THE EFFECT OF IGNITION TIMING ON ENGINE PERFORMANCE AND COMBUSTION BEHAVIOUR OF LPG-SI ENGINE USING LSI SYSTEM

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To my beloved parents, wife and friends
for their endless love, support and tolerance.

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ABSTRACT

Liquefied petroleum gas (LPG) is one of the potential alternative fuels for Spark Ignition (SI) due to its availability and acknowledged superior properties compared to the gasoline. However, implementing the latest generation of LPG on the SI engine, which uses liquid sequential injection (LSI) in the fuel delivery system, needs a detailed analysis of the engine characterization. A series of experiments were performed at various engine speeds from 1500 RPM to 3500 RPM with an increment of 500 RPM and the throttle position (TP) was set at 25%, 50% and 75%. The spark ignition angle was also tested from -5 SI °CA to -35 SI °CA Before Top Dead Centre (BTDC) with the increment of 5 SI °CA and runnings at stoichiometric condition. As a result, the LSI-LPG significantly improved the engine performance in the range between 0.3 % and 12.63% when the spark ignition angle was adjusted at the MBT locations. The Brake Specific Fuel Consumption (BSFC) also improved by about 4.5% to 13.6%. The CO and CO_2 from exhaust emissions reduced from 25% to 20%. Besides that, HC and NO_X was also reduced by 47% to 47.7 % compared to gasoline at MBT locations. The engine was simulated in actual driving conditions (90 km/h at 3000 RPM).The peak pressure indicated an improvement of 2.4% to 10% at all engine conditions, and the peak location was at 16.6°CA to 18.4°CA After Top Dead Centre (ATDC). The Coefficient of Variation (COV) was also lower than gasoline, ranging from 4.85% to 6.36%, which exhibited better combustion. In addition, the Rate of Pressure Rise (ROPR), Rate of Heat Released (ROHR) and Mass Fraction Burn (MFB) produced from LSI-LPG are better than gasoline when the spark ignition angle was adjusted at the correct location. Therefore, the use of LSI-LPG into the gasoline engine is able to improved engine performance without jeopardize the exhaust emission.

ABSTRAK

Gas petroleum cecair (LPG) adalah salah satu bahan bakar alternatif yang berpotensi digunakan pada enjin pencucuhan bunga api (SI) kerana kebolehdapatan dan sifat yang lebih baik bebanding petrol. Namun begitu, melaksanakan generasi terbaru LPG dengan menggunakan cara suntikan jujukan cecair (LSI) sebagai penghantaran bahan bakar mermerlukan analisis yang terperinci. Satu siri ekperimen dilakukan pada pelbagai kelajuan enjin dari 1500 RPM hingga 3500 RPM dengan kenaikan 500 RPM dan posisi pendikit (TP) ditetapkan pada 25%, 50% dan 75%. Sudut pencucuhan percikan api juga diuji dari -5 SI °CA to -35 SI °CA sebelum titik atas mati (BTDC) dengan kenaikan 5 SI °CA dan keadaan campuran minyak pada stoikiometrik. Keputusanya, LSI-LPG telah meningkatkan prestasi enjin pada 0.3% hingga 12.63% apabila sudut pencucuhan percikan di tala pada lokasi MBT. Pengunaan khusus bahan bakar (BSFC) juga bertambah baik pada kadar 4.5% hingga 13.6%. Pelepasan pencemaran ekzos CO dan CO_2 juga berkurangan dari 25% hingga 20%. Selain itu, HC dan NO_X juga menurun sebanyak 47% hingga 47.7% berbading petrol jika di tala pada keadaan MBT. Enjin tersebut telah di simulasikan dalam keadaan sebenar (90km/J pada 3000 RPM).Didapati tekanan pada puncak meningkat pada 2.4% hingga 10% pada semua keadaan enjin dan lokasi puncak pada 16.6°CA hingga 18.4°CA selepas titik atas mati (ATDC). Pekali variasi (COV) juga rendah dalam lingkungan 4.85% hingga 6.36% berbanding petrol, ini menunjukkan keadaan pembakaran yang baik. Selain itu, kadar kenaikan tekanan (ROPR), kadar pelepasan haba (ROHR) dan pecahan pembakaran jisim juga baik jika sudut pencucuhan ditala pada lokasi yang betul. Oleh itu, penggunaan LSI-LPG di dalam enjin petrol boleh memberikan peningkatan prestasi kuasa tanpa mengugat kadar pencemaran ekzos.

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LIST OF SYMBOLS AND ABBREVIATIONS

Acronyms

ATDC	After Top Dead Center
BTDC	Before Top Dead Center
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
CA	Crank Angle
CO_2	Carbon Dioxide
CO	Carbon Monoxide
C_3H_8	Propane
C_4H_{10}	Butane
CH_4	Methane
CI	Compression Ignition
CNG	Compressed Natural Gas
COV	Coefficient of Variations
DI	Direct Injection
ECU	Electronic Control Unit
EV	Electric Vehicle
HC	Hydrocarbon
IMEP	Indicated Mean Effective Pressure
LPG	Liquefied Petroleum Gas
LSI-LPG	Liquid Sequential Injection- Liquefied Petroleum Gas
MBT	Maximum Brake Torque
MFB	Mass Fraction Burnt
MMT	Million Metric Tons
MON	Motor octane number

MPI	Multi-port Fuel Injection
NO_X	Oxide of Nitrogen
PFI	Port Fuel Injection
RON	Research Octane Number
ROHR	Rate of Heat Release
ROPR	Rate of Pressure Rise
RPM	Rotation per Minute
SAC	Stand-Alone Controller
SD	Standard Deviation
SI	Spark Ignition
TBI	Throttle Body Injection
TC	Top Center
TP	Throttle Position
VE	Volumetric Efficiency

Symbols

a	Weibe Efficiency Factor
Γ	Specific Heat Ratio, C_p/C_v
d_p	Pressure different between two point
d_θ	Crank angle degree different
θ_d	Combustion Duration
θ_s	Spark Timing
λ	Air/fuel ratio
N	Weibe Form Factor
π	Pi = 3.142
P_{max}	Peak Presure
P_θ	Peak pressure Location
°	Degree
%	Percentage

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CHAPTER 1

INTRODUCTION

1.1 Background of study

In Malaysia, the number of registered road vehicles increases by 5% to 10% annually (Road Trasport Department of Malaysia, 2021). This is because the price of vehicles is lower compared to 10 years ago and people in Malaysia can afford it. This indicates that the economy in this country is improving and Malaysian are positively responding to the automotive industry. The increase in the number of registered road vehicles in Malaysia, especially in the urban area, has led to environmental issues. According to the Road Trasport Department of Malaysia, (2021), the number of motorcycles, motorcars, buses, taxis, rental vehicles, and goods vehicles and others increases about 10.86 million, 11.25 million, 0.052 million, 0.08 million, 0.02 million, 1 million and 0.48 million, respectively every year as shown in Figure 1.1. The motorcycle trend indicated a sharp growth from 0.467 million in 2016 to 13.532 million in 2018. Similar trend can be seen for motorcars which recorded an increase from 0.580 million in 2016 to 14.063 million in 2018. This trend can also be seen for vehiles such as goods vehicles, taxis, buses and rental vehicles.

The increment in numbers of vehicle will also affecting increasing the CO_2 emission, especially the emission produced by the transportation sector, is a critical problem because it affects the greenhouse gas, leading to global warming. In reducing the CO_2 emission in Malaysia, alternative fuels such as LPG in the latest generation would be introduced. The choice of LPG as the alternative fuels due to the source is readily available, lower price, more power, less pollutant emitted and the consumption still lower than the others conventional fuel in the market.

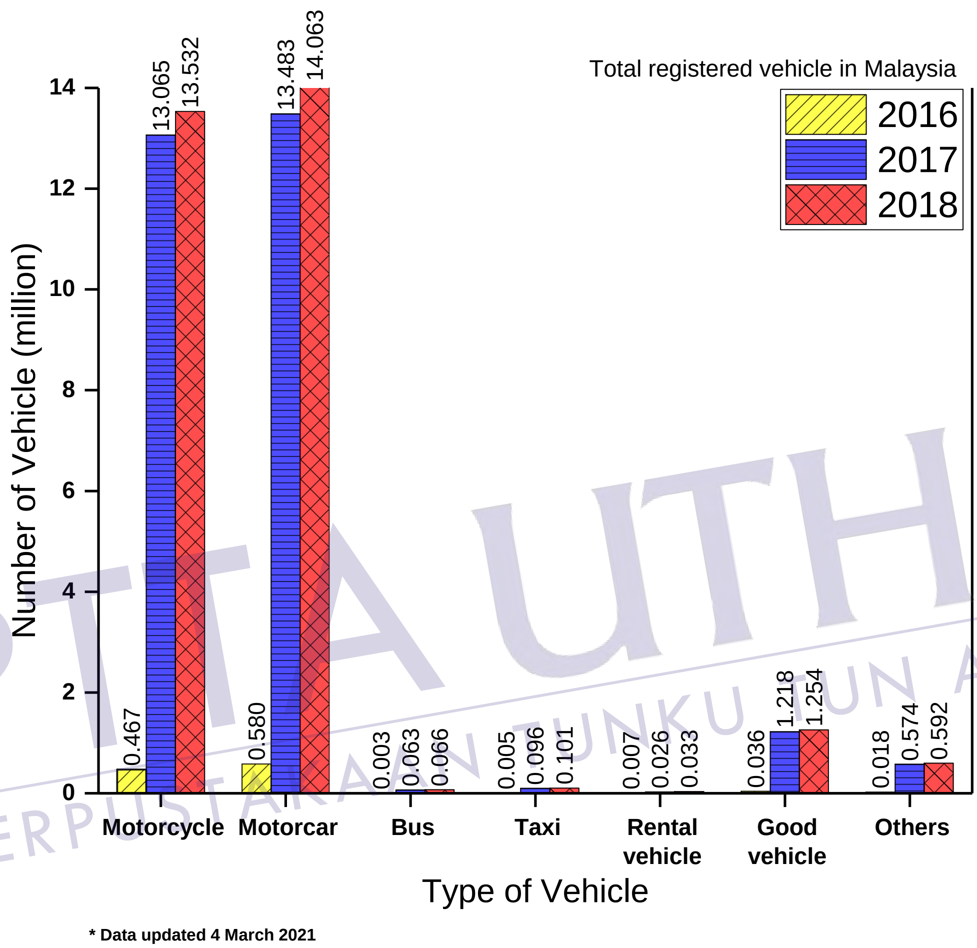

Figure 1.1: Total number of the registered vehicles in Malaysia from 2016 to 2018 (Reproduced from Road Trasport Department of Malaysia, 2021)

