Experimental analysis of liquid LPG injection on the combustion, performance and emissions in a spark ignition engine

Norrizal Mustaffa¹*, Mas Fawzi², Shahrul Azmir Osman², Mohd Mustaqim Tukiman²
¹ Department of Mechanical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, Malaysia
² Department of Energy and Thermofluids, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, Malaysia

*Corresponding authot: norrizal@uthm.edu.my

Abstract. In this study, the investigation of engine combustion, performance and emissions of liquid liquefied petroleum gas (LPG) injection was carried out using a four-stroke 1.6 L spark-ignition (SI) engine. The experiments were performed at 3,000 rpm and at four throttle positions (TP): 25%, 50%, 75% and 100%, and the results were compared with reference fuel, unleaded petrol (ULP). Analysis of combustion showed that the LPG has higher in-cylinder pressure and rate of pressure rise (ROPR) as the TP increased with respect to the ULP. The results also indicated that the rate of heat release (ROHR) and mass fraction burn (MFB) of LPG had risen earlier than ULP as the TP increased. In view of combustion stability, LPG has better stability at all TPs with lower variance, that is in the range of 2.6% to 13.1% than that of the ULP. Torque and brake mean effective pressure (BMEP) results revealed that LPG has higher value as compared with ULP. The brake specific fuel consumption (BSFC) of liquid LPG injection was found to be averagely lower than that of the ULP. Concurrently, the emissions of nitrogen oxides (NOₓ), hydrocarbon (HC) and carbon monoxide (CO) of liquid LPG injection were recorded to be higher than that of the ULP.

1. Introduction

Presently, LPG has emerged as one of the important alternative fuel and is a very promising energy source due to the good nature of LPG properties such as higher hydrogen-to-carbon ratio and no toxic aromatics in the emissions [1,2]. LPG also offers many advantages, especially in SI engine such as better fuel consumption than that of the ULP; it increases engine life by about 50%, where cylinder bore wear is reduced; prolongs the exhaust life system as compared to gasoline; reduces overall operational costs; and produces less harmful exhaust emissions [2-7]. However, there are some drawbacks of LPG as an alternative fuel such as reduction in power output by 5 to 10%, heaviness of LPG tank that requires more space than ULP tank does and the tank is filled only to 80% of the overall capacity [2,4,7].

In general, LPG has two methods of fuel delivery systems: gas or liquid injection system. The gas injection system is used from the first until the fourth generation of LPG system and the latest LPG generation uses liquid injection system [2]. Basically, there are three main differences between the gas and liquid injection systems, which are: (i) the operating pressure of the liquid injection system is kept high in order to maintain its liquid phase inside the fuel line; (ii) gas injection is usually returnless, while liquid injection provides recirculation of the LPG with the purpose to keep the temperature of the LPG.
below the evaporation temperature; (iii) in liquid injection, the fuel pump is always running to maintain the required injection pressure while in gas injection, the fuel pump only needs to run during low temperature operating conditions [8].

Theoretically, gas and liquid injections would give different values of volumetric efficiency. The latter strongly affects the engine performance more than the other parameters do [9,10]. In particular, gas injection produces lower volumetric efficiency as compared to the liquid injection because of either the absence of intake charge cooling due to vaporization of liquid fuel, or the displacement of fresh air in the intake system due to the volume occupied by the gaseous fuel. Liquid injection has the potential to give better power output because of the rapid vaporization of the liquid LPG, resulting in cooler and denser air-fuel mixture flowing into the combustion chamber, as stated by the Joule-Thompson effects [11,12,44]. The lower the temperature of the mixture, the lower the peak combustion temperature, and in turn, lowers the NOx emission. This also brought about the reduction of exhaust gas temperature by 20 to 30°C [8,10,13-15]. Based on Masi and Gobbato [9], the different volumetric efficiency of gas and liquid fuels is in the range of 4 to 8% and it is depending on several factors such as mixture strength, engine load and rotational speed of the engine, thermal pipe insulation, shape and dimensions of the intake system and fuel temperature.

2. Background study

Some studies on LPG gas injection conducted by few researchers were reviewed and summarized [7,16-19]. The power generated by the gas injection observed to be lower than that of the ULP in most of the testing conditions conducted by the authors. They concluded that it was attributed to the gaseous nature of LPG that promoted lower volumetric efficiency during the gas phase injection as compared with ULP. In view of emissions, the authors found that the CO, HC, and NOx emissions of LPG were lower than that of the ULP at all testing conditions due to the lower carbon-hydrogen ratio of LPG, high octane number and the ability to create a homogeneous mixture in the combustion chamber.

