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## Effects of Liquid LPG Injection on Combustion Stability in Spark Ignition Engine

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### ABSTRACT

LPG is an alternative fuel that commonly used in spark ignition engine. The research on introducing the LPG into the combustion chamber has been extended to the liquid injection rather than conventional method which is gas injection. The objective of this study specifically is to evaluate the effects of liquid LPG injection on the combustion stability as compared to the gasoline fuel. The study was conducted using 1600cc naturally aspirated engine at 2000rpm and 3000rpm at various throttle position, which were 25%, 50%, 75% and 100% of its opening. The statistical analysis has been used in determining the combustion effectiveness through peak pressure analysis from 250 continuous combustion cycle. The results were compared with the gasoline fuel for each experimental condition. The results showed that liquid LPG injection has produced better combustion stability than gasoline fuel at almost all tested conditions.

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## 1. Introduction

Commonly, alternative fuel is distinguished as liquid and gaseous fuels. Liquid fuel such as biofuel has the capability to reduce the carbon emissions, but the high processing cost makes it unviable to be commercially used. Thus, the use of gaseous fuel, especially liquefied petroleum gas (LPG) is growing worldwide due to its abundant availability and the ability to cater major concern of low carbon fuel. Properties of LPG such as high octane numbers and high calorific value are among the properties that might be beneficial to internal combustion engine [1-6].

According to the Autogas Incentive Policies [7], there are 26.8 million LPG vehicles have been recorded all over the world as per tabulated in Table 1. Turkey represents the country that has the highest number of LPG vehicle, meanwhile China is the lowest. In view of LPG consumption, Korea

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has dominated the LPG usage even though the refuelling sites in Korea are found less than another country. This is due to the largest share of LPG vehicle in Korea comes from taxis and light duty vehicles.

**Table 1**  
Automotive LPG market, 2016 [6]

Country	LPG consumption (thousand tonnes)	Vehicle (thousands)	Refuelling sites
Korea	3,515	2,185	2,031
Turkey	3,142	4,440	10,426
Russia	3,050	3,000	4,900
Italy	1,659	2,211	3,940
Poland	1,790	2,977	5,390
Thailand	1,466	920	950
Ukraine	1,385	2,250	3,500
Japan	1,002	221	1,440
China	990	165	550
Australia	532	360	2,500
Rest of the World	8,173	8,077	40,465
World	26,704	26,806	76,092

The bulk numbers of LPG vehicle basically are aftermarket conversion that consists of three main categories of fuel systems which are mixer, vapor phase injection and liquid phase injection. The usage of mixer and vapor phase injection has been broadly accepted by public user due to its established technology. However, based on the ref [6], the usage of liquid phase injection began to gain attention by public user in the year of 2016, and in general, it is normally will take a few years to gain the confidence and to penetrate the acceptance by public users.

Few study that related to the liquid LPG injection has been conducted by previous researcher [8-13] that focused on the engine performance and emissions during its operation. Even though several researches have been conducted, the study that concentrate on the combustion stability of liquid LPG injection is scarcely found. Study focused on combustion stability is crucial in determining the engine ability to produce consistent engine output other than an indicator of engine driveability. Therefore, the aim of this is to analyse the combustion stability of liquid LPG injection in spark ignition engine through the variation of maximum in-cylinder pressure over 250 continuous combustion cycle.

## 2. Experimental Setup

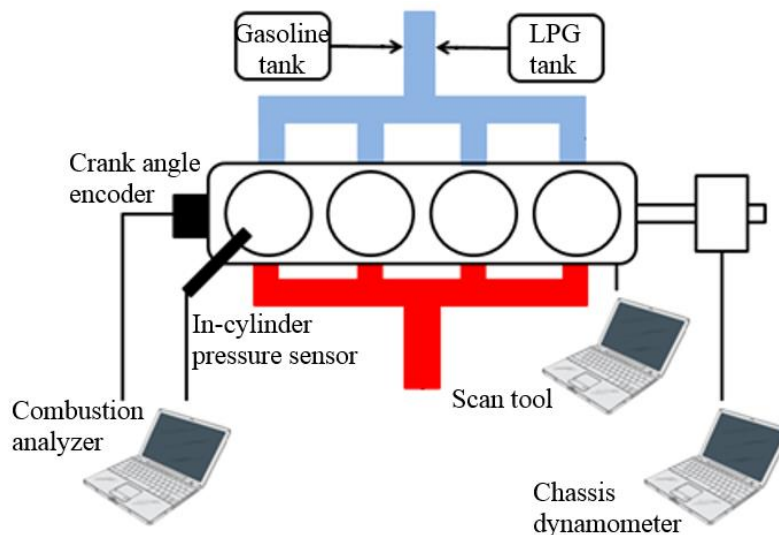
The experiments were performed using two different fuels which were LPG and gasoline. Gasoline was used as benchmark fuel whereby the result from LPG will be compared directly to gasoline. Table 2 shows properties comparison of LPG and gasoline. The properties indicated that the lower calorific value of LPG is higher than gasoline and it is an indicator that LPG has the ability to produce better engine performance than gasoline. However, it is strongly depending on the phase of the fuel being injected during injection phase.

