiment (Figure 3). The chassis dynamometer comprises two rollers that bear the load from the drive wheel of the motorcycle. The functions of the chassis dynamometer were to measure the motorcycle speed and determine the brake power at the wheel, fuel consumption, and specific fuel consumption. The dynamometer also included a wheel speed sensor, a loading unit consisting of a generator, and one pure resistance load

cell. The chassis dynamometer specifications are described in Table 2.

Table 2. Specifications of the chassis dynamometer.

Specifications	Value
Brake power	8 kW (Max)
Roller (diameter x length)	135 mm x 500 mm
Speed	80 km/h (Max)
Power supply	220 V/AC
Frequency	50 Hz

Testo was the exhaust gas analyzer that will be used in this study. Analyzers measured emissions: non-dispersive infrared analyzed CO emissions with $\pm 1\%$ accuracy, a flame ionization detector analyzed HC emissions with $\pm 0.5\%$ accuracy, and a chemiluminescence detector measured NOx emissions with 1 % accuracy.

Experimental results were measured when using motorcycle engines with three types of fuel supply systems. To ensure safety, the test speed with the maximum speed is 70 km/h. The atmospheric temperature during the test was 28°C. Each test model was performed for five minutes with the engine running steady. The value shown in this research is the average value for five minutes corresponding to each measurement. The measured values are shown in Figures 4-8.

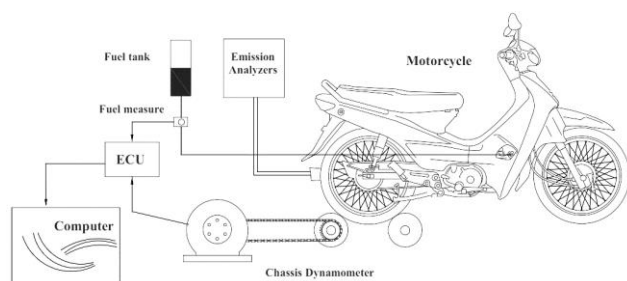


Fig. 3. Chassis dynamometer and test motorcycles.

4. RESULTS AND DISCUSSION

4.1 Performance and fuel consumption

In the experiment, the motorcycle was operated under the same conditions when changing the fuel supply system in turn. When testing LPG motorcycles with the mixer LPG fuel system and electronic fuel injection system, the measured power values are compared to the original gasoline motorcycle engine. The power characteristic graph has the same general trend, the power increasing with the increasing speed of the motorcycle. The liquid LPG fuel injection system increases the engine power significantly when at all motorcycle speeds; the measured power is equivalent to when the engine runs on gasoline. The most

significant power difference is only 3% at a vehicle speed of 50 km/h. This means that with the liquid LPG injection method, the LPG mass composition is put into the cylinder in each cycle. The gas mixture ratio between LPG fuel and the air is adjusted according to the original ECU with support. This system also overcomes the disadvantages of the mixed-type LPG system, which is that LPG occupies a large volume in the cylinder space. The fuel-air ratio is unstable and difficult to control, especially when the motorcycle is running at high speed. Therefore, the engine power improved significantly at high speed at 70 km/h; the engine power increased by 12% compared to when the engine used a mixer LPG system (Figure 4).

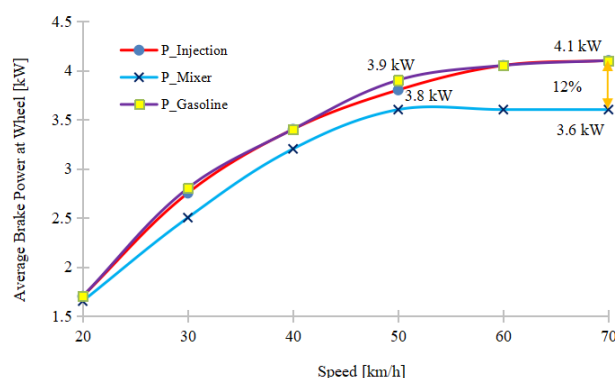


Fig. 4. Experimental result of Average brake power at the wheel.

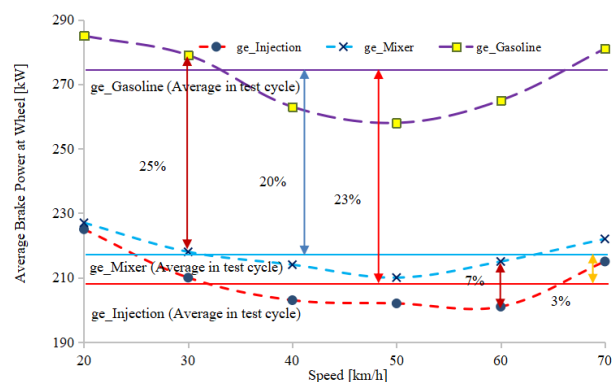


Fig. 5. Experimental result of specific fuel consumption.

The lowest specific fuel consumption while operating a motorcycle is measured in 40 km/h to 60 km/h (Figure 5). This range is the average speed when traveling and achieves the best economic efficiency when operating. The specific fuel consumption when using LPG decreases sharply when compared with gasoline fuel. Total fuel used for the whole test cycle (or an average of the test speeds) with three fuel systems shows that the specific fuel consumption is reduced by 23% when using LPG with an LPG liquid injection system and 20% less with the mixer LPG system. The most significant difference is measured in the test mode of 30 km/h; the reduction in fuel consumption is 25%. However,

when comparing the two types of LPG fuel systems, there is no significant difference when the average difference in the test cycle is only 3%. Combined with the comparison of the engine's power, it is clear that the LPG injection system has brought both economic and technical efficiency. Operating a motorcycle with this system ensures both powers and significantly reduces fuel costs.

