University of Southern Queensland

Faculty of Engineering and Surveying

REDUCTION OF NITROGEN OXIDES (NO_X) USING LIQUEFIED PETROLEUM GAS (LPG) IN SPARK IGNITION (SI) ENGINE

A dissertation submitted by

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ABSTRACT

Conventional fuels such as gasoline and diesel are causing serious environmental issues due to their high amount of pollutants. Moreover, emissions such as nitrogen oxides (NO_x), carbon monoxide (CO), sulphur oxides (SO_2) and so on have adverse impacts on the human body. Therefore, alternative fuels such as LPG are being considered to replace the role of conventional fuel in order to reduce these harmful emissions to a safer level. LPG is commonly used as a cooking fuel in Malaysia and is widely available commercially in small sized portable cylinders.

A study was conducted on the use of LPG in conventional two-stroke and four-stroke gasoline engines. The laboratory facilities were provided by UNITEN (University of Tenaga Malaysia). The engines were tested using LPG and gasoline so that comparisons of the emissions of pollutant gases and engine performance can be made. The results obtained are very encouraging in the emission aspect. The average reduction of emission gases from the LPG fuel system are 64% for NO_x, 31% for CO_2 and 57% for CO for the two-stroke engine. The four-stroke engine achieved a reduction of 41% for $NO_{x,}$ 11% for CO_2 and 40% for CO. On the other hand, the LPG fuel system also delivered a comparable torque and engine efficiency as compared to gasoline. The results of this research show the high potential of LPG as an alternative fuel for spark-ignition engines.

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Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set put in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Date

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GLOSSARY

BDC	Bottom dead center
C_3H_8	Propane
C_4H_{10}	Butane
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct current
EI	Emission index
HC	Hydrocarbon
HCN	Hydrogen cyanide
LPG	Liquefied petroleum gas
N_2	Nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
PM	Particular matter
PPM	Particle per million
PPMW	Particles per million by weight fraction
$Q_{exhaust}$	Energy lost in the exhaust flow
Q_{loss}	Other energy lost to the surroundings by heat transfer
rpm	Resolution per minute
SI	Spark-ignition
SO_2	Sulphur dioxide
SO_x	Sulfur oxide gases
TDC	Top dead center
THC	Total hydrocarbon
UNITEN	University of Tenaga Malaysia
VOCs	Volatile organic compounds
W	Watts
W_{acc}	Power to run engine accessories
W_{shaft}	Brake output power of the crankshaft

NOMENCLATURE

BP	Brake power
bsfc	Brake specific fuel consumption
EP	Electric power
I	Current
IP	Input power
$\dot{m}_f$	Mass flow rate of fuel
N	Engine speed
P	Power developed by engine
Q_{HV}	Lower calorific value of fuel
sfc	Specific fuel consumption
V	Voltage
π	3.142
τ	Torque (N.m)
η_f	Engine efficiency
ρ	Density
λ	Air-fuel ratio
ϕ	Equivalence ratio

CHAPTER 1

INTRODUCTION

1.1 Project Background

Environmental issues regarding the emission of conventional fuels such as gasoline and diesel are of serious concern worldwide. The standard emission from conventional fuel vehicles are hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM). These emissions are harmful gases which can have adverse impact on human body and destroy the environment by playing an important role in formation of the greenhouse effect, acid rain and global warming. Therefore, alternative fuels such as natural gas are being considered to replace the role of conventional fuel in order to reduce these harmful emissions from being released to the atmosphere. These alternative fuels may possibly contribute to a significant reduction in emission in most vehicles operating worldwide.

Natural gas had long been introduced to the market where application of cleanliness is emphasized. Liquefied petroleum gas (LPG) is one of the members of natural gases and has been declared as the “cleaner fuel” (Nett Technologies, 2004). LPG is increasingly chosen as the preferred burning fuel for all types of vehicles due to its advantageous fuel properties. According to Murray et al. (2000), LPG is proven to have lower emission of pollutants such as hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen oxides (NO_x) if compared to the conventional fuels. For examples, CO is reduced by over 20%, total hydrocarbon (THCs) by over 40% and NOx by over 30% (as compared to petrol) in light-duty vehicles. Whereas for heavy-duty engines, CO is reduced by over 90%, total hydrocarbon (THCs) by over 80% and NOx by about 60% (compared to diesel). Furthermore, particulate matter (PMs) is virtually eliminated from LPG vehicle emissions (Murray et al., 2000).

A lot of researches have been done to prove that vehicles using LPG as the burning fuel shows no decreased in efficiency compared to the conventional fuel operating vehicles along with its advantage of reduction in emission gases from the exhaust of an engine (Murray et al., 2000). Besides that, LPG has the capability to reduce the noise from a running engine, helping to effectively decrease noise pollution in urban areas especially during the traffic congestion period. LPG offers a reduction of around 50% perceived noise levels as a LPG operated bus shows a record of at least 2–3 dB reduction in comparison to a diesel operated bus (AEGPL 1998). There are currently over 4 million road vehicles using LPG in countries such as Italy, Holland, Japan, the USA, and Australia due to the vast advantages of LPG usage (Murray, et al., 2000). On the other hand, the popularity of LPG is increasing in our daily usage; it can also be used as a cooking and heating fuel, in flame weeding and other activities. This is the reason why LPG has being claimed to be the world's most multi-purpose fuel (World LP Gas Association, undated).

The selling price for consumer-grade of LPG is low compared to other hydrocarbons fuels such as petrol and gasoline. Even the Alternative Fuels Data Center (2004) has agreed that the cost of LPG in fleets is less than those of gasoline for a range of 5% to 30%. Moreover, the fueling station cost is either equivalent to, or lower than, that for a comparably sized gasoline dispensing system (Alternative Fuels Data Center, 2004). Due of the abundance of LPG and its important energy and environmental advantages, LPG has been promoted for usage in vehicles by the government. However the use of LPG requires that fueling, maintenance and storage facilities to be upgraded to a certain standard to ensure the operational safety of its users (Clean

Air Technologies Information Pool, 2005). Clean Air Technologies Information Pool (2005) showed that LPG storage and distribution location must meet a certain distance requirement to isolate it from residential properties and underground storage tanks. Maintenance facilities must include the detector to sense LPG leakage to prevent explosion due to leaks.

1.2 Objectives

The main aim of this research project is to analyze and prove the reduction of nitrogen oxides using liquefied petroleum gas in spark ignition engine. This research can be further divided into the sub-objectives listed below:

1. Conduct a detailed study on the history, properties and usage of LPG as an alternate fuel, and the factors and effects of NO_x emission.

2. Measure the concentration of emission gases such as NO_x, CO_2, CO and hydrocarbons from the two-stroke engine which using both the gasoline and LPG as the main fuel.

3. Evaluate the data collected from the experiment conducted for both gasoline and LPG in the two-stroke engine for different set of load conditions and engine speeds.

4. Comparative study of the use of conventional fuel and LPG in term of pollutants and feasibility of using LPG fuel as a suitable alternative in SI engines.

1.3 Methodology

First, a literature review of liquefied petroleum gas (LPG) and nitrogen oxide (NO_x) was performed to explain the background of LPG and NO_x formation. The literature survey was undertaken from various resources such as journals, conference articles, online sources, and reference books. All relevant information were analyzed to construct a precise summary of background information which included the history of LPG, advantages and limitations of LPG, physical and chemical properties of LPG, introduction of NO_x and formation of NO_x. At the same time, comparisons between gasoline and LPG were also noted.

Next, a review will be given on crucial engine performances such as engine efficiency, brake power and specific fuel consumption. The emission from the tail-pipe of the engine such as hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO) and particulate matter (PM) will also be explained.