Since the current study uses liquid LPG injection system, the literature related to the liquid injection was thoroughly reviewed and few references exist on the effect of liquid LPG injection on the performance and emission of SI engines. Fabbri et al., [20] examined the use of liquid LPG injection on 2000cc turbo engine. The injector was located at the intake manifold of each cylinder and the result showed that liquid LPG injection produced higher power as compared to the ULP. Li et al. [15] evaluated the effects of LPG injection methods in engine performance of SI engine. A single-cylinder four-stroke engine was modified to enable the use of liquid LPG direct injection, liquid LPG injection at intake port and gaseous LPG injection at the intake port. Liquid LPG direct injection had produced higher torque in the entire range of engine speed considered, followed by liquid LPG injection at intake port, original gasoline carburettor engine and gaseous LPG injection at intake port. Liquid injection was expected to produce higher power due to liquid LPG’s ability to absorb more heat to evaporate because the heat of vaporization of LPG is 1.434 times higher than that of the ULP. Liquid LPG direct injection allows for volumetric efficiency higher than the liquid LPG intake port case because of the absence of throttling devices that restrict the flow. In addition, directly injected LPG does not occupy any space in the intake manifold and LPG has high density that makes it available for the air a higher fraction of the in-cylinder volume.

An experimental study was conducted by Farrugia et al., [21] using 1174cc SI engine converted into liquid LPG single point injection with the injector placed upstream of the throttle body. They observed that the manifold absolute pressure of both ULP and LPG showed the same value up to approximately 3500 rpm engine speed while at higher engine speed, manifold absolute pressure in ULP mode became lower than that in LPG mode. Authors justified that this phenomenon occurred due to the LPG that had fully vaporized in the intake manifold, thus causing the increase in the fuel partial pressure value. The LPG produced was approximately similar to the power output of the ULP with a slight decrease of about 4% at 5000 engine speed. Here, the cooling effect of the liquid injection is the main factor in maintaining the performance of LPG.

In terms of emissions data, Farrugia et al., [21] found that LPG exhibited reduction in HC and CO emissions of around 35.7% and 56.5% by average, respectively. Myung et al. [22] conducted a series of experiment to investigate the toxic emissions characteristics of liquid LPG injection using three
different light duty vehicle emissions test cycles, they were the federal test procedure (FTP-75) mode, highway fuel economy test (HWFET) mode and new European driving cycle (NEDC) mode. The 2400cc converted engine showed little reduction of total hydrocarbon (THC) emission for FTP-75 mode and NEDC mode compared to the ULP. The reduction was due to the rapid LPG vaporization rate that substantially increased the amount of homogeneous mixture in the combustion chamber and improved the quenching effect in the crevice volume. However, in HWFET mode, THC showed the same value with ULP. The CO emission of LPG was found to be higher than that of ULP in the FTP-75 mode and NEDC mode. The authors stated that it was due to delayed catalyst activation during cold start conditions. In addition, NOx emission of ULP was recorded to be slightly higher than LPG in NEDC mode and equivalent in the FTP-75 and HWFET mode. For the CO2 emission and fuel economy, LPG produced about 96% and 79% reduction, respectively, as compared to the ULP. Reduction of CO2 was attributed to the lower carbon content of LPG while fuel economy was due to lower energy density than ULP.

Kwak et al., [23] analysed the THC emission characteristics of liquid phase multi-port LPG injection engine during cold start. The analysis was performed at three different spark timing conditions that were: 10° before top dead center, top dead center and 10° after top dead center. Each spark timing condition was conducted at five different excess air ratios with the engine operating condition was 1400 engine speed and coolant temperature was maintained at 25°C. Based on the observation, the THC was effectively reduced due to the effects of the spark timing retard regardless the excessive air ratio and this is a very applicable technique in reducing THC during cold start condition for liquid LPG injection. In addition, the authors also found that increasing the excess air ratio value would give a slight reduction in THC emission. Park et al., [24] conducted the comparison of emission characteristics of ULP and LPG in a spray guided type direct injection engine. A 1998cc engine was employed to operate at a constant speed that equalled to 2000 rpm throughout the experiment with 0.2 MPa BMEP. The authors observed that the CO emissions of LPG were higher than those with ULP by 20.3% and 26.5%, respectively, while the emissions level of HC and NOx were found to be lower in LPG as compared to the ULP by 25% and 26.5%, respectively.