The schematic diagram of this study is shown in Figure 1, complete with all the apparatus used in collecting the data. The spark plug type of in-cylinder pressure made by Kistler (6115B) was installed in the cylinder number one of the tested engines. A rotary encoder with 0.1 step of degree resolution was attached to the engine crankshaft in order to measure the engine rotation. The data of encoder and in-cylinder pressure were synchronized and analysed using National Instrument combustion analyser. The maximum in-cylinder pressure data were collected for 250 continuous combustion

cycle for each tested condition. The experiments were conducted at two different engine speed which were 2000rpm and 3000rpm. Each engine speed was running at four different throttle position, 25%, 50%, 75% and 100% of throttle valve position opening. The test engine was couple to 600 kW Dynapack eddy current chassis dynamometer for easy engine simulation at specified engine speed and a Bosch KTS 570 scan tool was used purposely to monitor the opening of throttle valve position. All the experimental data were measured and recorded for further analysis.

**Table 2**  
 Properties comparison of LPG and gasoline [14-17]

Properties	LPG	Gasoline
Chemical	C <sub>3</sub> H <sub>8</sub> / C <sub>4</sub> H <sub>10</sub>	C <sub>8</sub> H <sub>15</sub>
RON	96.5-105	89-98
MON	90-97	80-90
Lower calorific value (kJ/kg)	45600-46500	42100-44000
Flammability limit (%vol)	2.15-9.6	1.4-7.6
Flash point (°C)	-104	-40
Latent heat of vaporization (kJ/kg)	14.52	9.94



**Fig. 1.** Schematic diagram of the experimental setup

### 3. Result and Discussion

The analysis on the combustion stability is divided into two engine speed which were 2000rpm and 3000rpm. For better analysis, the gasoline fuel was used as reference point to the results generated from liquid LPG injection.

#### 3.1 Effects of Combustion Stability at 2000rpm

Figure 2 presents the variation of maximum in-cylinder pressure of gasoline and LPG for 250 consecutive engine cycles at 2000rpm and at four different throttle position; 25%, 50%, 75% and 100%. The maximum pressure for both fuels varies between cycles of combustion. This is dependent on several factors such as variation of mixture motion inside the cylinder during the combustion process, mass variation of fuel and introduced air into the cylinder, and mixing variation of fuel air charge and residual gases of the previous cycle[18]. In general, the cyclic variation obtained by gasoline is slightly higher than LPG at all throttle position. In view of maximum in-cylinder pressure,

LPG is capable to produce higher pressure than gasoline at all opening of throttle position. It is attributed to the increased of volumetric efficiency of LPG operation as compared to gasoline. The effect of liquid LPG injection has improved the mass of the air entrance into the combustion chamber. This is the main factor that contributes to a better maximum pressure of LPG [19-21].