On the practical side, experiments will be conducted on a modified gasoline engine in UNITEN laboratory to collect emission data from the exhaust engine and simultaneously, engine performance will also be recorded. The experiments will be conducted using different loads to collect the emission data. All the data will be analyzed to make comparisons between gasoline and LPG system. A conclusion is made after analyzing the data collected from the experiments. The steps of the project methodology as explained earlier are illustrated in the schematic diagram in the following page:

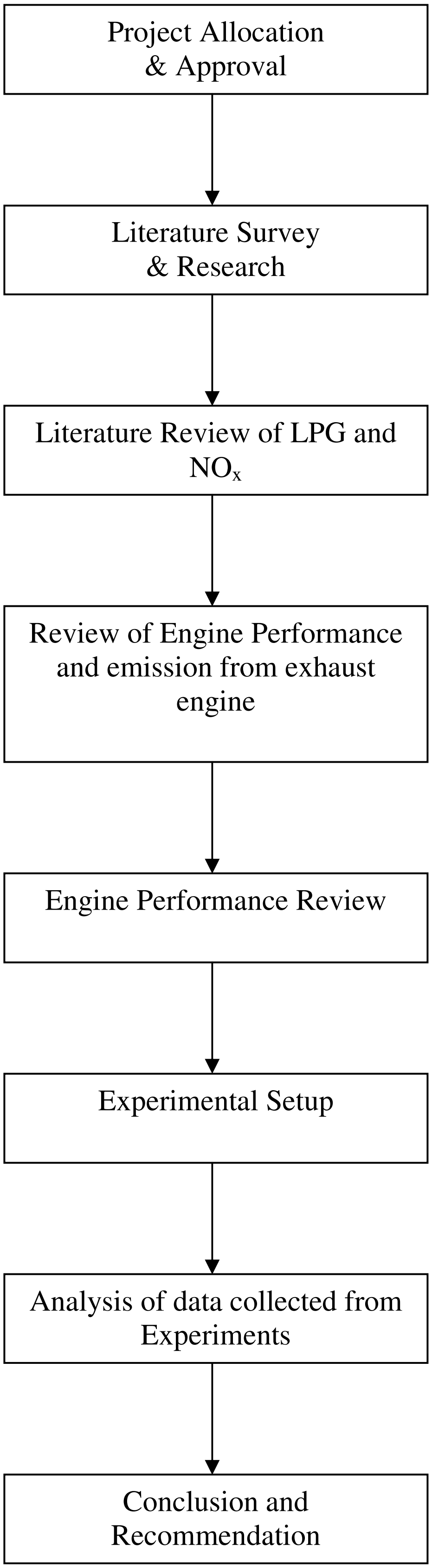

Figure 1.1: Project Methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Liquefied Petroleum Gas (LPG)

Liquefied Petroleum Gas (LPG) is a mixture of various hydrocarbons and its main components are either propane (C_3H_8) or butane (C_4H_{10}), or combination of the two. LPG is produced as the by-product of natural gas processing or crude-oil refining. According to West Virginia University's Alternative Fuel Vehicle Training Program, approximately 30% of LPG is produced from oil refining and another 70% is generated from the natural gas processing in the United States. United States Department of Energy’s Alternative Fuels Data Center (2004) shows that LPG is the most widely used alternative fuel in the world, with about 5.7 million vehicles currently using it.

According to Clean Air Technologies Information Pool (2005), LPG exists as gas state at atmospheric pressure and room temperature. As the name implies, LPG can be liquefied when compressed by moderate pressure or when the temperature is sufficiently reduced. In order to use it as burning fuel, LPG is stored in special steel tanks to keep it under certain pressure, up to 20 bars, to maintain its form in the liquid state. When the surrounding temperature increases, LPG will expand within the steel tank and therefore sufficient space is left to allow the expansion (EduGreen, undated). Moreover, the pressure in the LPG container must be always higher than the surrounding in order to ensure a steady supply at constant pressure. Thus, a regulator is used to release any extreme pressure build-up (EduGreen, undated). EduGreen (undated) also revealed that latent heat of vaporization is consumed when transforming LPG from liquid to gas state. Therefore, the exterior surface of the container is cold when the liquid boils as it obtains energy from the surroundings.

The benefits of easy storage and utilization make LPG an ideal energy source suitable for a wide range of application. LPG is a multi-purposed fuel which can be used as the burning fuel in transportation, industrial application, agricultural, leisure industry, cooking and space heating (World LP Gas Association 2004).

Hofmann reported that there are three different grades of LPG available in the market, namely the HD-5 Propane, Commercial Propane and Commercial B/P Mixture. Their compositions are tabulated below:

Component	HD-5 Propane	Commercial Propane	Commercial B/P Mixture
Propane	90% liquid volume (min)	Propane and / or propylene	Butanes and / or butylenes with
Propylene	5% liquid volume (max)	-	propane and / or propylene
Butane and heavier HC	2.5% liquid	2.5% liquid	-
Moisture content	Dryness test of NPGA	Dryness test of NPGA	-
Residual matter	0.05 ml	0.05 ml	-
Pentane and heavier HC	-	-	2 % liquid volume (max)
Total sulfur	123 PPMW*	185 PPMW*	140 PPMW*

Table 2.1: Types of LPG available in the market

*PPMW: Particles per million by weight fraction (Hofmann, undated).

2.1.1 History of Liquefied Petroleum Gas

According to National Propane Gas Association (2005), LPG began its history in the year of 1904 when it was discovered by a young chemist named Herman Blau in Germany. It was first given the name "Blaugas" and was mainly used for street lighting and home cooking closely surrounding the production plant. Blaugas was expensive to handle at that time as each pound of the gas is roughly 10 cents. EduGreen reported that in the year of 1912, an American scientist, Dr. Walter O. Snelling recognized that this gaseous fuel can be changed into the liquid state by applying moderate pressure, and this discovery eased the storage of LPG. American Gasol Co was the first company to bottle liquefied petroleum gas in steel cylinders and sell it commercially. The product was not widely used by the public due to the weight of the steel container. In the year of 1928, the weight of the steel cylinder tank had been improved through design and the two-stage regulator system was also upgraded to single regulator control. The usage of LPG was on the rise since then and was sold commercially (National Propane Gas Association, 2005).

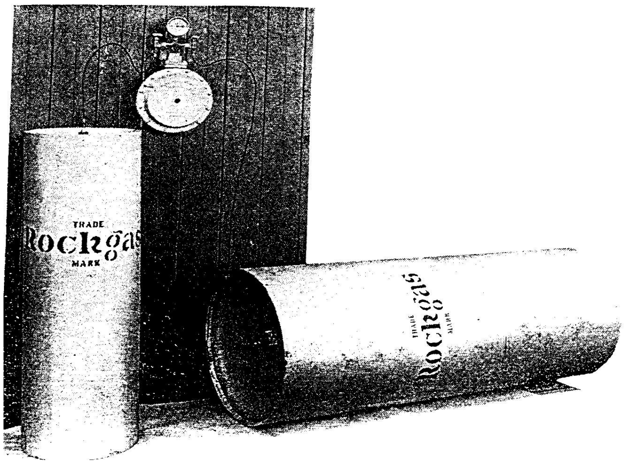

Figure 2.1: Type of cylinder and regulator system used in the year of 1912 (National Propane Gas Association, undated)

2.1.2 Physical and Chemical Properties of LPG

LPG has been and continued to be the most widely used alternative burning fuel. Listed below are some characteristics of LPG:

i. LPG is a colorless gas regardless of its state. Chilled water vapor condensed from the surrounding air will appear as white cloud around the LPG leakage point (Shell Gas LPG UK, 2004).

ii. LPG is odorless or has no smell. Stench agent such as Mercaptan is added before delivery to detect leakage. Mercaptan additive has an unpleasant and foul smelling so that leak can be easily detected (Shell Gas LPG UK, 2004).

iii. LPG is chemically reactive and will cause natural rubber and some plastics to deteriorate. Hence, it is advisable to use equipment specifically designed for LPG (Shell Gas LPG UK, 2004).

iv. LPG is highly volatile and flammable. Thus, it must be stored in a high ventilation rate area and kept away from any sources of ignition (EduGreen, undated).

v. LPG is a high performance fuel. LPG will only burn when the fuel to air ratio is between 1:10 and 1:50 range. (Shell Gas LPG UK, 2004).

vi. LPG vapor is denser than air. Propane is about one and a half times as heavy as air. Any leakage of LPG will sink to the ground and accumulate in low lying areas due to its high density property. Hence, LPG is not advisable to be stored in basements (Shell Gas LPG UK, 2004).

vii. Although LPG is non-toxic, it has an anesthetics effect when present in high concentrations. Therefore, LPG should always be kept away from children whenever possible (EduGreen).