Although several researches have been conducted, there is lack and unclear information, especially on the combustion analysis and stability of the liquid LPG injection. Therefore, this study aims to link the experimental analysis of combustion stability, performance and emissions of liquid LPG multi-point port injection (MPI) in an SI engine at four TPs: 25%, 50%, 75% and 100% at 3000 rpm. The novelty of this study lies in the comparison of effects on combustion analysis and stability between liquid LPG injection and ULP. The investigation of combustion particularly on in-cylinder pressure, ROPR, ROHR, and MFB were performed. In addition, the performance and emissions analysis have been performed as well.

3. Materials and experimental method

3.1. Fuels
The experiments were conducted using LPG and ULP as reference fuel. The ULP was bought from a petrol station while the LPG was obtained from a local LPG supplier; Table 1 shows the properties of LPG and ULP. Since Malaysian LPG is currently being used only for cooking purposes, the LPG was transferred to the automotive Toroidal LPG tank using a special rig that is connected to a diaphragm pump. The Toroidal LPG tank was installed in the vehicle spare tire space.

3.2. Experimental setup
A naturally aspirated four-stroke port fuel injection SI engine from Proton was employed for the experiments (Proton Gen 2). The engine was equipped with liquid LPG sequential MPI system that injects the LPG in liquid phase, unlike conventional injection system, gaseous phase. The engine specifications are shown in Table 2. A 600 kW Dynapack eddy current chassis dynamometer was used in this study. Fuel consumption was measured using an Ono-Sokki fuel flow rate detector (FZ-2100) with the flow accuracy of 0.1% that coupled with Ono-Sokki display unit (FM-2500). This fuel flow meter was used for both fuel, LPG and ULP. Since the LPG fuel system was in the liquid phase, there
was no issue that had risen during the usage of this fuel flow rate detector. Similar fuel flow rate detector was also used by Mizushima et al. [33] to measure the flow rate of LPG in his research. The exhaust emissions were analysed using Autocheck Gas analyzer that was capable of capturing CO, HC and NOx exhaust emissions.

**Table 1. LPG properties in comparison with ULP**

| Properties                    | LPG          | ULP          |
|-------------------------------|--------------|--------------|
| Chemical                      | C3H8 / C4H10 | C4H16        |
| 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         |
| Carbon, % composition         | 82           | 85-88        |
| Hydrogen, % composition       | 18           | 12-15        |

An in-cylinder pressure sensor was installed in the first cylinder of the engine in order to capture the pressure development during the experiments. The pressure sensor used was a Kistler pressure transducer 6115B spark plug type with the maximum capability of 20000kPa pressure measurement. A rotary encoder with the 0.1 degree of resolution was installed at the engine crankshaft pulley to capture the speed and the rotation angle of the engine. Both in-cylinder pressure and crank angle data were recorded simultaneously using National Instruments combustion analyzer data acquisition system (NI 9222 and NI 9411). The data were collected continuously for 250 engine cycles of each experiment and used for further analysis of the combustion stability for the tested fuels. The LPG supply and control system used was similar as per reported in [34]. Figure 1 shows the schematic diagram of the experimental setup. The experiments were run at 3000 rpm and the TPs varied at four different angles: 25%, 50%, 75% and 100%. Engine speed of 3000 rpm was chosen because at this engine speed, the vehicle ran at an average driving speed of 86 km/h. During the experiments, the mapping of air-fuel ratio (AFR) was remained as per manufacturer’s setting for both tested fuels. All the experimental data were measured and recorded accordingly.