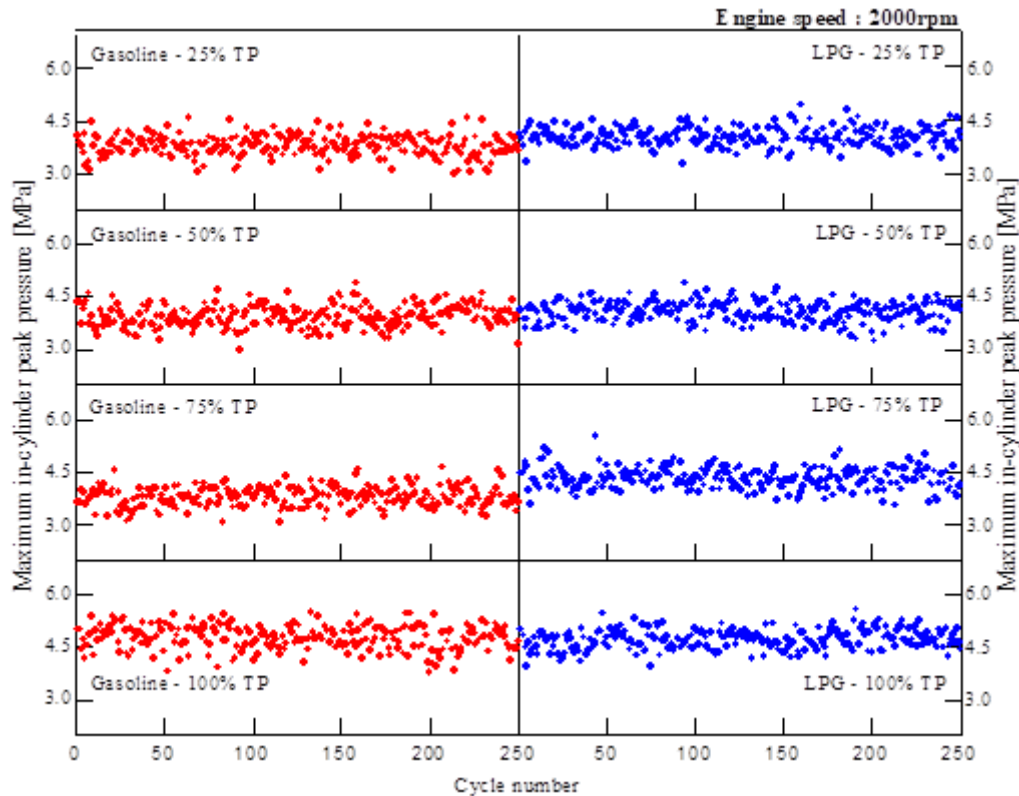


Fig. 2. Maximum in-cylinder pressure for 250 cycles at 2000rpm

Figure 3(a) displays that the average maximum in-cylinder pressure of the LPG is always higher than the gasoline. This indirectly revealed that the liquid LPG injection has better engine performance at 2000rpm. This is clearly due to the effects of the liquid LPG injection and this is supported by the higher calorific value of LPG as compared to gasoline. However, at 100% TP, the mean maximum in-cylinder pressure of LPG is identical with gasoline. This might be due to the uncontrollable parameters at maximum TP as the engine operates at extreme condition. Even though the mean maximum in-cylinder pressure at this condition is similar to gasoline, it is a good indicator of the engine performance as the worst possible power might be generated from the liquid LPG injection operation is similar to the gasoline operation. Thus, there is no issue with the power losses as found in gaseous LPG injection.

Standard deviation at all particular conditions for both fuels was calculated and plotted in Figure 3(b). From the figure, the standard deviation of LPG is clearly recorded as lower than gasoline except at 75% throttle position. The lower standard deviation means the maximum in-cylinder pressure data recorded over 250 combustion cycles has less fluctuation between the minimum and maximum values throughout the cycle. Thus, the gasoline operation has a large data spread out over a wide range of value than LPG except at 75% throttle position. In other words, the cycle to cycle combustion variation of gasoline is higher than LPG. This indirectly indicates that the combustion of LPG is better in term of its stability than gasoline.

The statistical analysis is extended to the calculation of coefficient of variation (COV) in order to evaluate the combustion stability of the tested fuels. As shown in Figure 3(c), at 2000rpm, the COV of LPG is lower than gasoline by 15.65%, 11.42%, 7.32% and 19.63% for 25%, 50%, 75% and 100% throttle position, respectively. COV is commonly used to analyse the precision and repeatability of a set of experimental data. Therefore, the lower COV value is proved that the LPG produces better combustion stability than gasoline at all tested conditions.