Table 2.2 illustrates the comparison of the properties of gasoline and LPG:

Property	Gasoline	Propane (LPG)
Chemical formula	C_4 to C_{12}	C_3H_8
Molecular weight	100-105	44.1
Composition, Weight %		
Carbon	85-88	82
Hydrogen	12-15	18
Oxygen	0	-
Specific gravity, 60°F/60°F	0.72-0.78	0.508
Density, lb/gal @ 60 °F	6.0-6.5	4.22
Boiling temperature, °F	80-437	-44
Reid vapor pressure, psi	8-15	208
Octane no.		
Research octane no.	90-100	112
Motor octane no.	81-90	97
(R+M)/2	84-96	104
Cetane no.	5-20	--
Water solubility, @ 70°F		
Fuel in water, volume %	Negligible	-
Water in fuel, volume %	Negligible	-
Freezing point, °F	-40	-305.8
Viscosity		
Centipoise, @ 60^oF	0.37-0.44	-
Flash point, closed cup, °F	-45	-100 to -150
Autoignition temperature, °F	495	850-950

Flammability limits, volume %		
Lower	1.4	2.2
Higher	7.6	9.5
Latent heat of vaporization		
Btu/gal @ 60°F	≈950	775
Btu/lb @ 60°F	≈150	193.5
Btu/lb air for stoichiometric mixture @ 60°F	≈10	-
Heating value		
Higher (liquid fuel-liquid water) Btu/lb	18,800-20,400	21,600
Lower (liquid fuel-water vapor) Btu/lb	18,000-19,000	19,800
Higher (liquid fuel-liquid water) Btu/gal	124,800	91,300
Lower (liquid fuel-water vapor) Btu/gal @ 60°F	115,000	84,500
Heating value, stoichiometric mixture		
Mixture in vapor state, Btu/cubic foot @ 68°F	95.2	-
Fuel in liquid state, Btu/lb or air	1,290	-
Specific heat, Btu/lb °F	0.48	-
Stoichiometric air/fuel, weight	14.7	15.7
Volume % fuel in vaporized Stoichiometric mixture	2	-

Table 2.2: Properties of Gasoline and LPG (Alternative Fuels Data Center, 2004)

2.1.3 Advantages of LPG

LPG is the most commonly used alternative fuel in the United States (Hofmann, undated) and it is increasingly chosen as the preferred fuel due to its great number of benefits towards the society as follows:

i. The amount of readily available LPG is aplenty in the market and its supply is estimated to last for at least another 75 years. There are over 700 retail stores in Texas to fulfill the demand of LPG (World LP Gas Association, 2004).

ii. The price of LPG is cheaper than other conventional fuels. Table 2.3 shows that LPG prices increase slower than gasoline in the past and in the near future (Hofmann, undated).

	Gasoline $ gallon equivalent	LPG $ gallon equivalent
Wholesale	0.93	0.52
Retail	1.39	0.98

Table 2.3: Projected 2000 Fuel Prices of LPG and Gasoline (Hofmann, undated)

iii. LPG has a comparable performance if compared to the conventional fuels with lower pollutant emission (Autogas, 2000).

iv. LPG is friendly to the environment. It produces less pollutant to the atmosphere with virtually no particulate matters (PM), low level of carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NO_x). LPG emits less greenhouse gases (GHG) compared to any other fossil fuel when measured through the total fuel cycle (World LP Gas Association, 2004).

v. For LPG that is used in commercial and domestic heating, it is portable because it is stored in steel tanks which are easily transferred to other places. LPG is sometimes referred to as the “pipeline on wheel” due to its portability (World LP Gas Association, 2004).

vi. LPG has a very good safety record over the years. The conversion kits readily available in the market enable LPG to continue being a widely used road fuel (Autogas, 2000).

vii. Researches have shown that engine maintenance is reduced significantly because LPG does not wash the lubricant oil from the cylinder walls or dilute the oil. Hence, engines using LPG as the burning fuel always enjoy a longer service life and reduced maintenance costs (Autogas, 2000).

2.1.4 Limitations of LPG

Although LPG has a great deal of advantages, it has some limitations too as listed below:

i. LPG is a non-renewable fossil fuel. If we use LPG faster than the rate of its generation, it will begin to deplete (Autogas, 2000).

ii. LPG is denser than air, and may pose a risk when leakage occurs as it will accumulate in low-lying areas (Autogas, 2000).

iii. A bulky storage tank is needed to store LPG. Hence, larger boot area is required to place the storage tank in place. The heavier storage tank also reduces the cargo capacity of fleet vehicles and may cause inconvenience as more journeys have to be taken (Autogas, 2000).

iv. Murray (2000) revealed that there exist a number of countries with under-developed technologies for LPG distribution system and therefore, limits its usage. For example, Malaysia does not have any LPG operating vehicle yet. LPGs are only used in residential homes as heating and cooking gas.

v. The contents of propane in LPG are different for most countries. For instance, LPG contains more than 90 % propane in UK, whereas in Italy the level can be as low as 20%. This fluctuation proves to be a barrier to standardization of LPG vehicles around Europe and the rest of the world (Murray et al., 2000).

2.1.5 Comparisons between Gasoline and LPG

West Virginia University's Alternative Fuel Vehicle Training Program published that the performance and drivability of LPG operating vehicles is essentially the same as gasoline operating vehicles. The displacement of air by LPG causes reduction in power of 4% if compared to an equivalent gasoline counterpart. Moreover, the evaporative cooling rate and increase in air density when gasoline fuel is used provides the added power (West Virginia University's Alternative Fuel Vehicle Training Program).

Engines powered by LPG are easier to start than gasoline engines in cold weather due to the earlier vaporization rate of LPG before being introduced into the engines (Hofmann, undated). Furthermore, Hofmann (undated) also revealed that LPG decreases soot formation in addition to reduction of mechanical abrasiveness and chemical degradation of the engine oil. Higher octane rating of LPG (110 to 120) allows higher compression ratio and thus help to resist engine knocks better than gasoline. However, a liter of LPG consists of 28% less energy than a liter of gasoline, which means that more consumptions of LPG is needed to provide same vehicle power than that of a gasoline engine (West Virginia University's Alternative Fuel Vehicle Training Program).

According to the research done by West Virginia University's Alternative Fuel Vehicle Training Program, LPG fueled vehicle owners need to install a slightly bigger tank in order to achieve the same driving range as gasoline vehicles. This might pose a problem for bi-fueled vehicles where two tanks have to be accommodated as the tanks are normally heavier than conventional fuel tanks for the same range (Murray et al., 2000).

2.1.6 **Safety Issue of LPG**

The studies of AEGPL (1998) have shown that LPG has a safe record if compared to other conventional fuel vehicles. LPG had been proven to be the safest fuel with the lowest accident rate throughout Europe. However, LPG does pose a different type of risk due to its natural properties when a leak occurs. LPG is a highly volatile fuel and pressure gradients will cause the leaking LPG to discharge fast enough to result the liquid LPG to evaporate before reaching the ground. Higher quantities of LPG spill will produce a boiling pool on the ground and LPG will continue to evaporate until there is no more left. Hence, LPG has the highest pool burning rate due to its active vaporization. The potential of LPG to cause an accidental explosion is almost twice compared to gasoline since LPG vapor has a higher tendency to be in contact with an ignition source due to its high volatile properties (National Transportation Library, 2004).

Normally, LPG is delivered to the storage station by tanker trucks. Correct settings of the pressure valve are a crucial element in the delivery process so that no leakage of LPG vapor occurs in an unusually warm day. The containers are of special design at 45 °C (115 °F) with a safety factor of 4:1. The design pressure used is 250 psig since vapor pressure of commercial LPG is 243 psig at the corresponding specific temperature. As a result, the tanker trucks possess a higher capability to resist the mechanical forces associated with an accident if compared to other conventional fuel transportations. The possibility of LPG leaks at joints and fittings is also higher as LPG fuel is transported at a higher pressure (National Transportation Library, 2004).

According to National Transportation Library (2004), there is a great safety risk associated with the transfer of LPG from tanker trucks to the fleet storage as LPG vapor will be released on disconnection when there is any human error. Luckily, LPG is odorized with the foul-smelling agent such as Mercaptan for easy detection of any leakage. However, LPG is denser than air and it will accumulate in the low-lying area if there is inadequate ventilation. Under this condition, leakage of LPG may go undetected. Thus, as a safety precaution to avoid gas build-up, LPG vehicles are not allowed to enter underground car parks and to use EuroTunnel in certain European countries (Murray et al., 2000).