4.2 Exhaust emissions

The results of measuring the concentration of harmful substances in the exhaust gas when the engine is operating with three fuel systems can be seen that when using LPG, the concentration of harmful substances decreases sharply. The difference is most significant for HC concentration when using LPG at low speed and high speed (Figure 6). At 20 km/h, the difference in HC concentration when the engine uses a liquid LPG injection system and gasoline carburetor system is 20% (1245 ppm vs. 1000 ppm). Compared with the mixer LPG fuel system, the HC concentration decreases slightly. However, a clear difference is that injection Liquid LPG controlled by the ECU provides a more suitable fuel ratio than a mixer LPG system. The reduced HC concentration shows an advantage of LPG over gasoline because LPG's main components are propane and butane, so the carbon component is lower than gasoline. Moreover, LPG evaporates and mixes with the air better than gasoline. The combustion process is better. Both of these causes lead to a sharp decrease in HC concentration.

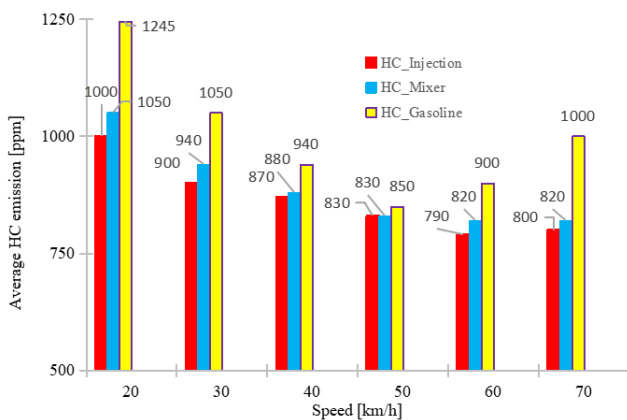


Fig. 6. Experimental result HC emission.

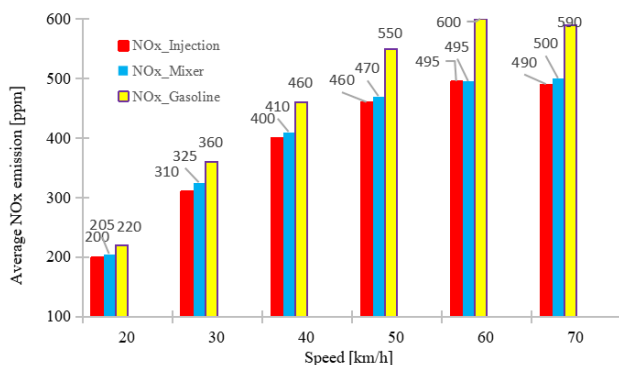


Fig. 7. Experimental result NO_x emission.

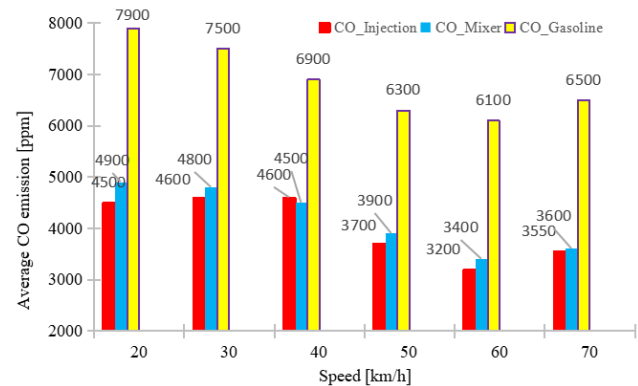


Fig. 8. Experimental result CO emission.

With the results of measuring NO_x and CO (Figures 7 and 8) concentrations giving similar results when the concentrations of these two substances both decrease when using LPG fuel, the liquid LPG injection system also improves the concentration of these toxic substances compared to the mixer LPG system. The concentration of NO_x increases gradually when the motorcycle speed increases, which is the general trend when the vehicle uses all three fuel systems. When the engine temperature increases, it is a catalytic condition for nitrogen to react with oxygen. This is the leading cause of this upward trend in NO_x. When comparing LPG with gasoline, the concentration of NO_x decreases compared to gasoline because the combustion temperature of LPG is lower than the combustion temperature of gasoline. The flame propagation speed of LPG is also slower than gasoline. Of the three toxic substances released into the environment, CO emission was the most substantial reduction. The most significant difference is at vehicle speed 70 km/h. CO concentrations are reduced by up to 53% when compared to gasoline-powered vehicles.

5. CONCLUSIONS

The research has successfully designed and installed a liquid LPG injection fuel supply system on the intake manifold for an LPG - gasoline bi-fuel engine. Experimental results show that the engine power is almost equivalent to running on gasoline. Using the gasoline fuel injection system and newly designing a second ECU to control more time when used for LPG—significantly improved engine power compared to a mixer LPG system. Moreover, the specific fuel consumption and the concentration of toxic substances are reduced. The study met the goal objectives. This is a simple LPG fuel injection system that is easy to install for many different motorcycles when just changing the input data to the second ECU about the mass flow of the fuel injector on a particular motorcycle engine. Therefore, the following research direction will be pre-programmed the second ECU to be suitable for all motorcycles on the market today.

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