COMBUSTION CHARACTERISTICS OF A SPARK IGNITION ENGINE OPERATING WITH LIQUID LPG INJECTION

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Special dedication to my parents, wife, family

Thanks for the love, support and memories

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ABSTRACT

Issues on global warming, stringent emissions regulation and unstable fuel price are among the primary reasons that lead to the usage of alternative fuels in internal combustion engines. Liquefied petroleum gas (LPG) is one of the most popular alternative fuels for spark ignition (SI) engines that received lots of attention due to its availability and acknowledged superior properties than gasoline. However, detail analysis on latest technology of liquid LPG injection that introduces the fuel in liquid phase during injection is scarcely found. With this motivation, a comprehensive experimental study on an SI engine has been conducted in order to evaluate effects of the liquid LPG injection. A series of experiments was performed at several engine speeds ranging from 1500rpm until 4000rpm with a step size of 500rpm. During the experiments, four throttle position (TP) were tested; 25%, 50%, 75% and 100%. The experimental results between liquid LPG injection and gasoline were compared. It was found that liquid LPG injection has the capability to increase the engine torque and brake power by 9.56% and 8.34%, respectively as compared to gasoline. Since the LPG has lower carbon to hydrogen ratio than gasoline, the reduction of carbon related emissions, CO_2 and CO were found lower in LPG operation by 9.15% and 58.55% respectively than gasoline at all testing conditions. Meanwhile, HC and NO_x were recorded higher for LPG, compared to gasoline at all testing conditions. Statistical analysis indicates that liquid LPG operation in SI engine exhibited better combustion stability with 14.87% lower coefficient of variation (COV) of maximum in-cylinder pressure peak throughout the testing than gasoline. In addition, liquid LPG injection also showed improvement on the in-cylinder pressure, rate of pressure rise (ROPR) and rate of heat release (ROHR) where the maximum plot of these parameters was found higher with the usage of liquid LPG injection than gasoline.

ABSTRAK

Isu pemanasan global, peraturan pelepasan gas kenderaan yang ketat dan harga bahan api tidak stabil adalah antara sebab utama yang membawa kepada penggunaan bahan api alternatif bagi enjin pembakaran dalaman. Gas petroleum cecair (LPG) adalah salah satu bahan api alternatif yang paling popular bagi enjin pencucuhan bunga api (SI) yang mendapat lebih perhatian kerana kebolehdapatannya dan beberapa sifat yang lebih baik berbanding petrol. Walaubagaimanapun, analisis terperinci terhadap teknologi terbaru suntikan LPG yang menyuntik bahan api dalam fasa cecair semasa suntikan amat sukar untuk dijumpai. Dengan motivasi ini, kajian eksperimen yang terperinci pada enjin SI telah dijalankan bagi menilai kesan suntikan LPG di dalam fasa cecair. Eksperimen dijalankan pada beberapa kelajuan enjin di antara 1500rpm hingga 4000rpm dengan setiap kenaikan 500rpm. Semasa eksperimen, empat kedudukan pendikit (TP) telah diuji; 25%, 50%, 75% dan 100%. Keputusan eksperimen antara suntikan LPG cecair dan petrol telah dibandingkan. Didapati bahawa LPG mempunyai keupayaan untuk meningkatkan prestasi kuasa daya kilas dan kuasa enjin sebanyak 9.56% dan 8.34%, berbanding petrol. Oleh kerana LPG mempunyai nisbah karbon kepada hidrogen yang lebiih rendah daripada petrol, pengurangan pelepasan gas CO_2 dan CO didapati lebih rendah bagi LPG iaitu sebanyak 9.15% dan 58.55% berbanding petrol pada semua keadaan ujikaji. Sementara itu, HC dan NO_x direkodkan lebih tinggi untuk LPG berbanding petrol pada semua keadaan ujikaji. Analisis statistik menunjukkan bahawa penggunaan LPG di dalam enjin SI telah menghasilkan kestabilan pembakaran yang lebih baik dengan pengurangan sebanyak 14.87% pekali variasi (COV) tekanan maksimum berbanding petrol. Selain itu, LPG juga menunjukkan peningkatan pada tekanan silinder, kadar kenaikan tekanan (ROPR) dan kadar pelepasan haba (ROHR) di mana plot maksimum bagi parameter ini didapati lebih tinggi dengan penggunaan LPG berbanding petrol.