For safety issues associated with fire hazard during storage, LPG is stored in above-ground tanks with thick gauge steel in the storage station. Natural circulation of air and the odious agent Mercaptan help to reduce the dangers of leakage in the weaker point of the LPG storage system such as joints, connection, and fittings. The major safety concern in the fleet storage is the external heating from fire plus the failure of the pressure relief system which will lead to pressure build-up in the tank. This will cause a fatal explosion and therefore, regular checks should be performed on the pressure relief devices to reduce the tendency of pressure build-up in the tank (National Transportation Library, 2004).

2.2 Introduction to Nitrogen Oxide (NO_x)

Control of pollutant emissions from fuel burning engines is of major environmental concern worldwide, especially for engineers who design engine components with the aim of minimizing the emission of nitrogen oxides (NO_x). NO_x is a very undesirable emission and play a major role in the formation of acid rain, greenhouse effect and the global warming issue and hence accelerates the process of icecap melting in north and south poles. In the 1950s, incidents of photochemical smog occurred in Los Angeles and were primarily due to the emission of unburned hydrocarbons and NO_x from vehicles (Haagen-Smit ,1952).

NO_x is the collective term for nitric oxide (NO) and nitrogen dioxide (NO_2) which are extremely toxic gases for humans. Accumulation of NO_x in a confined area can lead to fatality and may also cause harm to other materials. For instance, the color of plain paper will change from white to yellow, and thus degrade its quality causing losses, with the existence of just a few ppm (particle per million) of NO_x in the ambient air (Nett Technologies Inc., 2004). All fuel burning engines produce NO_x as a by-product of combustion. The compositions of NO_x include the nitrogen oxide (NO), nitrogen dioxide (NO_2) and small amount of other nitrogen-oxygen compounds. The nitric oxide (NO) comprises 90-95% of the composition of NO_x whereas nitrogen dioxide (NO_2) makes up the other 5% (U.S. Army Corps of Engineers).

2.2.1 Formation of NO_x

Basically, $NO_{x,}$ as the name implies, are generated from reaction between nitrogen and oxygen under high temperature and pressure conditions during the combustion process in an engine cylinder. Normally it takes place at the pre-combustion, combustion and post-flame regions where sufficient concentrations of oxygen and nitrogen are present. The formation of NO_x depends enormously on the temperature as the rate of dissociation of nitrogen is directly proportional to the temperature increase. Therefore, the higher the combustion reaction temperature, the more NO_x will be produced (Bacherach Institute of Technical Training). The chemical reactions of nitrogen and oxygen are as follows (Szczepanski, 1998):

$$NO + N \rightleftharpoons O + N_2 \qquad (2.1)$$

$$N + O_2 \rightleftharpoons NO + O \qquad (2.2)$$

$$N + OH \rightleftharpoons NO + H \qquad (2.3)$$

There are three different mechanisms of formation of NO_x:

i. Thermal NO_x

It is formed by the stabilization of atmospheric nitrogen in oxidizing atmospheres at a high flame temperature exceeding 1573K or 1300 °C. Thermal NO_x is generally produced during the combustion of both gases and fuel oils. The following chemical reactions were classified as an atom shuttle reaction (Zeldovich et al., 1947; Szczepanski. D 1998)

$$N_2 + O \leftrightarrow NO + N \qquad (2.4)$$

$$N + O_2 \leftrightarrow NO + O \qquad (2.5)$$

When the combustion is under fuel-lean conditions (with less air) and there is a rise in temperature, this will lead to an increase of NO_x emissions due to increased oxygen radicals forming in the combustion process. However, when the combustion is under fuel-rich condition (with excess air) the oxidation reaction will involve the OH and H radicals (Szczepanski. D 1998):

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$$N + OH \leftrightarrow NO + H \qquad (2.6)$$

$$H + N_2 \leftrightarrow N_2H \qquad (2.7)$$

$$N_2H + O \leftrightarrow NO + NH \qquad (2.8)$$

High activation energies are required for the dissociation of oxygen molecules and the disengagement of the triple bond of nitrogen. This phenomenon causes the formation of thermal NO_x to be largely dependent on the temperature, the degree of air to fuel mixing, the concentration of oxygen and nitrogen in the flame and duration of reaction occurred (Bacherach Institute of Technical Training).

ii. Fuel NO_x

It is formed by the reaction of coal-bound nitrogen compounds with oxygen at temperature exceeding 1123K or 850 °C. The formation of fuel NO_x is mainly dependent on the availability of oxygen and the combustion method. Under low oxygen conditions, hydrogen cyanide (HCN) reacts with oxygen atoms to form oxycyanogen and amine intermediates and NO is formed as the oxidization product (Bacherach Institute of Technical Training).

On the other hand, under excess oxygen conditions, the formation of N_2 is more favorable as the result of additional hydrogenated amine species and NO. The chemical reactions between amine intermediates, hydrocarbon radicals and NO are as follows (Szczepanski. D 1998):

$$NH_2 + NO \rightarrow N_2 + H_2O \qquad (2.9)$$

$$CH + NO \rightarrow HCN + O \qquad (2.10)$$

iii. Prompt NO_x

It is formed by the stabilization of atmospheric nitrogen in reducing atmospheres by the particles of hydrocarbon under fuel-rich conditions. Prompt NO_x is of great significance under the condition of very fuel-rich flames and nonessential to be compared with the influence of thermal and fuel NOx (Bacherach Institute of Technical Training).

2.2.2 Concentration of NO_x

The concentration of NO_x found in the emission of engines is dependent on the combustion temperature, the length of combustion time and the concentration of the nitrogen and oxygen in the engine. The measurement unit of NO_x is generally in parts per million (PPM) due to the dilution of NO_x percentage with the excess air level in the flue gases. NO_x value tends to peak at an air-fuel ratio of approximately 1.1 times stoichiometric with the condition of excess oxygen present (U.S. Army Corps of Engineers).

2.2.3 Effects of NO_x towards the Environment

The environmental problems caused by NO_x are now worldwide issues due to the seriousness of ozone reactivity and the amount of formation of smog. NO_x combines with water vapor in clouds to produce acid rain which pollutes clean water sources and corrodes metals used in our daily life. Acid rain also harms the growth of organisms in the lake and disturbs the balance of the ecosystem both on land and at sea. Apart from that, acidified soil is the also the result of acid rain and it causes damage to the root system of trees, disabling the nutrient absorption process and disrupting the natural process of photosynthesis. (Turns, 1996)

When NO_x react chemically with other atmospheric gaseous compounds such as "volatile organic compounds" (VOCs) under the sunlight, it will form smog. Smog is forefront to our environmental concerns as it reduces the visibility of surroundings and poses a health hazard to humans which includes irritation of eyes, respiratory and cardiovascular problems such as asthma and headaches (Southern Technologies).

Greenhouse effect is a global-warming phenomenon when heat energy from the sunlight is trapped by gases such as NO_x. This increases the average temperature of our planet and acts as a great threat to the life of crops, humans and the environment. The increased temperature will speed up the melting rate of the icebergs in north-south poles and there will be an increased risk of flooding in lower-terrain countries.

Next, ozone depletion is also related to the excessive emission of NO_x. Nitrogen oxides formed will allow more penetration of harmful ultraviolet solar radiation to the earth and lead to skin irritation for humans (Turns, 1996). The reaction mechanisms are listed below (Turns, 1996):

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \textbf{(2.11)}$$

$$NO_2 + O \rightarrow NO + O_2 \qquad \textbf{(2.12)}$$

Ozone (O_3) is destroyed in the first reaction to form nitrogen dioxide (NO_2), and then the nitric oxide (NO) is regenerated in the second reaction to repeat the ozone depletion step. These processes will continue and will only stop when the whole ozone layer is consumed (Turns, 1996).