1.1.1 Consumption of petroleum products in Malaysia

Figure 1.2 shows the consumption volume of petroleum products in Malaysia which includes conventional fuels such as gasoline and diesel from 2014 to 2019. The consumption trend for both fuels increased from 10.161 mtoe to 10.583 mtoe for diesel and from 12.705 mtoe to 13.811 mtoe for gasoline. This contradicted the trend for LPG that showed lower consumption from 2.632 mtoe to 3.017 mtoe. To ensure the consumption of petroleum products is balanced and in stable condition, alternative fuel technology needs to be introduced in this country. The optional alternative fuel such as LPG, compressed natural gas (CNG), biofuel, hydrogen, methanol and ethanol need to be highlighted to vehicle consumers to raise awareness of how crucial alternative fuel is. Consequently, petroleum product consumption is more stable and offers an additional benefit to the consumers in the future.

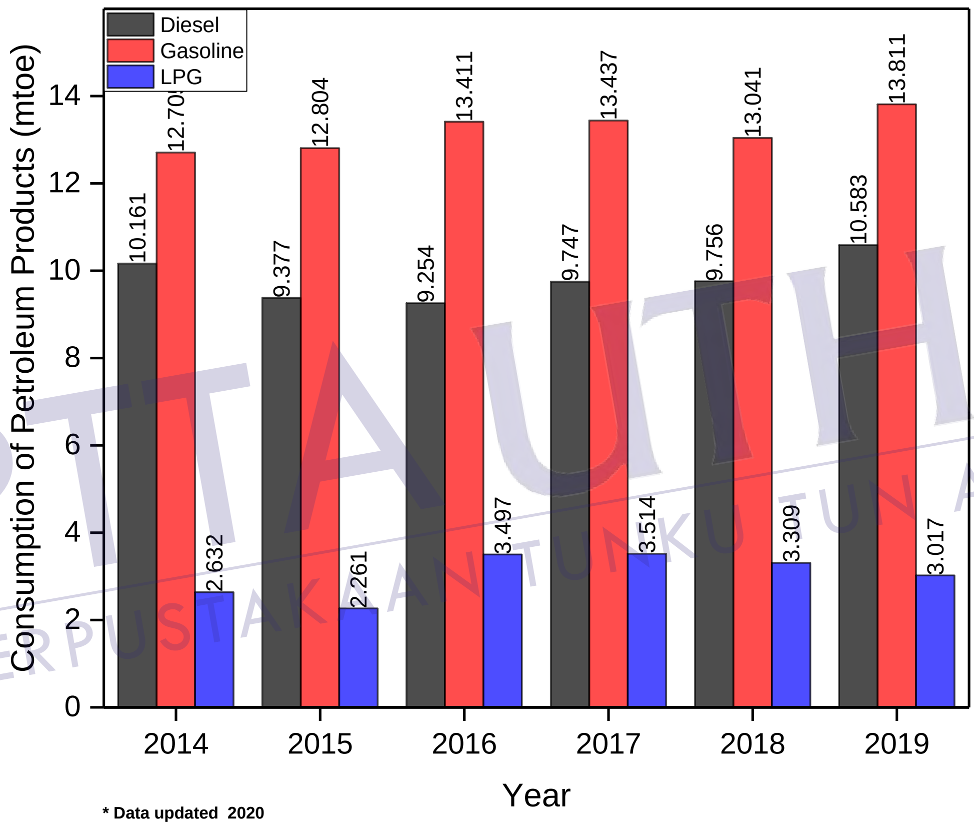

Figure 1.2 : The consumption volume of petroleum product from 2014 to 2019 in Malaysia (reproduced from Malaysia Energy Information Hub, 2020)

1.1.2 Instability of fuel price

Generally, the increasing consumption of petroleum products as discussed earlier has fluctuated the price of fuel supply and created economic turmoil, mainly in the transportation sector. The price of petroleum products such as gasoline and diesel is dependent on the demand and consumption of consumers worldwide. Figure 1.3 shows the comparison of fuel prices of countries with well-developed LPG in the transportation sector over the last two decades and have the largest market worldwide (Autogas Incentive Policies, 2020). Based on the data, Italy has the highest price of gasoline, followed by Korea and lastly Russia, with USD 1.88 per liter, USD 1.38 per liter and USD 0.66 per liter, respectively. In terms of the price of LPG, Malaysia has 3rd lowest price after Thailand and Russia and with USD 0.44 per liter, USD 0.39 per liter and USD 0.38 per liter, respectively. The price of LPG in Malaysia and other countries as shown in Figure 1.4 does not include the subsidy due to is invalid for industrial and commercial purposes. Nevertheless, the price of LPG in Malaysia without subsidy is still lower than the price of gasoline. It highlights the potential of LPG as an alternative fuel in the automotive industry, especially in Malaysia.

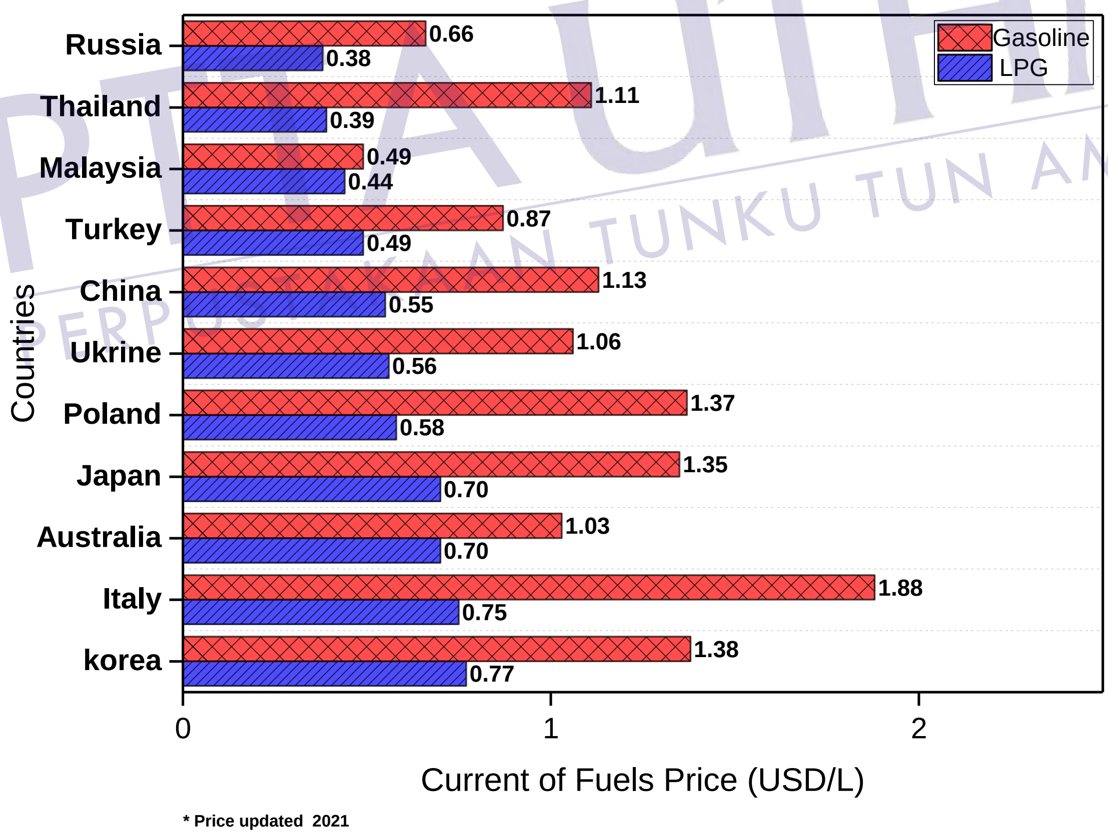

Figure 1.3: Comparison between LPG and gasoline prices among largest LPG consumer countries (reproduced from GlobalPetrolPrice.com, 2021)

In the case of the largest market country of LPG users, the government was provided incentive policies that could choose the alternative fuel such as LPG in the county. Another alternative is the automotive-fuel technology such as the electric vehicle (EVs), which is widely available commercially. However, the cost is high and millage is limited compared to alternative fuel. An alternative fuel offers practical price for consumers and benefits the environment. From an energy-security perspective, LPG has an advantage over conventional fuel due to an abundant supply from many sources in the world. According to Autogas Incentive Policies, (2020), the crude oil and gas field reserves give the flexibility of the modern refining process and offer the considerable potential to improve the meet demand for the transportation sector. Thus, LPG supply is expected to rise briskly in the next few years, parallel with the natural gas production and associated liquid extraction, which are the primary sources in the LPG worldwide.