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LIST OF SYMBOLS AND ABBREVIATIONS

π	-	Pi = 3.142
γ	-	Specific Heat Ratio, c_p/c_v
θ_d	-	Combustion Duration
θ_s	-	Spark Timing
a	-	Weibe Efficiency Factor
BDC	-	Bottom Dead Center
BMEP	-	Brake Mean Effective Pressure
BSEC	-	Brake Specific Energy Consumption
BSFC	-	Brake Specific Fuel Consumption
BDC	-	Bottom Dead Center
BTE	-	Brake Thermal Efficiency
C_3H_8	-	Propane
C_4H_{10}	-	Butane
CH_4	-	Methane
CI	-	Compression Ignition
CNG	-	Compressed Natural Gas
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
COV	-	Coefficient of Variation
DI	-	Direct Injection
dP	-	Pressure different between two selected point
$d\theta$	-	Crank angle degree different
ECU	-	Engine Control Unit
EGR	-	Exhaust Gas Recirculation
HC	-	Hydrocarbon
IMEP	-	Indicated Mean Effective Pressure

LPG	-	Liquefied Petroleum Gas
$\dot{m}_f$	-	Mass Flow Rate of Fuel, kg/h
MAP	-	Manifold Absolute Pressure, Pa
MFB	-	Mass Fraction Burnt, %
MPI	-	Multi Point Port Fuel Injection
n	-	Weibe Form Factor
N	-	Engine speed
N_2O	-	Nitrous oxide
NI	-	National Instrument
NEDC	-	New European Driving Cycle
NO_x	-	Nitrogen Oxides
PFI	-	Port Fuel Injection
ROHR	-	Rate of Heat Release
RON	-	Research Octane Number
ROPR	-	Rate of Pressure Rise
rpm	-	Revolution per Minute
SI	-	Spark Ignition
TBI	-	Throttle Body Injection
TDC	-	Top Dead Center
THC	-	Total Hydrocarbon
TP	-	Throttle Valve Position
V_d	-	Volume Displacement
WOT	-	Wide Open Throttle

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Climate change is a world problem that receives high attention and it is mainly related to the global warming. In general, climate change has affected the whole eco-system, including living and non-living things in this world. The increase of ocean and atmosphere temperature, rise of sea level and worse air pollution are among the examples of the dominant impact of climate change (IPCC, 2014). The occurrence of climate change is fundamentally associated to the increment of greenhouse gas emission concentration in our atmosphere, which retained the heat and acted just like a blanket.

Intergovernmental Panel on Climate Change (IPCC, 2014) has outlined that there are three main gases that caused global warming, namely, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). According to Szulejko *et al*., (2016), global temperature is forecasted to increase to 0.9^oC by year 2100 if there is no increment of CO_2 emission to the atmosphere after year 2015. However, Figure 1.1 shows that the global greenhouse gas emissions are found to be increased as the year increased, with the CO_2 is the main contributor to the total emissions. The source of CO_2 emission is shown in Figure 1.2 and it is revealed that the transportation and electricity sectors are the dominant contributors to the global CO_2 emission with a 34 % contribution each.

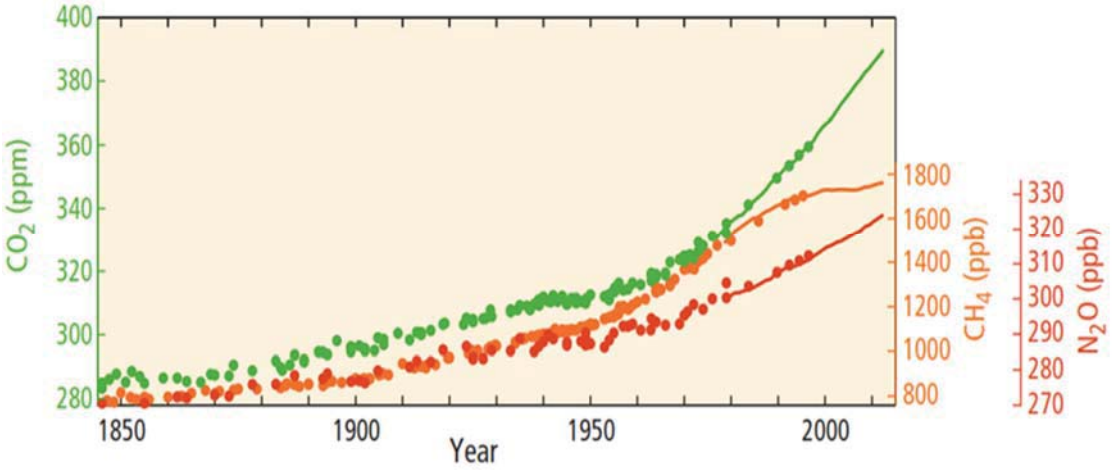

Figure 1.1: Globally averaged greenhouse gases emissions (IPCC, 2014)