**Table 2. Test engine specification [32]**

| Engine model    | S4PH – 1.6 |
|-----------------|------------|
| Number of cylinders | 4          |
| Valve train     | DOHC 16V   |
| Combustion chamber | Pentroof type |
| Bore x stroke   | 76.0mm x 88.0mm |
| Compression ratio | 10.0 : 1   |
| Fuel injection  | Indirect injection |
| Cooling system  | Water-cooled |
| Maximum torque  | 148Nm (4000rpm) |
| Maximum power   | 110hp (6000rpm) |
4. Results and discussion

In this study, effects of liquid LPG fuel on the combustion, performance and emissions of an SI engine were examined and compared with the reference fuel, ULP. Figure 2 presents the in-cylinder pressure versus crank angle during the compression and expansion process of the engine operating cycle at 3000 rpm for all TPs. The value was averaged over 250 consecutive combustion cycles. The figure mentioned beforehand clearly indicates that the in-cylinder pressure of both tested fuels had increased as the TP increased and LPG data showed higher maximum in-cylinder pressure than that of the ULP at all TPs. The reason for the higher maximum in-cylinder pressure for LPG was attributed to the effects of rapid vaporization of liquid LPG that had increased the inlet air mass charge into the combustion chamber. Other than that, higher amount of calorific value of LPG as compared to the ULP had also affected the maximum in-cylinder pressure generated.

ROPR of LPG and ULP relative to the degree of crank angle is illustrated in the Figure 3. In general, ROPR is frequently used as a measure of combustion generated noise and the value is the first derivative of in-cylinder pressure corresponding to the engine operation [35,36]. As for in-cylinder pressure, ROPR during LPG operation was higher than ROPR during ULP operation, and the maximum peak found at 100% TP was 243.44 kPa/CA for LPG and 208.50 kPa/CA for ULP. Note that, ROPR negative values are due to the expansion process. At 75% and 100% TPs, the ROPR of LPG increased earlier than ULP. Accordingly, the peak in-cylinder pressure of LPG in Figure 2 happened closer to the TDC. Since the engine test was conducted at similar ignition timing at each 75% and 100% TP, this revealed that the LPG has a shorter duration of flame development since the laminar flame speed of LPG is higher than ULP [37].

Figure 4 shows the ROHR of both ULP and LPG at 3000 rpm, four different TPs. The ROHR was calculated using first law-single zone heat release model and the methodology of ROHR calculation is referred to the Ref. [38,39]. The value depends on the types of fuels, instantaneity of in-cylinder pressure and cylinder volume relative to the engine rotation. From the figure, there is a negative ROHR of all TPs for both fuels at the start of combustion and this is due to the fuel vaporization process that is closely related to the energy of endothermic reaction and heat transfer from fresh charge air into vapor fuel [38,40]. Then, the conversion of chemical energy into thermal energy increases the ROHR before it proceeds to decrease after combustion because of the high heat loss at the expansion cycle. Based on the observation, the increase of TP resulted in the increase of ROHR due to the better turbulence intensity for both tested fuels. The better turbulence intensity is attributed to the increases of mass air volume entering the combustion chamber. However, the ROHR of LPG was found to have raised earlier than ULP as the TP increased and this result is in agreement as per reported in [41]. This is due to the advantages of gases fuel that has a better vaporisation rate than ULP. Other than that, gases fuel improve
the mixing of air, fuel and residual gases and indirectly produces faster flame speed than ULP. The faster the flame speed, the shorter the combustion duration and the better the ROHR produced.

Figure 5 shows the MFB of ULP and LPG at 3000 rpm. The MFB profile is similar to the S-shape. The MFB started from zero percentage and had exponentially increased to hundred percentage as the crank angle was increased. Theoretically, the combustion duration was referred at the 10% to 90% of the MFB plot. As illustrated in the figure, the MFB curve of LPG has shifted to the left as the TP increased and this indicates that higher percentage of LPG burnt than ULP at any crank angle throughout the combustion process as the TP increased. It means that the LPG burning rate became faster and the combustion duration became shorter as compared to the ULP when the TP increased. This is attributed to the higher flame speed of LPG than ULP as stated earlier and the increase of kinetics energy of molecules and higher reaction activation energy due to the increase in gas temperature [38].
Figure 6 presents the variation of maximum in-cylinder pressure produced by ULP and LPG at 25%, 50%, 75% and 100% TPs, 3000 rpm for 250 continuous engine cycles. The result shows that maximum in-cylinder pressure increased as the throttle opening increased. At 25% TP, the tabulation of maximum in-cylinder data for both fuels were almost similar but slightly higher for LPG. However, the significant differences were found at 75% and 100% TPs. This is due to the increase of volumetric efficiency of the LPG at higher engine speed. The liquid LPG injection reduced the intake air temperature and increased the mass of air within the combustion chamber. Table 3 shows the average maximum in-cylinder for all tested conditions of both fuels. Interestingly, all the maximum pressures of LPG was found to be higher than that of the ULP. It revealed that the liquid LPG injection had improved the combustion by utilizing the energy content of LPG that has the calorific value higher than ULP by 6.9% per kilogram fuel [4,7,16]. By comparing the results, it is noticeable that the improved in-cylinder pressure of LPG does indicate the better engine performance since the higher maximum in-cylinder pressure is directly proportional to the torque and power generated.