1.2 Problem statement

LPG is commonly used in the cooking industries as the sources are readily available and the price is lower than other gaseous. Accordingly to the Malaysia Standard MS 775:2005, the use of LPG fuel delivery system in the internal combustion engine was established in 2005 and it is expected that the Malaysian government will be introducing LPG as an alternative fuel in the future, parallel with the Malaysia Automotive Roadmap, (2014) and Update on Malaysia Automotive Background of NAP 2020 (MARii, 2020). Since Asian countries such as Korea, China, Japan, and Thailand start using LPG as an alternative fuel, the price of conventional fuel has increased. With the high demand for fuel but limited sources, the price of gasoline and diesel has the potential to increase in the future. As technology matured, the LPG system was using Liquid Sequential Injection (LSI) that promising better engine performance and exhaust emission fundamentally.

However, in reality several issue emerged such as engine under power, unstable cycle and highly emission production are being highlighted when LSI-LPG introduced in the SI engine. Deep dive analysis to overcome the limitation could be potentially bring the gap in this research, where the effects of adjust spark ignition timing in the LSI-LPG system in influencing the quality engine output and exhaust emission. Next, the relationship of effect combustion stability limit which respect to the peak pressure in each cycle. Lastly, to finding the suitable of combustion characteristics location for each MBT location for LSI-LPG system to enhancing the engine performance and exhaust emission in the SI engine.

1.3 Objectives

The objectives of this study are:

a. To investigate the range of variable spark ignition timing for producing the MBT condition when operated with LSI-LPG latest generation.
b. To determine the quality of engine performance and exhaust emission behaviors at various spark ignition timing angles in the SI engine using the LSI-LPG system.
c. To characterize the limit of combustion stability in the LSI-LPG system in the SI engine at variable spark ignition timing angle using the tabulation of peak pressure in-cylinder analysis.
d. To evaluate the combustion characteristics of the LSI-LPG system at various spark ignition timing angles that focus on the in-cylinder pressure, rate of pressure rise (ROPR), rate of heat release (ROHR) and mass of fraction burnt (MFB) at maximum brake torque (MBT) locations.

1.4 Scope of study

The scopes of study in this research are:

a. The composition of LPG used in this research is 60% butane and 40% propane, according to the Materials Safety Data Sheet (MSDS, 2015) of LPG in Malaysia.
b. The experiment used unleaded gasoline (RON95) and LPG liquid phase, namely the LSI-LPG system. Which, to compare the performance, exhaust emission, combustion stability and combustion characteristics.

c. The research used 1.6L engine capacity which was equipped with the latest generation of multi-port fuel injection (MPI) with a retrofitted LSI-LPG fuel system.

d. The variables of spark ignition angle were set from -5 °CA to -35°CA BTDC to identify the maximum brake torque (MBT) for both fuels.

e. The analysis of the engine involved:

   i. Engine performance
      - Brake power (BP)
      - Maximum brake torque (MBT)
      - Brake specific fuel consumption (BSFC)

   ii. Exhaust emission
      - Carbon monoxide (CO)
      - Carbon dioxide (CO_2)
      - Hydrocarbon (HC)
      - Oxides of nitrogen (NO_X)

   iii. Combustion stability was set up at the engine speed of 3000 RPM and accelerated in the range of between 90 km/h and 100 km/h via engine dynamometer, which simulated the real driving condition on the road.
      - Peak pressure (P_{max})
      - Peak pressure location (P_θ)
      - Standard deviations (SD)
      - COV of peak pressure ($COV_{Peak\ pressure}$)

   iv. The condition engine set up for combustion characteristic was the same with combustion stability.
      - In-cylinder pressure
      - Rate of pressure rise (ROPR)
      - Rate of heat release (ROHR)
      - Mass fraction burnt (MFB)

f. The experimental work was conducted via chassis dynamometer with steady-state conditions and the engine was set at:
    i. various engine speeds: 1500 RPM (low engine speed), 2000 RPM to 2500 RPM (medium engine speed) and 3000 RPM to 3500 RPM (high engine speed)
    ii. three different throttle positions: 25%, 50% and 75%.

g. All the tested parameters were compared with gasoline as the data baseline.

1.5 Significance of study

The outcome of this study provided a comprehensive experimental analysis of the latest generation of LPG, namely liquid sequential injection (LSI) LPG system which produced a higher engine output and improved the exhaust emission in the SI engine. This was done by controlling the spark ignition timing angle with stoichiometric air/fuel access. The analysis of the effects of adjusted spark ignition angle to enhance the LSI-LPG latest generation system focused on the engine performance, exhaust emission, combustion stability and combustion characteristic. This study is highly required in establishing the reference for LPG as an alternative fuel, especially in the Malaysia transportation sector, which is parallel with Malaysia Standard, MS775:2005.

The analysis revealed that the engine output and exhaust emission were improved when the proper adjustment for the LSI-LPG system in the SI engine. It started by identifying the optimum spark ignition timing angle in various engine conditions until the maximum brake torque (MBT) was produced . An early or late spark ignition angle was affected by the result of engine output in lower torque. The analysis was extended to the combustion process,including combustion stability and combustion characteristic.

This study provides the latest database of LSI-LPG, which will become the benchmark for future research, especially for Malaysian context as available references about alternative fuels are limited to certain engine conditions and parameters. The analysis was conducted using the Malaysia commercial available engine, which is often used in the taxi. Therefore, the LSI-LPG system is also applicable for public transports, which can help to reduce exhaust emission and pollution. The outcome of the study will open the public's eyes about the alternative fuel in the SI engine that gives a range of optimum setting of spark ignition timing when using this system. This use of the alternative fuel improves the engine output, fuel consumption and exhaust emission.

1.6 Organization of this thesis

This thesis consists of five chapters covering the details about the experiments on the characteristics of the LSI-LPG fuel delivery system with various spark ignition timing angles to improve engine performance and exhaust emission. The first chapter started with the research background, problem statement, objectives of the study, scope of the study and significance of the study, and the organization of the thesis.

The next chapter discussed the internal combustion process and the LPG generation system from previous studies. This chapter also reviewed the effects of spark ignition timing angle adjustments for previous LPG generations. Sources of the engine performance, exhaust emission, combustion stability and combustion characteristic were also presented.

In chapter 3 the research methodology was described in detail. This chapter discussed the standard operation of the instruments such as the set up of the dynamometer, engine tuning, formula used in the experiments and modification for retrofitted LSI-LPG in the SI engine.

Chapter 4 discussed the results of the experiments. The optimum spark ignition timing angle analysis to achieve the maximum brake torque (MBT) was discussed in detail. In addition, this chapter also discussed the finding of engine performance, exhaust emission, combustion stability and combustion characteristics.

Finally, chapter 5 concluded the study based on the objectives and the results of the study. In addition, the contribution of the research and recommendations for future direction work were also drawn in the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the review of previous studies related to the evolution of the LPG system and the spark ignition angle to produce maximum brake torque (MBT) in the spark ignition (SI) engine. The spark ignition angle variations give the operating engine output to maximize the work produced during a cycle. The ignition timing is essential for driveability and exhaust emission reduction. The review starts with the concept of retrofitting spark ignition (SI) and the automotive trends which are required to make this project successful.

2.2 Spark ignition (SI) engine

The internal combustion engine (ICE) has been widely used in the automotive industry for over a century. Basically, the ICE is divided into two types of ignition: SI and compression ignition (CI) engine. The SI engine needs the spark plug as an igniter to start the combustion, while in the CI engine, for the start of the combustion process, high compression and temperature are required for the air mixture to be self-ignited (Heywood, 1988; Pulkrabek, 2004).

The SI engine uses air/fuel mixer to generate the power output and exhaust emission. A full combustion cycle requires two revolutions of the crankshaft to complete the process, corresponding to the four-stroke of a cylinder piston. The four-stroke SI engine is operated based on a typical sequence: intake stroke, compression stroke, expansion stroke, and exhaust stroke are illustrated in Figure 2.1. The angle between the crankshaft and the cylinder's axis refer to the crank angle degree (CAD). The stroke process has a negatively valued angle during intake and compression stroke, while a positive value during the expansion and exhaust stroke. This process is divided into two conditions: when the position of the piston is at the top, it is called the top dead centre (TDC) and when position of the piston is at the bottom, it is called the bottom dead centre (BDC).