2.2.4 Factors Affecting NO_x Emissions

There are several factors which affect the formation of NO_x in the engine and they are listed below (U.S. Army Corps of Engineers):

i. The air-fuel ratio (λ) plays a major role in determining the amount of emission of NO_x as oxides of nitrogen are formed by the reaction of nitrogen in the fuel with oxygen in the combustion air. When the air to fuel ratio is greater than one which indicates that the combustion is in the lean condition, the fuel mixture has considerably less amount of fuel and excess amount of air. Engines designed for lean burning can achieve higher compression ratios and hence produce better performance. However, it will generate high amount of NO_x due to the excess oxygen present in the air.

ii. Combustion temperature is also one of the primary factors that influence the formation of NO_x. The formation of NO_x is directly proportional to the peak combustion temperature, with higher temperatures producing higher NO_x emissions from the exhaust.

iii. The amount of nitrogen in the fuel determines the level of NO_x emissions as fuels containing more nitrogen compounds result in higher levels of NO_x emissions. Choices of fuel type alter the formation of both the theoretical flame temperature reached and rate of radioactive heat transfer.

iv. The firing and quenching rates also influence the rate of NO_x formation where a high firing rate is associated with the higher peak temperatures and thus increases the NO_x emission. On the other hand, a high rate of thermal quenching results in lower peak temperatures and contributes to the reduction of NO_x emission.

v. Engine parameters such as load and speed of engine also influence the NO_x emissions from the exhaust. When the engine is running under lean conditions, it emits less NO_x. However the nitric oxide (NO) emissions will consequently increase as the engine load increases. The effect of load becomes less significant when the engine is running close to stoichiometric air to fuel ratio. On the other hand, engine speed may increase or decrease the NO emissions as higher engine speed increases the burned gas mass fraction and thus offsets the peak temperature, depending on the exact engine conditions (Bauza, and Caserta, 1997).

2.2.5 NO_x Reduction Techniques

According to Turns (1996), the rate coefficient for the $O + N_2 \rightarrow NO + N$ reaction has a very large range of activation temperature and hence the formation of NO_x increases at a fast rate at temperatures above 1800K. One of the effective methods to reduce the production of NO_x significantly is to decrease the peak temperature. Any modifications that lower the peak temperature will lower NO_x emission from the exhaust. Mixing the flue or exhaust gases with fresh air or fuel has demonstrated to be a great way of lowering the combustion temperature in spark-ignition engines. Figure 2.2 shows the correlation of NO_x reduction with diluents heat capacity for a spark-ignition engine.

Since the amount of nitrogen in the fuel determines the level of NO_x emissions, therefore reduction of NO_x emissions may be accomplished by replacing the fuel type to a fuel which contains lower nitrogen content and thus lowers the peak flame temperatures and the combustion excess air requirement (U.S. Army Corps of Engineers). Natural gases such as LPG appear to be the best alternative to replace the current conventional fuel. Conversion to these fuels can be achieved by additional equipments to modify the current engine to allow substitute LPG fuel to be used.

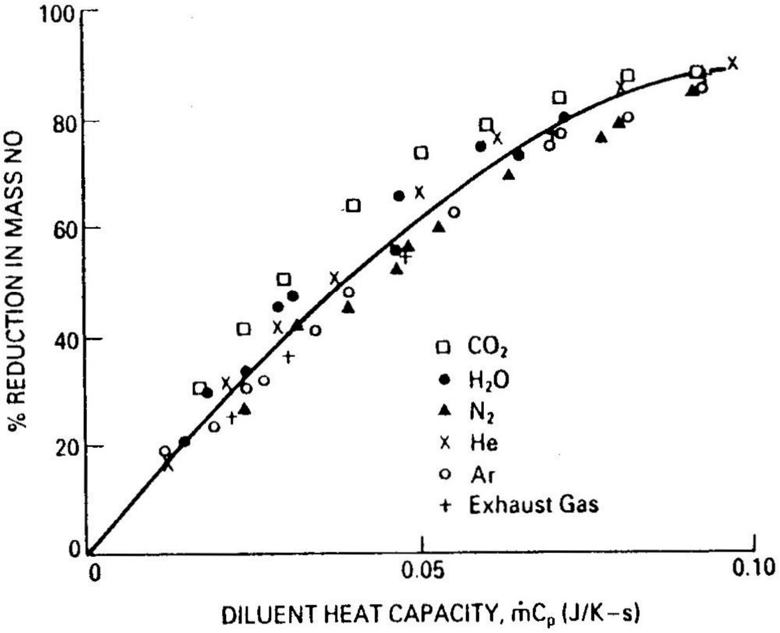

Figure 2.2: Correlation of NO reduction with diluent heat capacity for a spark-ignition engine (Turns, 1996)

Another engine parameter which results in high levels of NO_x emission is the spark timing. Retarding the spark timing shifts the combustion event closer to top-dead-center resulting in lower peak cylinder pressures, and thus produces lower temperature and reduces the NO_x emission. However, retarding the spark timing has significant fuel economy penalties as a side effect (Turns, 1996).

Turns (1996) also mentioned that the amount of NO_x emission from an engine is strongly linked to the time the combustion products spend at high temperature. In other words, the NO_x yield is directly proportional to the amount of time the combustion is held at high temperature. Unfortunately, adjustments of the time-temperature relationship will sacrifice some useful operations of the engine. Therefore, it is not a practical approach to reduce the formation of NO_x by reducing the duration of fuel spent at high temperatures.

Apart from that, staged combustion is an effective method in reducing NO_x emissions. It is refers to a rich-lean and lean-rich combustion sequence taking place in the combustion chamber. According to Turns (1996), the concept of staged combustion is mainly about rapid mixing of the fuel and air, and making use of the good stability and low NO_x emissions associated with the rich combustion together with the complete combustion of unburned CO and H_2 in the lean stage where the production of extra NO_x is low. The control of the mixing process in practice is the key factor of this staging process to reduce the emission of NO_x from the engine exhaust. Reductions of NOx emissions are attainable from the range of 10 to 40% with the staged combustion technique.

With the modifications of the automotive applications alone, it is insufficient to reduce the emissions of NO_x to the level below the legislated standard. Therefore, catalytic converters such as three-way catalysts are very helpful to aid the reduction of NO_x emissions. In a three-way catalyst, the concentrations of CO, HC, and NO_x in the exhaust must be in stoichiometric proportion in order to result in a simultaneous removal of all three major exhaust pollutants as mentioned above.

2.3 Other Emissions of LPG

Other than nitrogen oxide (NO_x), the internal combustion process of spark ignition (SI) engines using liquefied petroleum gas also produces undesirable emissions such as carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2) and hydrocarbons (HC). These emissions pollute the environment and contribute to global warming, acid rain, smog, odors, and respiratory and other health problems (Southern Technologies).

The emission level of these pollutants can be expressed as emission index (EI) and it is defined as the ratio of the mass of species *i* to the mass of fuel burned by the combustion process. Emission index has the unit of emissions flow per fuel flow (Turns, 1996).

$$EI_i = m_{i,emitted} / m_{F,burned} \qquad (2.13)$$

Therefore, emissions indices for carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2) and hydrocarbons (HC) are as follows:

$$(EI)_{co} = m_{co,emitted}\,[g/sec] / m_{F,burned}[kg/sec] \qquad (2.14)$$

$$(EI)_{co2} = m_{co2,emitted}\,[g/sec] / m_{F,burned}[kg/sec] \qquad (2.15)$$

$$(EI)_{so2} = m_{so2,emitted}\,[g/sec] / m_{F,burned}[kg/sec] \qquad (2.16)$$

$$(EI)_{HC} = m_{HC,emitted}\,[g/sec] / m_{F,burned}[kg/sec] \qquad (2.17)$$

2.3.1 Carbon Monoxide (CO)

Carbon monoxide (CO) is a colorless, odorless, poisonous gas that is less dense than air under ordinary conditions (U. S. Consumer Product Safety Commission, 2005). It is produced by the incomplete burning of solid, liquid, and gaseous fuels and is the main product formed in rich combustion processes (Turns, 1996). CO is formed when there is insufficient oxygen to convert all the carbon in the fuel to carbon monoxide (Turns, 1996). CO also can be combusted to supply additional thermal energy (Pulkrabek, 1997):

$$CO + \tfrac{1}{2}\,O_2 \rightarrow CO_2 + heat \qquad (2.17)$$

Normally, the CO emission of a spark ignition engine will be about 0.2% to 5%. CO is found in a rich amount in stoichiometric and slightly lean mixtures due to the dissociation of carbon dioxide at typical combustion temperatures (Turns 1996). Fuel-air equivalent ratio is the most important engine parameter that affects the level of carbon monoxide emission. All other variables only cause second-order effect which is less substantial (Turns, 1996).

2.3.2 Carbon Dioxide (CO_2)

Carbon dioxide is considered as the major greenhouse gas, and it can cause death by suffocation if inhaled in large amounts (Southern Technologies, undated). CO_2 has the tendency to absorb heat radiation of the sun, thus creating a thermal radiation shield which reduces the amount of thermal radiation energy allowed to escape from the Earth. As a result of this, the temperature of Earth rises and accelerates the melting rate of polar ice caps and expansion of oceans into low lying areas (Southern Technologies, undated). To reduce the emission of CO_2 efficiently, engines with higher thermal efficiency that are able to operate at the lowest level of excess air are used (Southern Technologies, undated).