The in-cylinder pressure data at 3000 rpm for all TPs were further analyzed using statistical method in determining the combustion stability of both tested fuels. The data varied for each cycle due to few factors such as engine characteristics that are related to the mixture ratio formation and cycle to cycle movement [42]. The 250 consecutive cycles of in-cylinder pressure data were averaged and based on the standard deviation calculation, it shows that the LPG standard deviation is lower than that of the ULP for all TPs, as depicted in Table 4. This demonstrated that the tabulation of data produced by LPG is closer to the mean of data and the variation of LPG data is lower than that of the ULP.

The coefficient of variation (COV) of in-cylinder pressure data for 250 cycles was computed in order to analyse the combustion stability of both tested fuels. As displayed in Figure 7, the COV of LPG was found to be lower for all TPs than that of the ULP. The lower value of COV described that LPG produced better combustion stability than ULP at all TPs: 25%, 50%, 75% and 100% by 7.9%, 7.7%, 13.1%, and 2.6% respectively. Thus, it revealed that the LPG yielded better cyclic variation in terms of maximum in-cylinder pressure produced. These results explained that the use of liquid LPG in SI engine had improved the engine combustion especially in views of combustion stability. The improvement is due to the effects of liquid LPG injection that produces better volumetric efficiency and better air mass at each cycle combustion as compared with ULP.

Figure 8 shows the torque and BMEP generated from the naturally aspirated SI engine at four TPs angle. Torque was recorded at various TPs and the value was compared between ULP and LPG. In general, torque represents the capability of certain engine to carry out the work. Meanwhile, BMEP was calculated from the torque value and the data was displayed in the same figure. Basically, BMEP indicates the average pressure applied to the each piston for the tested engine and it is an effective parameter to compare the engine performance with another engine. The plot of BMEP was found to be identical with torque plot since BMEP is the function of torque. From the bar chart, torque and BMEP presented an increment pattern as the TP increased. The results exhibited that liquid injection of LPG has higher engine torque and BMEP as compared with ULP. This improvement is due to higher calorific value and volumetric efficiency of LPG that gave better combustion efficiency and higher in-cylinder pressure. This result is consistent with the previous studies that have been reported in [15,20]. However, the result was found against [21] due to the difference in the injection method employed such as throttle body injection.

Figure 9 presents the BSFC of both tested fuels at all tested conditions. Generally, BSFC is a measure of how efficiently fuel is being used and converted into a specific engine power. Based on the figure, 25%, 50% and 75% TPs indicated that BSFC produced by LPG was found to be lower than that of the ULP and the result is in agreement with Ref[9,45]. It shows less amount of LPG is required in order to produce similar engine output. This is strongly supported by the LPG properties that have higher energy content compared with ULP. However, at maximum TP, BSFC of LPG was observed comparable with ULP.
Figure 6. Variation of in-cylinder peak pressure of ULP and LPG at 3000rpm under 250 cycles.

Table 3. Average maximum in cylinder peak pressure (MPa) for all TPs.

| TP     | 25%  | 50%  | 75%  | 100% |
|--------|------|------|------|------|
| ULP    | 3.84 | 4.15 | 3.96 | 5.13 |
| LPG    | 3.98 | 4.34 | 4.58 | 5.74 |

Table 4. Standard deviation of both tested fuels at 3000 rpm under 250 cycles.

| TP     | 25%  | 50%  | 75%  | 100% |
|--------|------|------|------|------|
| ULP    | 0.33 | 0.43 | 0.45 | 0.33 |
| LPG    | 0.30 | 0.40 | 0.39 | 0.32 |

Figure 7. COV of in-cylinder pressure data for ULP and LPG at 3000 rpm under 250 cycles.