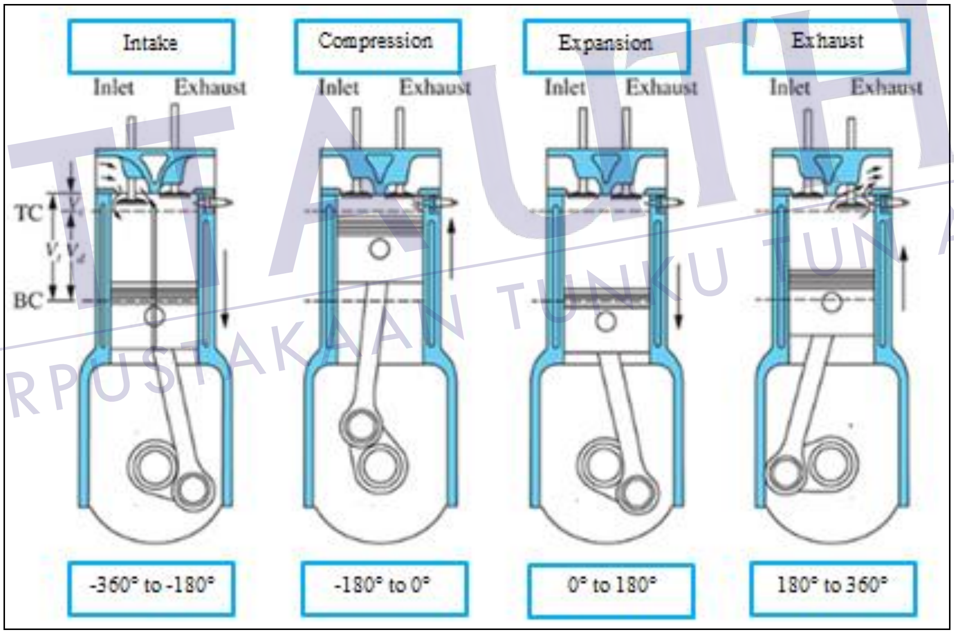

Figure 2.1: The four-stroke operating cycle in the combustion process

On the intake stroke, the piston travels from TDC to BDC. During this process, the air/fuel mixture is drawn into the cylinder through the inlet valve due to pressure reduction and then the valve exhaust is closed. The movement of the piston produced a differential pressure and created a vacuum effect.

On the compression stroke, the piston moves upwards to TDC and the pressure of the air/fuel mixture contained in the cylinder steadily increases. When the piston almost reaches the TDC position, the spark plug ignites the mixture and the combustion starts.

The combustion continues to the expansion stroke, where the chemical energy in the fuel is now being converted into power output, heat and emission. The pressure increases due to the expanding burning mixture in the cylinder, driving the piston to move downwards until BDC. As a result, the forces from the expansion stroke were transferred to the crankshaft rotation and supplies the work into the flywheel.

The last process is the exhaust stroke. In this process, the piston moves from BDC to TDC, and sweeps all the burn and unburn gas into the exhaust valve. During this process, the intake valve is closed. The process of the four-stroke cycle ends when the piston reaches TDC condition and the cycle is repeated.

According to Heywood, (1988), the SI engine is classified into four services group for the class of road vehicle, as depicted in Table 2.1. The classification is based on the maximum engine power, which are 70kW, 75kW, 200kW and 150kW.

Table 2.1: Classification of road vehicle categories according to service (Heywood, 1988; Mustaffa, 2019)

Class	**Service**	**Approximate engine power range (kW)**
Road vehicle	Motorcycle/Scooter	0.75 -70
	Small passenger car	15-75
	Large passenger car	75-200
	Light commercial	35-150

2.2.1 Type of fuel delivery system on SI engine

The fuel delivery system in the SI engine is an important technique that supplies fuel into the intake manifold. The air and fuel will be mixed before entering the combustion chamber. The process of entering the combustion chamber depends on the specific engine speed and throttle position (TP). In addition, the premixed fuel also depends on the type of the fuel delivery system technique in the SI engine. There are four types of fuel delivery technique, which is carburetor, throttle body injection (TBI), Multi-port fuel injection (MPI) and direct injection (DI) (Heywood, 1988; Phuong, 2006; Sendyka & Noga, 2013). The history of the timeline for fuel delivery system technique is shown in Figure 2.2.

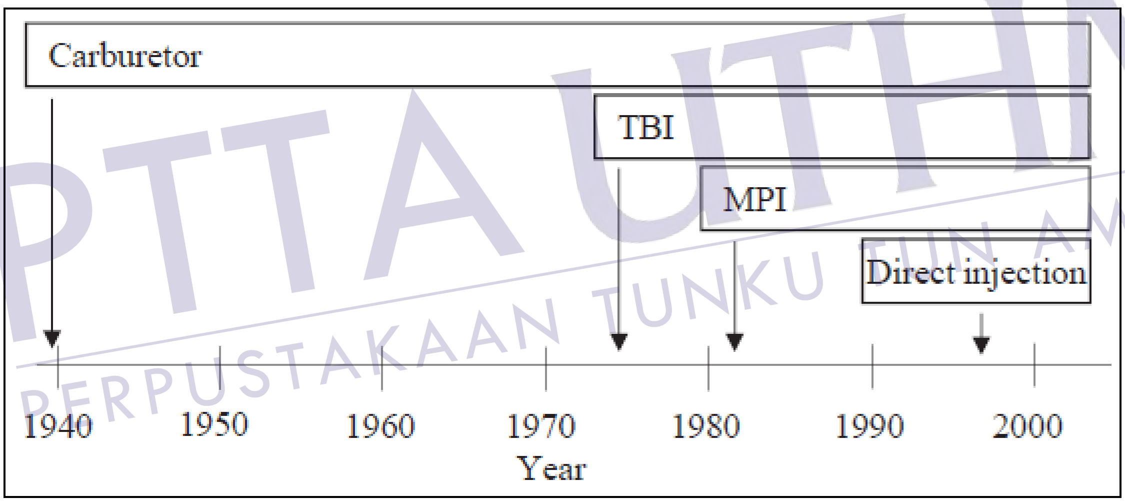

Figure 2.2: The history of fuel delivery system technique (Mustaffa, 2019)

The oldest fuel delivery system is a carburetor which uses the Bernoulli principle. The concept uses a pressure difference from airflow and fuel supplied from higher pressure to lower pressure location created at the venture throat. The fuel is atomized by the air stream and mixed during travel from the intake manifold before entering the combustion chamber. In the carburetor system, the air/fuel ratio is not effectively controlled in different engine conditions because the system uses an open-loop system; that is, no feedback signal is transmitted to trigger the output of the combustion from the exhaust (Heywood, 1988; Sendyka & Noga, 2013). Figure 2.3 shows the fuel delivery system diagram for carburetor in the SI engine.

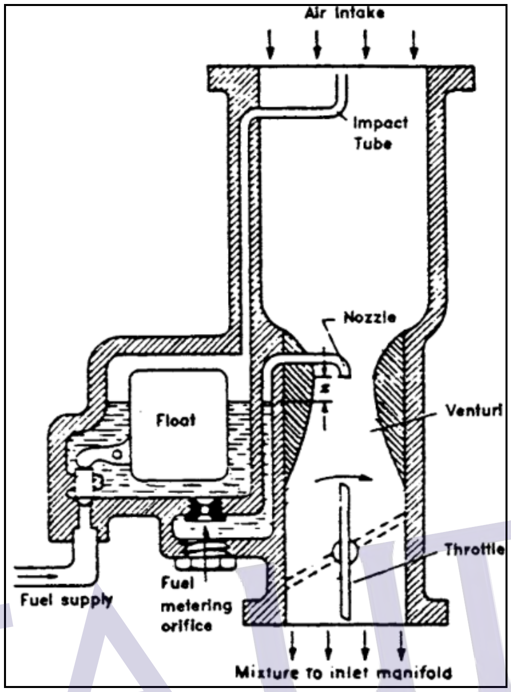

Figure 2.3: The diagram of fuel delivery system for carburetor (Arnold, 1999)

TBI system consists of one or two fuel injectors mounted on the throttle upstream, as shown in Figure 2.4 (i). The single-port injection will supply the fuel for all engine cylinders at one time. The air/fuel has been mixed during travel from the intake manifold to the intake valve like a carburetor. However, the injector from the TBI system is capable of controlling the demand for fuel according to the engine condition. The data from the oxygen sensor located in the exhaust manifold will be processed by the electronical unit and the fuel delivery system is more precise and the air/fuel ratio is accurate, making the engine performance better than carburetor system. The TBI system has weaknesses due to the unequal division in terms of the route of air/fuel traveling into the intake manifold for each cylinder (Sendyka & Noga, 2013).

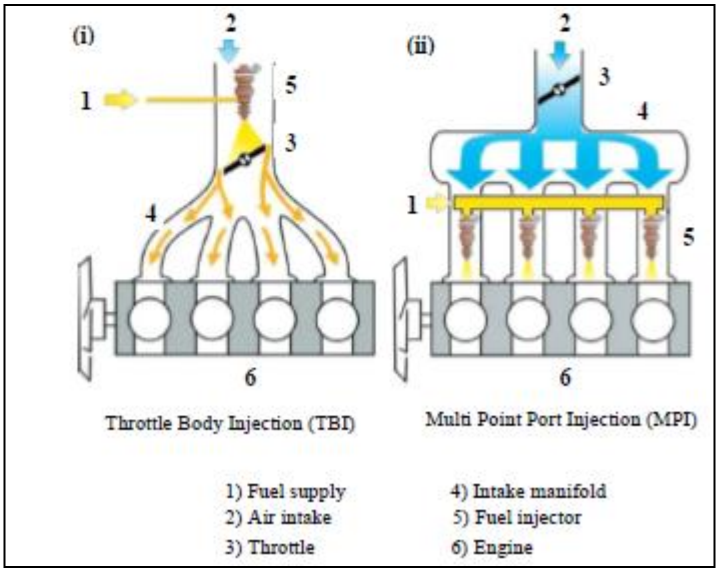

Figure 2.4: The methods of fuel delivery system for TBI and MPI (Sendyka & Noga, 2013)

The MPI fuel delivery system is better than the TBI system. The individual injector is located at the intake port downstream for each cylinder, as shown in Figure 2.4 (ii). The unequal division for air/fuel traveling into the intake valve is eliminated in this system. Other than that, the distance of injectors is reduced, so the air/fuel mixture has extra cooling effect and the wall wetting problem that frequently happens in the TBI system is also resolved. The operation of the MPI system is controlled by the electronic control unit (ECU) as corresponding to the cylinder firing sequence.