2.3.3 Sulphur Dioxide (SO_2)

Sulfur dioxide (SO_2) belongs to the family of sulfur oxide gases (SO_x). These gases dissolve easily in water and are produced when sulfur or fuels containing sulfur are oxidized (Southern Technologies, undated):

$$S + O_2 = SO_2 \qquad \textbf{(2.18)}$$

SO_2 dissolves in water vapors to form acid, and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to the people and environment. Moreover, oxidation of SO_2 will further produce SO_3 in the atmosphere under the influence of sunlight (Southern Technologies, undated):

$$2SO_2 + O_2 = 2SO_3 \qquad (2.19)$$

Some of the SO_3 will also be introduced directly from the combustion processes alongside SO_2. SO_3 will react rapidly with moisture from the atmosphere to form sulfuric acid, which is the main element in acid rain (Southern Technologies, undated):

$$SO_3 + H_2O = H_2SO_4 \qquad (2.20)$$

It had been proven that even with sophisticated combustion techniques; there had been no significant improvement of reduction in the emission of sulphur dioxide. Therefore the best way to solve this problem is the selection of low sulfur content fuels such as LPG (Southern Technologies, undated).

2.3.4 Hydrocarbons (HC)

According to Ferguson (1986), exhaust gases leaving the combustion chamber of a spark ignition engine contains a lot of hydrocarbon components depending on the type of engine used. Some of the exhaust hydrocarbons are not found in the parent fuel and are attributed to other sources. Similar to carbon monoxide (CO), hydrocarbons are also a product of incomplete combustion of fuel (Nett Technologies, undated).

Listed below are three principle mechanisms responsible for the existence of hydrocarbons in the exhaust of the spark ignition engines (Heywood, 1988):

i. Flame quenching at the combustion chamber walls, leaving a layer of unburned fuel mixture adjacent to the wall.

ii. The filling of crevice volumes with unburned mixture which, since the flame quenches at the crevice entrance, escapes the primary combustion process.

iii. Absorption of fuel vapor into oil layers on the cylinder wall during intake and compression strokes, followed by desorption of fuel vapor into the cylinder during expansion and exhaust strokes.

Hydrocarbons from LPG emission contain only short chain hydrocarbons and are not likely to consist of toxic components which can be found in gasoline hydrocarbons emissions. However, LPG hydrocarbons emissions often causes nuisance when LPG engines operate indoors (Nett Technologies, undated).

CHAPTER 3

ENGINE

3.1 Two-stroke Engine

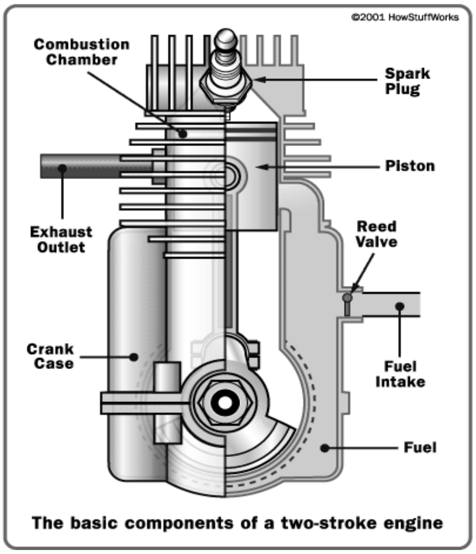

Figure 3.1: Basic components of a two-stroke engine (HowStuffWorks Inc., 2005)

As the name implies, two-stroke engines need only two piston strokes to complete a cycle. The principle of operation of a two-stroke engine is as follows:

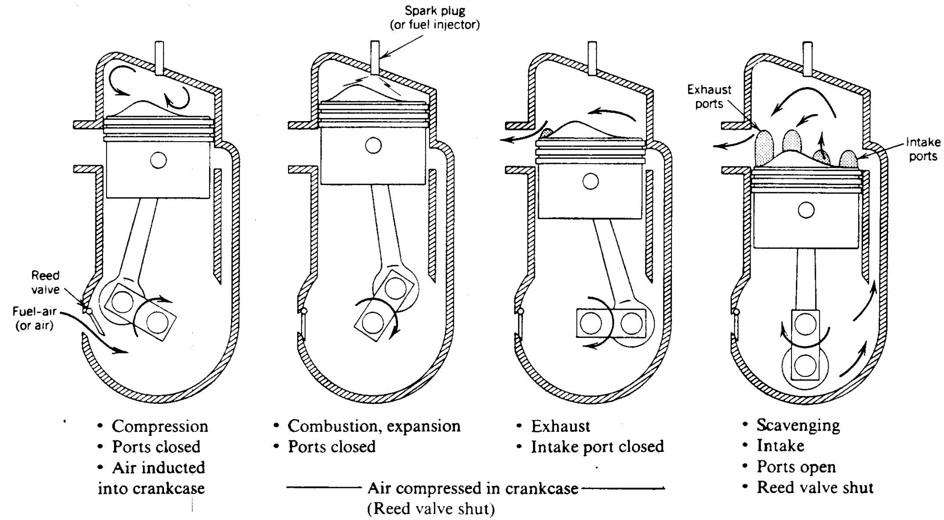

Figure 3.2: Cross-scavenged two-stroke engine (Colin, 1986)

According to Matt (2000), the fuel/air mixture is first allowed to enter the crankcase by sub-atmospheric pressure created during the downward stroke of piston. The piston is shaped so that the incoming fuel mixture will not go straight into the cylinder and out of the exhaust port. The reed valve is forced closed by the increasing crankcase pressure once the piston reverses direction so that the fuel mixture is compressed. As the piston travels further, the piston uncovers the intake port, permitting the compressed fuel mixture to escape around the piston into the main cylinder, and exhaust gases begin to leave through the exhaust port. The process of pushing out of the remaining exhaust and filling the cylinder with the incoming air is called scavenging. During compression, the momentum in the crankshaft drives the piston to rise and compresses the fuel mixture. The spark plug ignites the fuel mixture and the expansion of the burning fuel drives the piston downwards to complete a cycle.

3.1.1 Advantages of Two-stroke Engine

Two-stroke engines have three significant advantages over four-stroke engines as listed below:

i. Construction of two-stroke engines is simplified since they do not contain valves, thus reducing cost and possessing a higher power per unit weight (HowStuffWorks Inc., 2005).

ii. Two-stroke engines have significant power boost per weight and per volume compared to four-stroke engines because two-stroke engines has a power stroke twice as frequent as the four-stroke engine of the same cylinder displacement (HowStuffWorks Inc., 2005).

iii. Devices such as camshaft and mechanical timing devices which are required in a four-stroke engine are not needed in a two-stroke engine due to the high power density (HowStuffWorks Inc., 2005).

3.1.2 Disadvantages of Two-stroke Engine

However, two-stroke engines are used where efficiency is not of primary concern due to the limitations described below:

i. Generally, the parts of two-stroke engines wear at a much faster rate due to the lack of proper lubrication system, and thus two-stroke engines normally have lower durability than four-stroke engines (HowStuffWorks Inc., 2005).

ii. Two-stroke engine has the problem of “short-circuiting” which produces blue smoke characteristic of unburned hydrocarbons and thus reduces fuel economy. Short-circuiting permits as much as 20-40% of the air/fuel to flow directly out of the cylinder when the intake and exhaust valves are opened at some point during the two-stroke cycle (U.S. Army Corps of Engineers, undated).

iii. Two-stroke engines produce pollution problems since badly worn two-stroke engines emit huge amounts of oily smoke to the environment (HowStuffWorks Inc., 2005).

3.2 Four-stroke Engine

As the name implies, there are four piston movements in a four-stroke engine before the entire engine firing sequence is repeated. The four-strokes of the cycle are the intake, compression, power and exhaust. Note that spark plug in the four-stroke engine only fires once every other revolution and this produces less power compared to the two-stroke engine.