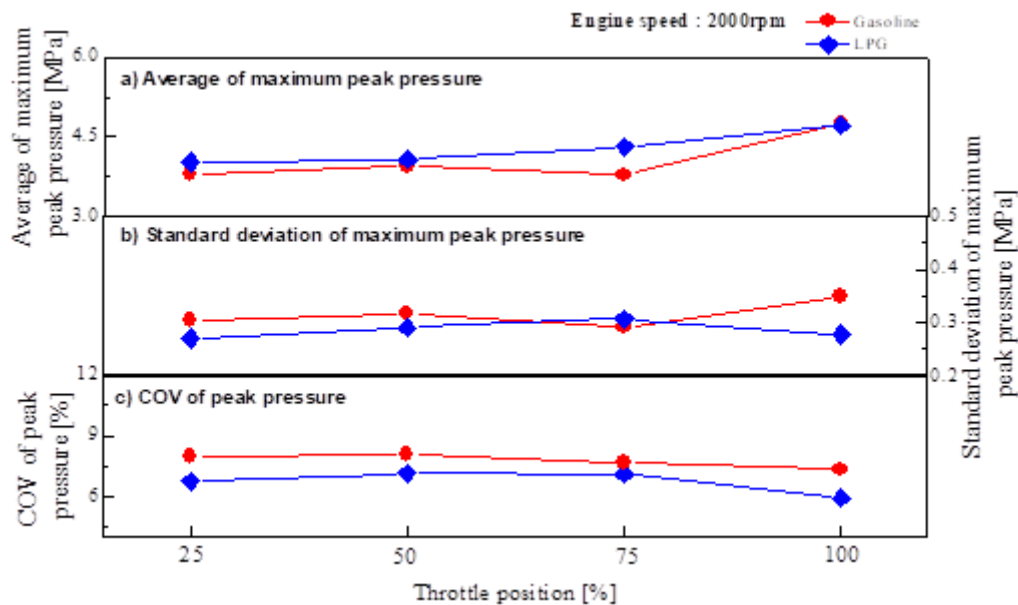


Fig. 3. Statistical analysis of peak in-cylinder pressure at 2000rpm

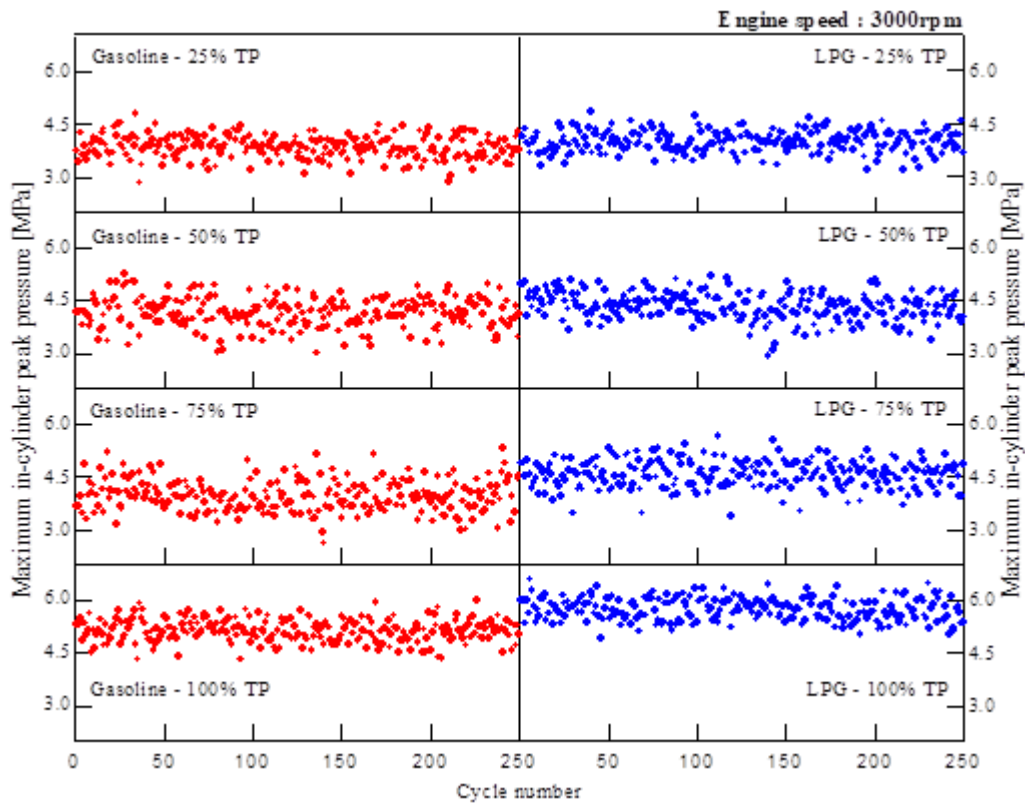
### 3.2 Effects of Combustion Stability at 3000rpm

Figure 4 illustrates 250 continuous cycles of maximum in-cylinder pressure plot at 3000rpm for several throttle position. The plot obviously presents that LPG has higher maximum in-cylinder pressure than gasoline and it increases with the increased of throttle position opening. At 25% throttle position, the tabulation of maximum in-cylinder pressure data for both fuels are almost similar but slightly higher for LPG. However, the significant differences are found at 75% and 100% throttle position. This reveals that the significant effects of liquid LPG injection on the maximum in-cylinder pressure occurred as the engine speed increases from 2000rpm to 3000rpm at 75% and 100% throttle position. This might be due to the improved of turbulent effects that introduce better air fuel mixture for combustion to happen as the engine speed and TP increase.