The latest technology for the SI engine is the DI fuel delivery system, as shown in Figure 2.5. In this fuel delivery system, the fuel injector is mounted with individual conditions in the head cylinder. The fuel injector directly injects the fuel into the combustion chamber and the air and fuel are mixed during compression stroke condition in the cylinder. The air/fuel mixture is easy to mix and the higher piston profile is given the advantage of producing a turbulent effect in combustion chamber. As a result, the DI system can produce a higher engine output with lesser gas emission than the MPI fuel delivery system (Mustaffa, 2019; Sendyka & Noga, 2013; Heywood, 1988).

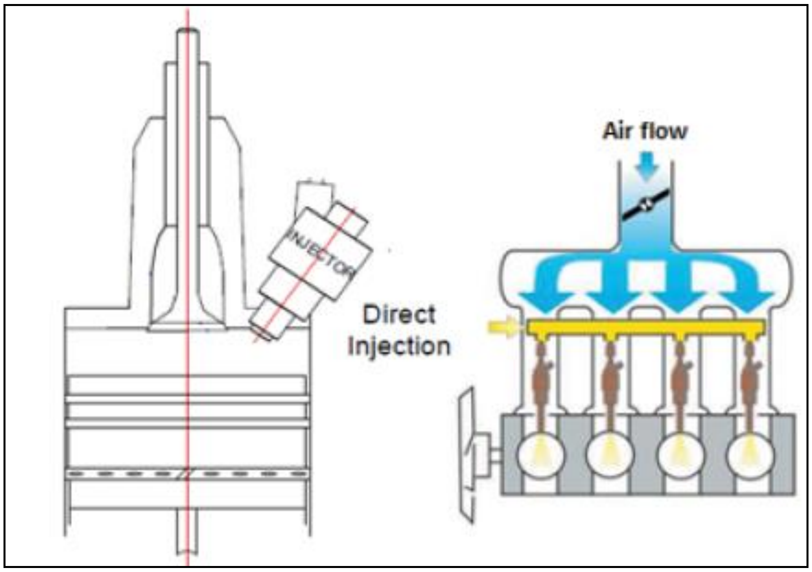

Figure 2.5: Diagram for DI fuel delivery system in SI engine (Sendyka & Noga, 2013)

2.3 Exhaust emission pollution

The automotive industry and transportation have grown tremendously every year, the worldwide. The SI and diesel engine contribute to air pollution in urban areas, resulting from the exhaust emissions which include CO, CO_2, HC and NO_X. The exhaust emission contributes to global warming and health problems (Costa *et al.*,2012; Pulkrabek, 2004).

2.3.1 Carbon Monoxide (CO)

Carbon monoxide is a byproduct of incomplete combustion when fuel is burned during the combustion process. The production rate of CO in exhaust emission during combustion is dependent on the air/fuel mixture value. In a rich mixture of air/fuel ratio, the oxygen is insufficient to react with the entire carbon atom and the combustion is not fully oxidize. The increase in CO exhaust emission is also related to a leaky injector, high fuel pressure and improper close loop control in the ECU system (Toyota, 2012; Pulkrabek, 2004).

2.3.2 Carbon Dioxide (CO_2)

Generally, carbon dioxide consists of greenhouse gas (GHG) and the increase in the gas leads to global warming. Hydrocarbon (HC) in fuel content usually reacts with oxygen and produces water vapor (H_2O) and CO_2 during the combustion process. According to Gumus (2011), the use of fuel in lower carbon content per unit energy gives the potential to reduce CO_2 emission. The increase of CO_2 gas emission is a critical issue worldwide. This is due to the GHG indicates higher thermal radiation to humans. Thus, introducing alternative fuel with lower carbon content such as LPG can solve this problem.

2.3.3 Hydrocarbon (HC)

Hydrocarbon (HC) emission refers to raw unburned fuel and indicates incomplete combustion in the engine. This problem occurred because of the lower air intake temperature which contributes to the poor mixing of air/fuel during combustion. As a result, partial misfire occurs and the HC emission increases. The other reason is a delay in ignition timing and the air/fuel mixer is under the rich condition. To avoid this problem, the mixture needs to set in the right condition according to the engine load and requirement of fuel. Another method is by using an alternative fuel apart from gasoline (Toyota, 2012).

2.3.4 Oxides of Nitrogen (NO_X)

According to Pulkrabek, (2004), nitrogen oxides (NO_X) is produced at high temperature and pressure during the combustion process. In this process, nitrogen reacts with oxygen to form NO_X and produces exhaust emissions. Factors that lead to the increment of NO_X are faulty exhaust gas recirculation (EGR) system operation, incorrect spark or injection timing, and fuel properties. Increasing emission of NO_X is a hazard to the ecosystem and affecting the ozone. In addition, NO_X also affects the respiratory system and irritation of eyes, noses and throats (Osman, 2014; Pulkrabek, 2004; Heywood, 1988).

2.4 Influence of alternatives fuel in the engine system

According to Mustaffa, (2019), introduce the alternative fuel in internal combustion engine for both SI and CI engine are allowed several factors of benefit. This factor is:

i. To follow the stringent exhaust emission regulation and improve the engine output in term of performance through the related with chemical properties of the alternative fuel
ii. To counterbalance the usage of petroleum base
iii. To diversify uses of conventional fuel and protect the sustainability
iv. To guarantee the usage of conventional fuel is enough for the future

Several alternative fuels, such as LPG, ethanol, methanol, natural gas, and biogas, had received a lot of attention due to their promising capability to produce a similar or improved engine performance and exhaust emission. Therefore, the focus of this study was on optimizing the performance, exhaust emission, combustion stability and combustion characteristic with fine-tune the maximum brake torque (MBT). In this research, LPG was selected as an alternative fuel for the SI engine.

2.5 Introduce Liquefied petroleum gas (LPG) as an alternative fuel

LPG is commonly used in the cooking industry because it is a clean fuel. Meanwhile, in the automotive industry, LPG is called “Autogas” which primarily consists of a mixture of propane (C_3H_8) and butane (C_4H_{10}). At present, the usage of LPG in the internal combustion engine as an alternative fuel is expanding in the world. According to AIP (2017)and Masi (2012), the use of LPG in the internal engine has been used mainly in countries such as Italy, Turkey, Russia, Thailand and Korea due to its abundance and low cost compared to conventional fuel. Besides that, the use of LPG as an alternative fuel is unlimited and is also used in electricity generation.. However, the output in terms of performance and exhaust emission from the engine is still unsatisfactory and a primary concern..

2.5.1 LPG composition

There is no specific standard value for the percentage of mixture composition of propane and butane in LPG. According to Masi, (2012); Campbell *et al.*, (2004) the mixture composition depends on the country's season, refining process, properties of the supply crude oil, and refined product cost. In addition, to ensure proper vaporization process, propane will be added more to the composition of LPG especially during the winter season in a four-season country.

Table 2.2: Comparison of LPG mixture composition by country (Mustaffa, 2019; MSDS, 2015;Gas Malaysia, 2011; Mustafa & Gitano-Briggs, 2009; Saleh, 2008)

Country	**Propane (%)**	**Butane (%)**
Malaysia	40	60
Austria	50	50
Australia	70	30
Belgium	50	50
France	35	65
German	90	10
Italy	25	75
United Kingdom	100	0
Netherland	50	50

Generally, about 60% production of LPG is from the processing of conventional natural gas and the rest is from the refining of gasoline (Mustaffa, 2019). Table 2.2 shows the several mixtures of LPG composition in European countries and Malaysia. In Malaysia, the LPG mixture composition is 60% propane and 40% butane (detailed specification in Appendix A) and France has a nearly identical LPG mixture composition (Gas Malaysia, 2011). Although the mixture of LPG composition is different for every country, the engine output is still in the range and comparable with conventional fuel used in SI or CI engine.

2.5.2 LPG properties

LPG, known as a clean gas, is colorless, odorless and used in the cooking industry. The advantage of LPG is that it has no corrosive activity and does not contain aromatic hydrocarbon. However, to ensure the gas is safe to use, the ethyl mercaptan is added to the LPG. This helps to detect leakage through the smell of pungent odor. Since the composition of LPG varies according to country, the summarized properties between LPG and gasoline fuel is presented in Table 2.3.

Based on the chemical properties data for LPG, carbon and hydrogen are lower than gasoline fuel, making LPG capable of reducing the exhaust emission. In terms of the boiling point, LPG will be changed into gaseous form when placed in a room temperature, meanwhile, gasoline fuel will still be in a liquid form. This indicates that the LPG has a lower boiling point than gasoline. For the comparison of density, the LPG has 20% lower density than gasoline at 15°C. According to Boretti & Watson, (2009), the lower density from LPG reduces volumetric efficiency compared to gasoline during the combustion process. However, the density of LPG is sensitive to the change of the surrounding temperature and composition of both gas butane and propane. Figure 2.6 shows the increment of butane composition percentage which is capable of increasing the density.