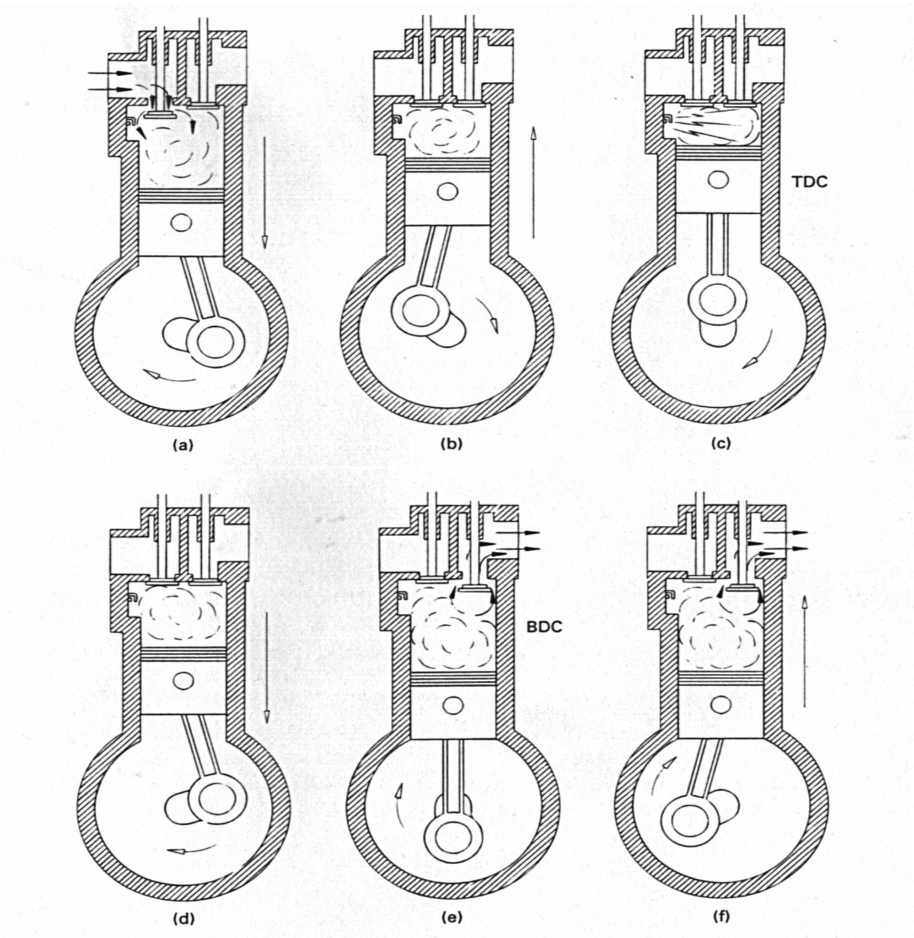

Figure 3.3: The movement of four-stroke engine, from (a) intake stroke to (b) compression stroke (c) ignition and combustion (d) power stroke (e) exhaust valve opens (f) exhaust stroke (Pulkrabek, 1997)

The engine cycle begins with the intake stroke where the piston moves downward from TDC (top dead center) to BDC (bottom dead center), allowing a fresh charge of air/fuel mixture to be drawn pass the intake valve and into the combustion chamber. The intake valve closes when the combustion chamber is full with the low pressured fuel and air mixture. During the compression stroke, the piston is pushed back up, reducing the volume and compressing the air/fuel mixture. As the air/fuel mixture is ignited during the power stroke, heat is released and transformed into combustion products such as water, carbon dioxide, carbon monoxide and other components. The combustion process increases the temperature and pressure in the combustion chamber. After the spark plug ignites the mixture in the power stroke, the piston is pushed downwards by the expanding gases. As the volume of the chamber increases due of the piston's motion, the pressure and temperature of the gases are decreased. At the end of the power stroke, the pressure of gases approaches atmospheric pressure. The exhaust stroke starts when the exhaust valve is opened by the cam or lifter mechanism and pushes out the residual gases. The exhaust valve closes at the end of the exhaust stroke and the engine begins another cycle. The exhaust stroke completes the combustion process and fuel is converted into forward motion with each motion of the piston as it rises and falls to turn the crankshaft that is responsible for turning the wheels (U.S. Army Corps of Engineers, undated).

3.3 Engine Performance

Engine performance is another major concern in this research project alongside the main aim of analyzing the reduction in the emission of nitrogen oxides using liquefied petroleum gas in spark ignition engine. Some indicators of engine performance such as input power, brake power, specific fuel consumption and engine efficiency are calculated to compare the engine performance between gasoline and LPG.

3.3.1 Input Power

The input power of an engine refers to the maximum energy that can be put into the engine, and is given by:

$$IP = Q_{HV} \times \dot{m}_f \qquad (3.1)$$

Where IP = Input power (kW)

Q_{HV} = Lower calorific value of fuel (MJ/kg)

$\dot{m}_f$ = Mass flow rate of fuel (kg/s)

$Q_{HV_{Gasoline}}$ = 42.1 MJ/kg

$Q_{HV_{LPG}}$ = 46.37 MJ/kg

3.3.2 Brake Power

Brake power refers to the power delivered by the engine. During internal combustion, chemical energy from the fuel is converted to generate heat to do work. However, the heat generated cannot be fully converted to work, and some of that are lost to the exhaust flow and to the surroundings by heat transfer. Indicated power (IP), which is used to push the piston to do the work, is used to subtract the friction power to obtain the brake power of an engine. Greater power can be generated by increasing displacement and speed. Brake power is given by:

$$\mathrm{BP} = \mathrm{IP} - \mathrm{FP} \tag{3.2}$$

$$BP = \frac{2\pi N\tau}{60\times 10^{3}} \tag{3.3}$$

where BP = Brake power (kW)

π = 3.142

N = Engine speed (rpm)

τ = Torque (N.m)

Torque is usually used as a measure of an engine's ability to do useful work, and it has the unit of Nm or lbf-ft. Apart from that, torque also refers to the measure of the work done per unit rotation (radians) of crank. The magnitude of the torque acting on a body is equal to the product of the force acting on the body and the distance from its point of application to the axis around which the body is free to rotate. It should be noted that only the force component that lies on the rotation plane and perpendicular to the radius from the axis of rotation to the point of application contributes to the value of torque (Answers.com). Torque is given by:

$$\tau = \frac{60P}{2\pi N} \tag{3.4}$$

Where τ = Torque (Nm)

P = Power developed by engine (W)

π = 3.142

N = Engine speed (rpm)

In this research project, the brake power generated is converted to electrical power (EP), which is used to supply electricity to light the electric bulbs. Therefore, the brake power is measured as follows:

$$BP = EP = V \times I \tag{3.5}$$

where BP = Brake power (kW)

EP = Electric power (kW)

V = Voltage (V)

I = Current (A)

3.3.3 Specific Fuel Consumption (sfc)

Specific fuel consumption measures the amount of fuel needed to provide a given power to an engine for a given period. It is an important parameter to compare gasoline and LPG in terms of economic aspect. Sfc is largely dependent on engine design, for example, a typical gasoline engine has a sfc of about 0.3 kg/kWh. However, sfc is inversely related with engine efficiency – a lower value of sfc shows better engine performance. The sfc is defined as:

$$sfc = \frac{\dot{m}_f}{P} \tag{3.6}$$

where sfc = Specific fuel consumption (kg/kWh)

$\dot{m}_f$ = Mass flow rate of fuel (kg/h)

P = Power output (kW)

and

Brake specific fuel consumption (bsfc) is given by:

$$bsfc = \frac{\dot{m}_f}{BP} \tag{3.7}$$

where bsfc = Brake specific fuel consumption (kg/kWh)

$\dot{m}_f$ = Mass flow rate of fuel (kg/h)

BP = Brake power (kW)

There are several factors which affect the value of bsfc. For instance, higher compression ratio delivers a greater bsfc as it extracts more power from the fuel. On the other hand, the value of bsfc will decrease if the combustion occurs with a fuel with equivalence ratio near to unity (Ø = 1). Bsfc will be of greater value at high speed as the friction losses are increased.