Figure 8. Torque and BMEP of ULP and LPG at 3000 rpm.
Next, the emissions of both tested fuels were analyzed. Figure 10 compared the results of NO\textsubscript{x} emission for ULP and LPG at various TPs, 3000 rpm. Theoretically, NO\textsubscript{x} formation is related to the combustion temperature, as discussed in the Zeldovich mechanism. From the graph, the NO\textsubscript{x} emission of LPG was found to be extremely higher than ULP at all TPs. However, the NO\textsubscript{x} emission of LPG was found to be reduced at 100% TP but still remained higher than ULP. This is attributed to the higher calorific value of LPG compared to ULP that would significantly improve the engine operation, thus increasing the exhaust gas temperature of LPG. High gas temperature induced higher NO\textsubscript{x} emission, however, at maximum throttle opening, NO\textsubscript{x} produced by LPG was found to have been greatly reduced and this is due to the effect of rich condition, whereby excess LPG introduced did significantly affect the NO\textsubscript{x} emission.

Figure 11 depicts the HC emission of ULP and LPG at 3000 rpm for four different TPs. The presence of HC in exhaust emission signified that the unburnt fuel during combustion. The main reason for HC formation is the effects of piston crevice that will trap the fuel in the crevice volume [37]. Other reasons for HC formation are lack of oxygen present, low temperature and non-homogeneity of mixture [17]. As shown in the figure, HC emission of LPG was recorded to be higher than that of the ULP and the maximum HC occurred at the maximum TP for both tested fuels. The plot of HC emissions was inversed of NO\textsubscript{x} emissions plot, whereby at 25%, 50% and 75% TPs, the NO\textsubscript{x} emission was higher and HC emission was found to be lower. Meanwhile, at 100% TP, the pattern was contradictory. This is due to the effects of combustion temperature that produced higher NO\textsubscript{x} and lower HC emissions when the combustion temperature was high [17]. Other than that, the reason for the higher HC at maximum TP is due to the SI engine behaviour that operated with rich mixture in order to preserve the engine components [43,44]. For better HC emission, adjustment of ignition timing and injection duration at optimum condition might need to be applied.

Figure 12 shows the CO emission for both tested fuels at 3000 rpm. The CO was plotted at all tested TPs. Generally, CO is the by-product of incomplete combustion and it represents the mixture of the combustion, either lean or rich mixture, for a certain AFR. From the bar chart, it was observed that the CO emissions of 25%, 50% and 75% TPs were almost zero. Again, this was attributed to the engine behaviour that ran in the lean mixture condition. In lean mixture condition, the amount of fuel injected into the combustion chamber was insufficient, thus creating an imbalanced AFR. As a consequence, almost all of the fuels were completely burnt out due to the copious amount of air present and very small fuel quantity left to produce CO. On the other hand, CO emission at maximum TP exhibited that the LPG has higher CO emission than ULP and the occurrence of higher CO value for both fuels were due to the excessive fuel entering the combustion chamber, thus leading to the incomplete combustion. However, the higher CO of LPG as compared to the ULP was attributed to the lower fuel density of LPG that may have introduced higher amount of fuel quantity injected into the combustion chamber than ULP at similar testing condition, thus promoting higher CO emission.
5. Conclusions

Experimental work to compare the LPG and ULP in the same SI engine was performed and analyzed thoroughly at specified testing conditions. Based on the results, several conclusions were drawn. They are as follows:

1. The comparative study shows that liquid LPG injection is capable of producing better in-cylinder pressure than ULP at 3000 rpm. This is due to several factors such as the vaporization rate, calorific value and flame speed. In view of ROPR and ROHR, it was also observed to be better than ULP as the starting point of climbing value that was found earlier than ULP. It was dominantly found as the TP increased.

2. The MFB results revealed that the percentage of LPG fuel burnt and LPG burning rate were always faster than ULP at any degree of the crank angle. The value was also dominantly observed as the TP increased similarly with regards to ROPR and ROHR.

3. The pressure variation analysis disclosed that liquid LPG injection is capable in reducing the variation of engine cycle combustion as compared with ULP. The combustion stability was also found to have improved with the use of liquid LPG injection at all TPs and it was confirmed by the COV analysis.

4. The comparison of performance parameters showed that liquid LPG injection have increased the engine torque and BMEP as compared with ULP. Meanwhile, for BSFC, the significant improvement was observed at 50% and 75% TPs.

5. In view of emissions, average NOx, HC and CO emissions were higher for liquid LPG as compared with the ULP.

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