Table 2.3: Comparison of properties between LPG and gasoline (Mustaffa, (2019); Suyabodha,(2017); Nayak *et al.*, (2016); Chitragar.,(2016); Erkuş *et al.*, (2015)

Fuel Properties	**LPG**	**Gasoline**
Chemical formula	Butane C_4H_{10} and propane C_3H_8	C_8H_{18}
Boiling point	-44.5*	225
Density at 15 °C (kg/l)	0.57	0.75
Odor additive	Ethyl Mercaptan	Hydrocarbon
Research octane number (RON)	96.5-105	89-90
Motor octane number (MON)	90-97	80-90
Vapor pressure (kPa)	803	700
Lower calorific value (kJ/kg)	45600-46500	42100-44000
Specific gravity at 4-15 °C	0.5647*	0.7034
Flammability limit (in air) (vol%)	2.15-9.6	1.4-7.6
Flash point (°C)	-104*	-40
Autoignition temperature (°C)	405-540	250-290
Flame speed (cm/s)	37-38.2	37.5
Latent heat vaporization (kJ/kg)	14.52	9.94
Carbon, % composition	82	85-88
Hydrogen, % composition	18	12-15
Sulphur (mg/kg)	37.053	5.088
Relative molecular mass (kg/Kmol)	104	114.2
Stoichiometric air-fuel ratio (kg/kg)	15.5-15.8	14.7-14.9

***Similar with Malaysia LPG (refer to Appendix A and B)**

In comparing the research octane number (RON), the LPG produces about 96.5 to 105 and gasoline produces about 89 to 98. This fact indicates that the LPG has a higher RON compared to gasoline. This is why LPG is capable of running on higher compression ratio engines, which would give better thermal efficiency during the combustion process. In addition, it also prevents the engine from the knocking phenomena (Krishnaiah.,2016).

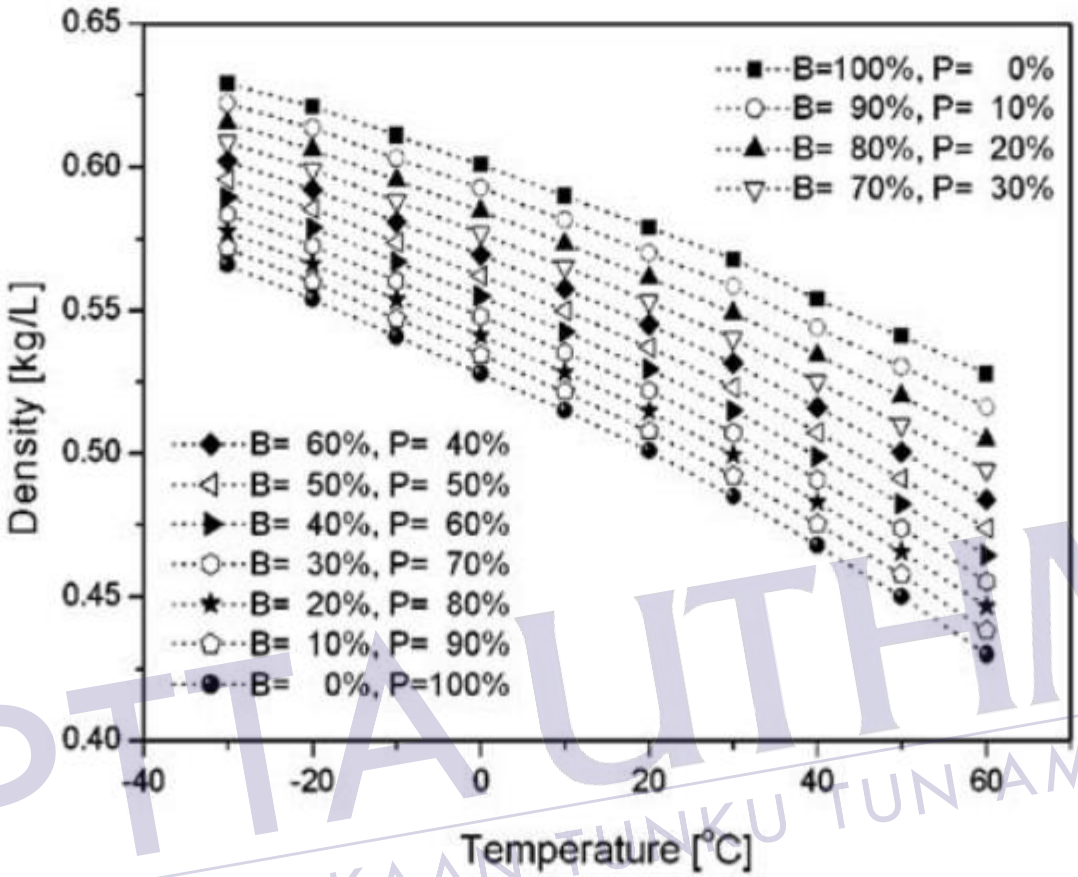

Figure 2.6: Effects of the percentage of composition on LPG density (Sim *et al.*, 2005)

In terms of evaporation pressure, the LPG produces higher than gasoline which is about 803kPa and the gasoline is about 700kPa. The higher vapor pressure can enhance the air/fuel mixing process and reduce the condition of the local rich mixture region during the combustion process. As a result, the production output of the NO_X emission from LPG would be reduced compared with gasoline (Kim *et al*., 2013; Park *et al.*, 2013). According to the study by Sim *et al.*, 2005, the vapor pressure is directly proportional to temperature as shown in Figure 2.7 and the percentage of propane/butane composition also affects the evaporation pressure process at the higher temperature.

LPG is still higher for the calorific value than gasoline. This situation gives the advantage to improve the engine output and extend the engine life cycle. Based on previous studies by Chitragar *et al.*, (2016); Saraf, (2014); Li *et al.*, (2002), the exhaust gas temperature of LPG is higher compared to gasoline fuel. Meanwhile, for mileage per charge, LPG has recorded a lower reading than gasoline due to its lowe energy density per unit volume. Besides that, gasoline has higher specific gravity than LPG (Boretti & Watson, 2009).

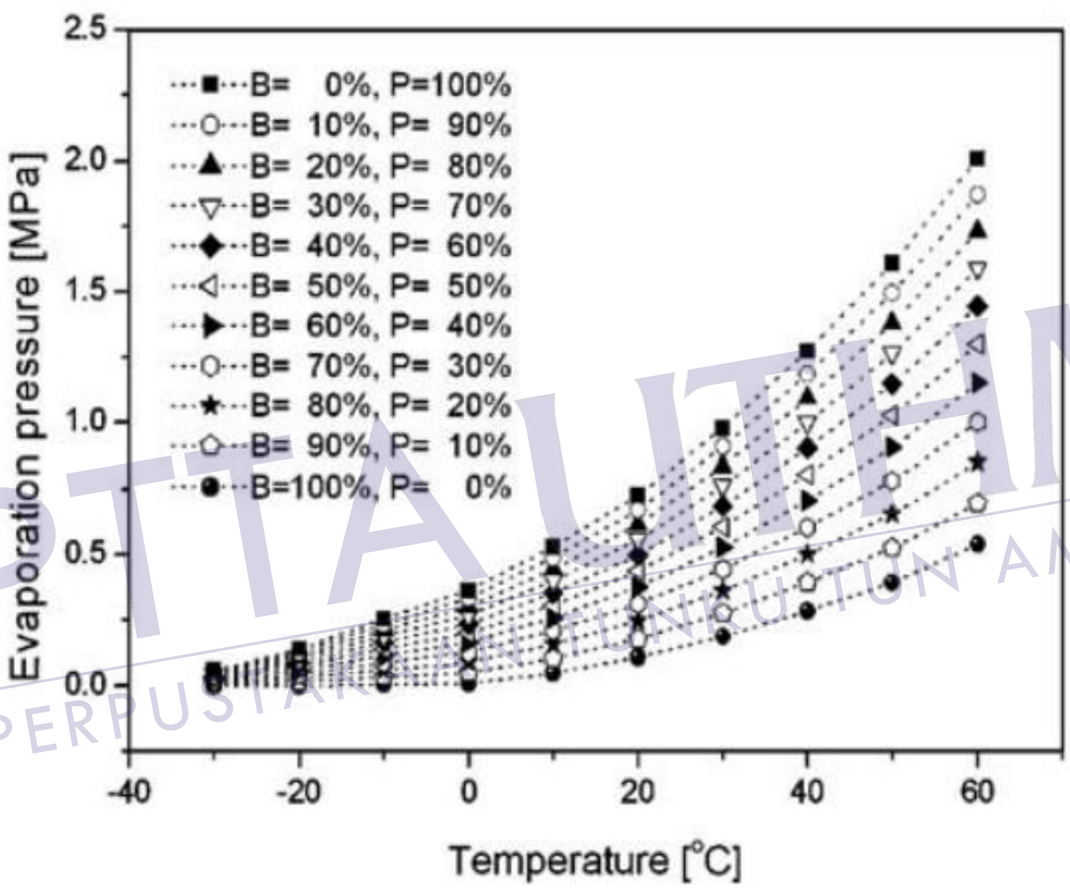

Figure 2.7: Effects of temperature on evaporation pressure of LPG (Sim *et al.*, 2005)

The flammability limit is a percentage of fuel burned in the air. In terms of combustion definition, the mixer capability to propagate the flame in condition too lean or too rich. In this condition, LPG has a wider range of flammability limit than gasoline. The extra safety precautions are necessary to avoid any accident.