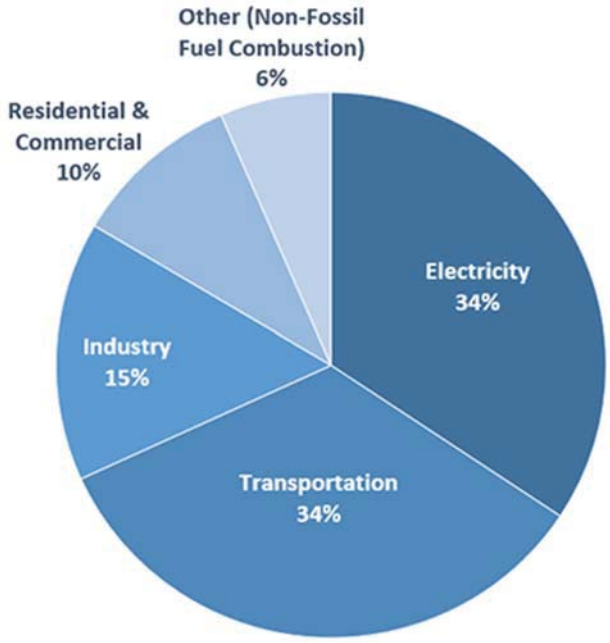

Figure 1.2: CO_2 emission by source (EPA, 2018)

In the transportation sector, the usage of alternative fuel in order to lower the carbon related emissions has become popular since a few years ago. However, the cost and availability of the fuel are major concerns that required to be clearly scrutinized. Commonly, this 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 (Bayraktar & Durgun, 2005; Biscoff *et al.,* 2012; Johnson, 2003; Myung, *et al.,* 2012; Selim, 2004).

According to the Autogas Incentive Policies (AIP, 2017), there are 26.8 million LPG vehicles have been recorded all over the world as per tabulated in Table 1.1. Turkey represents the country that has the highest number of LPG vehicle, meanwhile China is the lowest. In view of LPG consumption, Korea 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. 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 AIP (2016), the usage of liquid phase injection began to gain attention by public user in the year of 2016, and in general, it normally will take a few years to gain the confidence and to penetrate the acceptance by public users.

Table 1.1: Automotive LPG market, 2016 (AIP, 2017)

Country	**LPG consumption (thousand tones)**	**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 motivation behind the usage of LPG in these countries is basically due to the lower price of LPG as compared to gasoline. Figure 1.3 shows the comparison of fuel pump price in year 2016 between gasoline and LPG. Despite the price is varied depending on the country, it is pointed out that the LPG has an average 50% lower price compared to gasoline. Similar price difference is also observed in Malaysia; LPG and gasoline prices are 0.25 USD and 0.54 USD per liter, respectively. However, the Malaysian LPG price is based on the LPG cooking price, since there is no LPG vehicle and refuelling station. Thus, it creates a very high potential for Malaysia to use LPG as an alternative fuel due to its relatively low price than gasoline and the capability to reduce greenhouse gas emission that is closely related to the carbon emissions. Other than that, higher energy content in 1kg of LPG compared to 1kg of gasoline gives extra advantages to the usage of LPG as an alternative fuel. Currently, Malaysia focuses only on the CNG as an alternative fuel and LPG does not receive attention. This might be due to the lack of awareness and unavailable technical data of LPG implementation on the Malaysian vehicle.