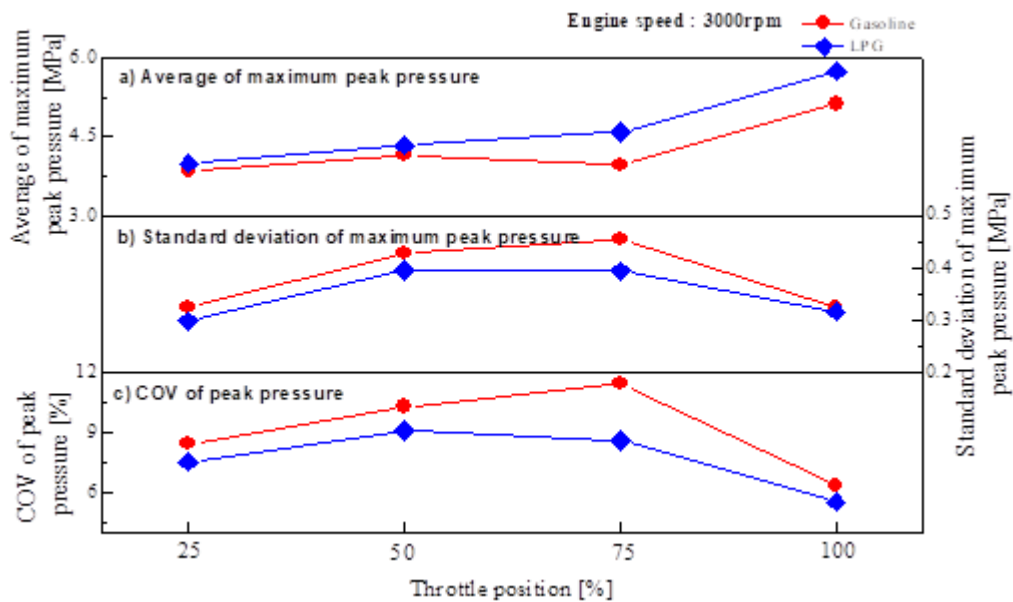
Figure 5(a) shows the average value of maximum in-cylinder pressure of 250 continuous cycles. From the figure, the in-cylinder pressure increases parallel with the increased of throttle position. The significant improvement is observed to occur at this condition after 75% throttle position. It is revealed that the liquid LPG injection has improved the combustion by utilizing its higher energy content as compared to gasoline. By comparing the results, it is noticeable that the improved in-cylinder pressure of LPG indicates better engine performance since the higher maximum in-cylinder pressure is directly proportional to the generated engine performance parameters.

Figure 5(b) presents the standard deviation of maximum in-cylinder pressure of 250 continuous combustion cycles. It is revealed that the standard deviation of gasoline at 3000rpm is higher than the one at 2000rpm. However, the standard deviation of the LPG is lower than the gasoline at this engine speed for all throttle position. The pattern is almost similar with the COV plot in Figure 5(c). Therefore, it can be concluded that the LPG produces a better cyclic variation of maximum in-cylinder

pressure and better combustion stability as compared with gasoline at all throttle position identical with the engine speed of 2000rpm.



**Fig. 4.** Maximum in-cylinder pressure for 250 cycles at 3000rpm



**Fig. 5.** Statistical analysis of peak in-cylinder pressure at 3000rpm

#### 4. Conclusion

The analysis of combustion stability is performed through maximum peak of in-cylinder pressure over 250 combustion cycle. The combustion stability of liquid LPG injection has found capable to produced better stability with less variation of combustion pressure from one cycle to another cycle as compared to gasoline at all tested condition. It is confirmed through the statistical analysis of COV where the liquid LPG injection has averagely reduced the COV compared to gasoline. The comparative study also showed that liquid LPG injection is able to give better maximum in-cylinder pressure than gasoline. In general, LPG has better combustion characteristics than gasoline at almost all tested condition.

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