In comparing the flashpoint, the LPG has a lower flashpoint compared to gasoline. This means that the LPG is easier to ignite and reduce the delay during the flame development process. For the autoignition temperature, LPG has higher autoignition than gasoline, ranging from 405 °C to 540 °C. This shows the LPG in the combustion chamber is difficult to combust and avoid the knocking process. The flame speed is related to the percentage of composition of LPG. In this case, the flame speed ranges from 37 to 38.cm/s for LPG, while gasoline is 37cm/s. The flame speed is essential for the burning rate and the total combustion duration as it occurred at the correct location. If the flame speed is lower, the ignition timing needs to be advanced to produce complete combustion which has similar or better engine output than gasoline. As a result, the engine produces a higher output and reduces the emission (Krishnaiah *et al.*, 2016; Homdoung *et al.*, 2014).

All the properties are essential to determine the suitability of the engine characteristics for the LPG retrofitting process in the SI engine. These properties will give effects that would either improve the engine output or otherwise. However, it also depends on the engine setting and its characteristics as there are many significant parameter effects during the combustion process.

2.5.3 Advantages and disadvantages of LPG as an alternative fuel

The use of LPG as an alternative fuel in the internal combustion engine has been documented and recommended by many researchers because it is comparable with conventional fuel (gasoline and diesel). Previous studies summarized several advantages and disadvantages of using LPG (Mustaffa, 2019; Çinar *et al.*, 2016; Flekiewicz & Kubica, 2016; Erkuş *et al.*, 2015; Ambaliya, 2014; Homdoung *et al.*, 2014).

i. Utilizing the LPG on the engine enables running on the higher compression ratio condition and produces higher thermal efficiency. Besides that, the engine has smoother combustion due to the lower engine stability effect condition.
ii. The fuel consumption for LPG improved compared to conventional fuel.
iii. LPG increases about 50% engine life cycles due to the low amount of sulphide in the fuel. Thus, it is capable of extending the life span of the cylinder bore, combustion chamber and spark plug.

REFERENCES

Autogas Incentive Policies. (2017). A Country-by-Country Analysis of Why and How Governments Encourage Autogas and What Works. *World LP Gas Association*.

Alasfour, F. N. (1998).NO_X Emission from a Spark Ignition Engine using 30%ISOButanol-Gasoline Blend: PART 2 - Ignition Timing. *Applied Thermal Engineering*, *18*(8), 609–618.

Alvarez, C. E. C., Couto, G. E., Roso, V. R., Thiriet, A. B., & Valle, R. M. (2018). A Review of Prechamber Ignition Systems as Lean Combustion Technology for SI Engines. *Applied Thermal Engineering*, *128*, 107–120.

Ambaliya, A. M. (2014). Effect of Compression Ratio and Spark Timing onPerformance and Emission of Dedicated 4-Stroke S.I Engine Fuelled With LPG *: A Technical Review*. *3*(1), 1052–1058.

Arnold. (1999). *Design of Gas- Handling Systems and Facilitie*. Santiago: Santiago Pacheco of Paragon Engineering Services, Inc.pp 467-492;1999.

Autogas Incentive Policies (2020). A Country-By-Country Analysis of Why and How Governments Encourage Autogas and What Works. *World LP Gas Association*.

Boretti, A., & Watson, H. C. (2009). Development of a Direct Injection High Efficiency Liquid Phase LPG Spark Ignition Engine. *SAE Technical Paper*. 2009-01-1881.

Campbell, M., Wyszyński, Ł. P., & Stone, R. (2004). Combustion of LPG in a Spark-Ignition Engine. *SAE Technical Paper*. 2004-01-0974.

Ceviz, M. Akif, Çavuşoĝlu, B., Kaya, F., & Öner, I. V. (2011). Determination of Cycle Number for Real In-Cylinder Pressure Cycle Analysis in Internal Combustion Engines. *Energy*, 36(5), 2465–2472.

Ceviz, Mehmet Akif, Kaleli, A., & Güner, E. (2015). Controlling LPG Temperature for SI Engine Applications. *Applied Thermal Engineering*, 82, 298–305.

Chitragar, P. R., Shivaprasad, K. V., Nayak, V., Bedar, P., & Kumar, G. N. (2016). An Experimental Study on Combustion and Emission Analysis of Four Cylinder 4-Stroke Gasoline Engine Using Pure Hydrogen and LPG at Idle Condition. *Energy Procedia*, , 525–534.

Çinar, C., Şahin, F., Can, Ö., & Uyumaz, A. (2016). A comparison of Performance and Exhaust Emissions with Different Valve Lift Profiles Between Gasoline and LPG Fuels in a SI Engine. *Applied Thermal Engineering*, 107, 1261–1268.

Costa, M., Sorge, U., & Allocca, L. (2012). Increasing Energy Efficiency of a Gasoline Direct Injection Engine Through Optimal Synchronization of Single or Double Injection Strategies. *Energy Conversion and Management*, 60, 77–86.

Djouadi, A., & Bentahar, F. (2016). Combustion Study of a Spark-Ignition Engine from Pressure Cycles. *Energy*, 101, 211–217.

Eriksson, L. (1999). *Spark Advance Modeling and Control*. In PhD Thesis. Link¨oping University, SE–581 83 Link¨oping, Sweden;1999

Erkuş, B., Karamangil, M. I., & Sürmen, A. (2015). Enhancing the Heavy Load Performance of a Gasoline Engine Converted for LPG use by Modifying the Ignition Timings. *Applied Thermal Engineering*, 85, 188–194.

Erkus, B., Surmen, A., & Karamangil, M. I. (2012). The Effect of Ignition Timing on Performance of LPG Injected SI Engine. *Energy Education Science and Technology Part A: Energy Science and Research 2012 Volume (issues)* 28(2): 889-896

Farrugia, M., Briffa, A., & Farrugia, M. (2014). Liquid State LPG Conversion of an Older Vehicle. *SAE Technical Paper* No. 2014-01-2613.

Flekiewicz, M., & Kubica, G. (2016). The Use of Gaseous Fuels Mixtures for SI Engines Propulsion. *IOP Conference Series: Materials Science and Engineering*, 148(1).

Gas Malaysia. (2011). *Chemical Safety Data Sheet, Liquefied Petroleum Gas*.

GlobalPetrolPrice.com. (2021). *Global Fuel Price in World*. Retrieved from https://www.globalpetrolprices.com/gasoline/diesel/LPG_prices/June 2021

Gumus, M. (2011). Effects of volumetric efficiency on the performance and emissions characteristics of a dual fueled (gasoline and LPG) spark ignition engine. *Fuel*

Processing Technology, *92*(10), 1862–1867.

Hamada, K. I., Rahman, M. M., Abdullah, M. A., Bakar, R. A., & A. Aziz, A. R. (2013). Effect of Mixture Strength and Injection Timing on Combustion Characteristics of a Direct Injection Hydrogen-Fueled Engine. *International Journal of Hydrogen Energy*, 38(9), 3793–3801.

Heywood, J. B. (1988). *Internal Combustion Engine Fundementals*. McGrawHill series in mechanical engineering (1st Edition). New York: McGraw-Hill.

Heywood, J. B. (2018). *Internal Combustion Engine Fundementals*. McGrawHill series in mechanical engineering (2nd Edition). New York: McGraw-Hill.

Homdoung, N., Tippayawong, N., & Dussadee, N. (2014). Effect of Ignition Timing Advance on Performance of a Small Producer Gas Engine. *International Journal of Applied Engineering Research*, 9(13), 2341–2348.

Kakaee, A. H., Shojaeefard, M. H., & Zareei, J. (2011). Sensitivity and Effect of Ignition Timing on the Performance of a Spark Ignition Engine: An Experimental and Modeling Study. *Journal of Combustion*, *2011*.

Kang, K., Lee, D., Oh, S., & Kim, C. (2001). Performance of an Liquid Phase LPG Injection Engine for Heavy Duty Vehicles. *SAE Technical Paper* No. 2001-01-1958.

Kim, K., Kim, J. J., Oh, S., Kim, C., Lee, Y., Choi, K., Park, S. (2013). Experimental Evaluation of Engine Control Strategy on the Time Resolved THC and Nano-Particle Emission Characteristics of Liquid Phase LPG Direct Injection (LPG-DI) Engine during the Cold Start. *Fuel Processing Technology*, 106, 166–173.

Kim, K., Kim, J., Oh, S., Kim, C., & Lee, Y. (2017). Evaluation of Injection and Ignition Schemes for the Ultra-Lean Combustion Direct-Injection LPG Engine to Control Particulate Emissions. *Applied Energy*, 194, 123–135.

Krishnaiah, R., Ekambaram, P., & Jayapaul, P. B. (2016). Investigations on the Effect of Piston Squish Area on Performance and Emission Characteristics of LPG Fuelled Lean Burn SI Engine. *SAE Technical Papers*, 2016-1051–1060.

Lawankar, S M, Dhamande, L. P. (2012). Comparative Study of Performance of LPG Fuelled SI Engine at Different Compression Ratio and Ignition Timing. *International Joural of Mechanical Engineering and Technology(IJMET)*, 3(3), 337–343.

Lawankar, S. M., Dhamande, L. P., & Khandare, S. S. (2012). Experimental Study of Effect of Ignition Timing and Compression Ratio on NOx Emission of LPG Fuelled Engine. *International Journal of Scientific & Engineering Research*, 3(10), 10–13.

Li, L., Wang, Z., Deng, B., Han, Y., & Wang, H. (2002). Combustion and Emissions Characteristics of a Small Spark-Ignited LPG Engine. *SAE Technical Papers*, (724).