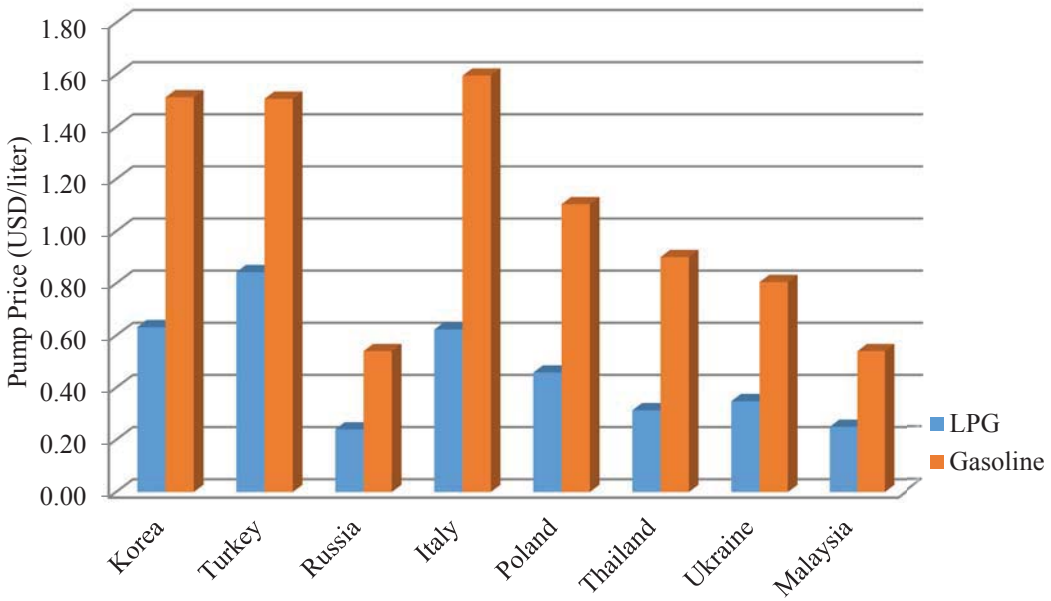

Figure 1.3: Comparison of pump price at the year of 2016 between gasoline and LPG (AIP, 2017)

1.2 Problem statement

In Malaysia, there are two types of gaseous fuel commercially available which are CNG and LPG. CNG has been widely used as an alternative fuel in transportation sector especially in spark ignition (SI) engine in order to reduce the fuel consumption and emissions, meanwhile LPG has only been used as cooking fuel. However, the Malaysian Standard MS 775:2005, LPG fuel system in internal combustion engines has been readily available since 2005 and it is expected that the Malaysian government will officially introduce LPG as another alternative fuel for SI engine in near future. Since the comprehensive analysis as well as the research database on the liquid LPG injection is not available enough especially for Malaysian light duty vehicles, therefore it is a necessity to anticipate and overcome any limitation and problem associated with liquid LPG injection. Based on this motivation, it is therefore, imperative for this research to provide experimental analysis on the performance, emissions, combustion stability and combustion characteristics of liquid LPG injection as a benchmark and platform for future reference. All the mentioned parameters should also be evaluated in comparison with gasoline as to give a ground of any values.

1.3 Objectives

The objectives of this research are:

i. To characterize the SI engine performance operated with liquid LPG injection.
ii. To determine the exhaust emissions behaviour of liquid LPG injection in SI engine.
iii. To investigate the combustion stability using the tabulation of maximum in-cylinder pressure of liquid LPG injection in SI engine.
iv. To evaluate the combustion characteristics that focused on the in-cylinder pressure, rate of pressure rise (ROPR), rate of heat release (ROHR) and mass fraction burnt (MFB) operated with the liquid LPG injection.

1.4 Scope of study

The scope of study is as follows:

i. The research is focused only on an SI engine with a capacity of 1.6 liter.

ii. The latest generation of the LPG supply system, liquid LPG injection multi point port fuel injection (MPI) was used for this research.

iii. The experiments were conducted at 25%, 50%, 75% and 100% throttle valve positions (TP).

iv. The engine speeds were varied from 1500rpm until 4000rpm with the step of 500rpm for each TP.

v. Steady state tests on the chassis dynamometer were performed at the specified testing condition.

vi. The investigation parameter covered as follows:

   a. Performance: torque, brake power, brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC).

   b. Exhaust gases: CO_2, carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x).

   c. Combustion stability: standard deviation and coefficient of variation (COV) of the maximum in-cylinder peak pressure.

   d. Combustion characteristics: in-cylinder pressure, ROPR, ROHR, MFB.

vii. All the tested parameters were compared with gasoline as reference point.

1.5 Significance of study

From this study, the comprehensive experimental analysis of the liquid LPG injection on SI engine is highly required in preparing the established reference for liquid LPG injection technology especially for Malaysian transportation sector, in parallel with the Malaysian Standard, MS 775:2005.

The analysis is expected to expand and create the database of latest LPG injection technology for the benchmark and open the acceptance of public user to use LPG as an alternative fuel in SI engine. Since the analysis is conducted using Malaysian commercial available engine, the analysis is very useful in providing the tangible reference especially for Malaysians. Other than that, the analysis is beneficial for other researchers because the available reference is limited to certain testing condition and parameter only.

1.6 Organization of this thesis

This thesis is divided into five chapters. Chapter 1 is an introduction that covers the background study, problem statement, objectives and scope of this study. The literature review is presented in Chapter 2. The basic information related to the LPG, comparison of gas and liquid LPG injection and its effects on the performance and emission are reviewed. In Chapter 3, engine conversion process, experimental apparatus and experimental setup towards the completion of the study are presented. The results of the study are compiled, analyzed and discussed in detail in Chapter 4. Finally, Chapter 5 summarizes the conclusions and recommendations for future works.

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