Li, L., Wang, Z., Wang, H., Deng, B., & Xiao, Z. (2002). A study of LPG Lean Burn for a Small SI Engine. *SAE Technical Papers*, (724).

Li, X., Song, D., Liu, B., & Li, Q. (2011). Effect of Ignition Advance Angle on Liquid Phase LPG Injection Engine Performance. *Advanced Materials Research*, 156–157, 473–476.

Li, X., Yang, L., Pang, M., & Liang, X. (2010). Effect of LPG Injection Methods on Engine Performance. *Advanced Materials Research*, *97–101*(May), 2279–2282.

Magnusson, J. (2007). *An Investigation of Maximum Brake Torque Timing based on Ionization Current Feedback*. Master's Thesis. Linköping University:2007

Malaysia Automotive Roadmap. (2014). *Malaysia Automotive Roadmap 2013-2025*. *Malaysia Automotive Institute*.

Malaysia Energy Information Hub. (2020). *Final Consumption of Petroleum Products*. Retrieved from https://meih.st.gov.my/statistics

MARii. (2020). *Update on Malaysia Automotive Background of NAP 2020. Malaysia Automotive Robotic and IoT Institute*

Masi, M. (2012). Experimental Analysis on a Spark Ignition Petrol Engine Fuelled with LPG (Liquefied Petroleum Gas). *Energy*, 41, 252–260.

Masi, M., & Gobbato, P. (2011). Measure of the Volumetric Efficiency and Evaporator Device Performance for a LPG SI Engine. *Proceedings of the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2011*, 60, 392–409.

Mizushima, N., Sato, S., Ogawa, Y., Yamamoto, T., Sawut, U., Takigawa, B., Konagai, G. (2009a). Combustion Characteristics and Performance Increase of an LPG-SI

Engine with Liquid Fuel Injection System. *SAE Technical Papers*, 4970.

Mizushima, N., Sato, S., Ogawa, Y., Yamamoto, T., Sawut, U., Takigawa, B., Konagai, G. (2009b). Combustion Characteristics and Performance Increase of an LPG-SI Engine with Liquid Fuel Injection System. *SAE Technical Paper* No. 2009-01-2785.

MSDS. (2015). *Materials Safety Data Sheet Lpg in Malaysia* (1st Edition). Malaysia.

Mustafa, K. F., & Gitano-Briggs, H. (2009). Liquefied Petroleum Gas (LPG) as an Alternative Fuel in Spark Ignition Engine : Performance and Emission Characteristics. *Proceedings of ICEE 2009 3rd International Conference on Energy and Environment*, (December), 7–8.

Mustaffa, N. (2019). *Combustion Characteristics of a Spark Ignition Engine Operating with Liquid Lpg Injection*. Universiti Tun Hussein Onn Malaysia:2019

Mustaffa, N., Fawzi, M., Osman, S. A., & Tukiman, M. M. (2019). Experimental Analysis of Liquid LPG Injection on the Combustion, Performance and Emissions in a Spark Ignition Engine. *IOP Conference Series: Materials Science and Engineering*, 469(1).

Natural Resources and Enviroment. (2021). *Malaysia: CO_2 Country Profile*. Retrieved from Our World in Data website: https://ourworldindata.org/co2/country/malaysia/ June 2021

Nayak, V., Rashmi, G. S., Chitragar, P., & Mohanan, P. (2016a). Combustion Cyclic Variation of a LPG Fuelled MPFI Four Cylinder Gasoline Engine. *Energy Procedia*, *90*(December 2015), 470–480.

Osman, S. A. (2014). *Characterization of a C.I Engine Operated Using Retrofit Fuelling Concept*. Universiti Tun Hussein Onn Malaysia;2014

Park, C., Park, Y., Oh, S., Lee, Y., Kim, T. Y., Kim, H., … Kang, K. Y. (2013). Emission Characteristics of Gasoline and Lpg in a Spray-Guided-Type Direct Injection Engine. *SAE Technical Papers*, 2.

Pecqueur, M., Ceustermans, K., Huyskens, P., & Savvidis, D. (2008). Emissions Generated from a Suzuki Liane Running on Unleaded Gasoline and LPG Under the Same Load Conditions. *SAE Technical Papers*, (724).

Pham, P. X., Vo, D. Q., & Jazar, R. N. (2017). Development of Fuel Metering

Techniques for Spark Ignition Engines. *Fuel*, *206*, 701–715.

Phuong, P. X. (2006). *Comparison of Liquid and Gaseous Liquefied Petroleum Gas Injection in a Spark Ignition Engine*. University of Sydney:2006

Pilusa, T. J., Mollagee, M. M., & Muzenda, E. (2012). Reduction of Vehicle Exhaust Emissions from Diesel Engines Using the Whale Concept Filter. *Aerosol and Air Quality Research*, 12(5), 994–1006.

Pulkrabek. (2004). *Engineering Fundamental of the Internal Combustion Engine* (2nd edition). Pearson Prentice-Hall.

Raslavičius, L., Keršys, A., Mockus, S., Keršiene, N., & Starevičius, M. (2014). Liquefied Petroleum Gas (LPG) as a Medium-Term Option in The Transition to Sustainable Fuels and Transport. *Renewable and Sustainable Energy Reviews*, 32, 513–525.

Road Trasport Department of Malaysia. (2021). *Bilangan Terkumpul Kenderaan Bermotor di Malaysia*. Retrieved from https://www.data.gov.my/p/mengenai-data-gov-my/June 2021

SAE J1349 Standard. (2004). *Surface Vehicle Standard J1349*. *4970*, 1–9.

Saleh, H. E. (2008). Effect of Variation in LPG Composition on Emissions and Performance in a Dual Fuel Diesel Engine. *Fuel*, *87*(1), 3031–3039.

Saraf, R. R. (2014). Comparative Assessment on Performance and Emissions of LPG / Gasoline Bi-fuel Passenger Car PFI Engines. *SAE International*, 4970.

Saraf, R. R., Thipse, S. S., & Saxena, P. K. (2009). Comparative Assessment on Performance and Emissions of Lpg/Gasoline Bi-fuel Passenger Car PFI Engines. *SAE Technical Papers*, 4970.

Sendyka & Noga. (2013). Combustion Process in the Spark-Ignition Engine with Dual Injection System. *Advance in Internal Combustion Engines and Fuel Technology*.

Shehata, M. S. (2010). Cylinder Pressure, Performance Parameters, Heat Release, Specific Heats Ratio and Duration of Combustion for Spark Ignition Engine. *Energy*, 35(12), 4710–4725.

Sim, H., Lee, K., Chung, N., & Sunwoo, M. (2005). A Study on the Injection Characteristics of a Liquid-Phase Liquefied Petroleum Gas Injector for Air-Fuel Ratio Control. *Proceedings of the Institution of Mechanical Engineers, Part D:*

Journal of Automobile Engineering, 219(8), 1037–1046.

Simsek, S., & Uslu, S. (2020). Investigation of the Impacts of Gasoline, Biogas and LPG Fuels on Engine Performance and Exhaust Emissions in Different Throttle Positions on SI Engine. *Fuel*, 279(June), 118528

Siriwardena, S., Hunt, G., Teisl, M. F., & Noblet, C. L. (2012). Effective Environmental Marketing of Green Cars: A Nested-Logit Approach. *Transportation Research Part D: Transport and Environment*, 17(3), 237–242.

Suyabodha, A. (2017). Comparison the Rate of Energy Consumption Between Gasoline95 and LPG in Spark Ignition Engine under Real Driving Conditions. *Energy Procedia*, 118, 164–171.

Synák, F., Čulík, K., Rievaj, V., & Gaňa, J. (2019). Liquefied Petroleum Gas as an Alternative Fuel. *Transportation Research Procedia*, 40, 527–534.

Toyota. (2012). Combustion Chemistry. *Emissions*.

Türköz, N., Erkuş, B., Karamangil, M. I., Sürmen, A., & Arslanoğlu, N. (2014). Experimental investigation of the effect of E85 on engine performance and emissions under various ignition timings. *Fuel*, 115, 826–832.

Vipavanich, C., Chuepeng, S., & Skullong, S. (2018). Heat Release Analysis and Thermal Efficiency of a Single Cylinder Diesel Dual Fuel Engine with Gasoline Port Injection. *Case Studies in Thermal Engineering*, 12, 143–148.

Viswanatha, H. C., Shanmugam, R. M., Srinivasan, L., & Kankariya, N. M. (2011). Experimental studies on the Effect of Vaporizer Heating and Transition Temperature in a Bi-Fuel LPG Vehicle. *SAE Technical Papers*.

Watson, H. C., & Phuong, P. X. (2007). Why Liquid Phase LPG Port Injection has Superior Power and Efficiency to Gas Phase Port Injection. *SAE Technical Paper* No. 2007-01-3552.

Yamin, J. A. A., Gupta, H. N., & Bansal, B. B. (2003). The Effect of Combustion Duration On The Performance and Emission Characteristics of Propane-Fueled 4-Stroke S. I. Engines. *Emirates Journal for Engineering Research*, 8(1), 1–14.

Yeom, K., Jang, J., & Bae, C. (2007). Homogeneous Charge Compression Ignition of LPG and Gasoline using Variable Valve Timing in an Engine. *Fuel*, 86(4), 494–503.

Zareei, J., & Kakaee, A. H. (2013). Study and The Effects of Ignition Timing on Gasoline Engine Performance and Emissions. *European Transport Research Review*, 5(2),