3.3.4 Engine Efficiency

Engine efficiency is defined as the ratio of the effective or useful output to the total input in an engine. It also accounts for the fraction of fuel that burns during combustion. For any engine:

$$\text{Power generated} = W_{shaft} + W_{acc} + Q_{exhaust} + Q_{loss} \tag{3.8}$$

where W_{shaft} = Brake output power of the crankshaft

W_{acc} = Power to run engine accessories

$Q_{exhaust}$ = Energy lost in the exhaust flow

Q_{loss} = Other energy lost to the surroundings by Heat transfer

For one engine cycle in a single cylinder, the fuel conversion efficiency η_f is given by:

$$\eta_f = \frac{W_c}{m_f Q_{\mathrm{HV}}} = \frac{P}{\dot{m}_f Q_{HV}} \tag{3.9}$$

and it can be presented the form of:

$$\eta_f = \frac{3.6}{(sfc)Q_{HV}} \tag{3.10}$$

Where η_f = Engine efficiency

P = Output power produced per cycle (kW)

$\dot{m}_f$ = Mass flow rate of fuel per cycle (kg/s)

Q_{HV} = Lower calorific value of fuel (MJ/kg)

sfc = Specific fuel consumption (kg/kWh)

CHAPTER 4

EXPERIMENTAL SETUP

4.1 Introduction

The main objective of the experiment is to investigate the effects of replacing gasoline with liquefied petroleum gas (LPG) and to prove the reduction of nitrogen oxides in a spark ignition engine. All the experimental setups were provided by UNITEN. A Yamaha ET950 engine and Honda GX160 were employed as the test engine in the analysis. Some modifications of the engine are made so that it is possible to switch between LPG and gasoline as the burning fuel and to ease the experiment process. For instance, a mixer is introduced in the generator set so that it is compatible to both LPG and gasoline fuel. The mixer allows air and LPG to mix together to obtain the correct ratio before entering the combustion chamber. It is a cross flow type mixer which is connected to the LPG steel tank via a flexible hose. Besides that, due to fact that LPG has lower velocity flame and hence burns slower compared to gasoline, the spark timing was advanced by shortening the gap between the electrode and insulator nose. According to Toyota Inc. (2005), spark advance control timing gives the maximum engine efficiency by continuously adjusting the spark timings to deliver peak combustion pressure. However by doing so, it results in an increase in the emission of NO_x.

An electrical power load circuit was attached to the test engine to allow variation of the engine power using the bulb switches. Combinations of different values of engine loads were used in the experiment to evaluate the performance and pollutant emissions of the engine to compare between gasoline and LPG fuels.

4.2 Engine Specifications

The compression ratio of LPG and gasoline are almost the same - 10.7:1 and 11:1 to 15:1 for LPG and gasoline fuel systems respectively. Therefore, very little modifications are required on the original gasoline engine. Tables 4.1 and 4.2 show the specifications of the two-stroke engine and four-stroke engine used in the experiment respectively.

Model	Yamaha ET950 Two-stroke Gasoline Engine
Rated Voltage	240 V
Frequency	50 Hz
Rated output	0.65 kVA
Maximum output	0.78 kVA
DC output	None
Cooling system	Forced air cooled
Displacement	63.1 cc
Maximum engine power	2.0HP/3600RPM
Starting system	Recoil
Dimensions (LxWxH)	366x308x376 mm
Dry weight	20.2kg
Fuel tank capacity (full)	4.2 L
Operating hours	6.3 hrs
Bore x stroke	45 x 39.7 mm
Noise level	57 dBA

Table 4.1: Specifications of Yamaha ET950 two-stroke engine

Model	Honda GX160 K1 Four-stroke Gasoline Engine
Type	4-stroke, overhead valve single cylinder , inclined by 25°
Total Displacement	163 cm^3 (9.6 cu in)
Bore & Strike	68 x 65 mm (2.7 x 1.8 in)
Max Horsepower (Gross)	4.0 kw / 4,000 min^{-1}(5.5hp / 4,000rpm)
Compression Ratio	8.5: 1
Fuel Consumption	310 g/kWh (230 g/HPh, 0.51 lb/HPh)
Cooling System	Forced-air
Ignition System	Transistorized magneto ignition
Ignition Timing	25° B.T.D.C (fixed)
Spark Plug	BPR6ES (NGK), W20EPR-U (DENSO)
Carburetor	Horizontal type, butterfly valve
Lubricating System	Splash
Oil Capacity	0.6 lt (0.63 US qt, 0.53 Imp qt)
Starting System	Recoil or electric start
Stopping System	Ignition primary circuit ground
Fuel Used	Automotive unleaded gasoline (minimum 86 pump octane)
Fuel tank capacity	3.6 lt (0.95 US gal, 0.79 imp gal)

Table 4.2: Specifications of Honda GX160K1 four-stroke engine

4.3 Description of Experiment Equipments

The apparatus used in the experiment involve a load bank, digital power meter, pressure sensor, crank angle encoder, flow meter, venture air meter, gas analyzer, digital thermocouple and data acquisition system.

4.3.1 Control Panel

A control panel as shown in Figure 4.1 acts as a digital readout system which consists of the following components:

i. Direct current ammeter
ii. Electric bulbs which act as load bank
iii. Digital flow meter
iv. Direct voltmeter

4.3.2 Load Bank

The load bank consists of 36 electrical bulbs which are arranged in rows and columns of six. Each bulb consumes 100W of power and is controlled by a switch. An electrical power load circuit is attached to the engine control panel to provide the engine with output loads used to power the electric bulbs. In this experiment, the output loads were set to be 0, 200, 400 and 600 Watts.

4.3.3 Digital Power Meter

The present test system is able to investigate the engine performance using different values of engine loads by switching the desired number of electric bulbs. The value of electric power, which was consumed by the electric bulbs, is measured by a digital power meter.

4.3.4 LPG Storage Cylinder

LPG is stored under pressure at 800 kPa in a steel tank. Due to the fact that LPG is highly volatile and flammable, it is stored in a high ventilation rate area and kept away from any sources of ignition in the experiment lab. Moreover, the LPG steel tank is equipped with pressure relief valves to prevent the release of LPG vapors to the atmosphere.

4.3.5 Pressure Regulator

The main function of the pressure regulator is to provide precise fuel pressure regulation to the air and fuel mixer (Hofmann, undated). It is used to reduce the high pressure in the LPG storage tank to a level close to the atmospheric pressure and hence ensure the safe transforming of liquid state of LPG to the vapor state. The pressure regulator will allow higher flow of LPG when the demand on the regulator increases with the engine load, and vice-versa.

4.3.6 Pressure Sensor and Crank Angle Encoder

Engine pressure sensor and crank angle encoder are used to evaluate the indicated power of the engine.

4.3.7 Flow Meter and Venturi Air Meter

LPG flow meter and venturi air meter are operated to measure the specific fuel consumption and the air to fuel ratio. The data collected are then displayed on a Pressure versus Volume diagram, specific fuel consumption versus load diagram and equivalent air-fuel ratio versus load diagram using data acquisition system.

4.3.8 Digital Thermocouple

A digital thermocouple is used to measure the body temperature and the exhaust temperature of the engine accurately during the experiment when running the engine using LPG and gasoline.

4.3.9 Gas Analyzer

For the purpose of data collection of pollutant emissions from the engine using both LPG and gasoline, a commercial portable exhaust gas analyzer (AutoLogic, undated) was employed to measure the content of exhaust gas emissions such as NO_x, CO_2, CO and HC at different loads in a closed environment. AutoLogic gas analyzer is a user friendly device which does not require extensive computer knowledge. Apart from that, the analyzer also provides the measurements of Lambda and Air to Fuel ratio.

The gas analyzer has a protective design which is mounted in a durable high strength aluminum case that keeps all the connections safe from any accidental shocks. The gas analyzer also features automatic water removal to remove any water from the exhaust of the engine. Water is removed continuously as the system is operated to eliminate frequent purging. Besides that, the gas analyzer also has zero air port which helps to measure pollutant emissions accurately. Figure 4.2 shows the automatic filtering and water removing device that contains in the gas analyzer.

Figure 4.1: AutoLogic gas analyzer

Figure 4.2: Automatic filtering and water removing

4.3.10 Air Fuel Mixer and Air Filter

The air fuel mixer was used to ensure the mixing of LPG and air at the precise air to fuel control ratio for combustion while the air filter was used to deliver high airflow and dirt protection to the engine.

4.3.11 Data Acquisition System

The engine test bed is attached to a desktop computer for reception and collection of data using a software program called IMC Look 3.2. The software program is useful to evaluate the performance of the test bed engine as it records useful data such as air flow, engine speed, pressure, volume, and crank angle.

4.4 Experiment Procedures

The analysis was first performed on the gasoline fuel system and then switched to LPG. A control valve was used to change the operation from gasoline to LPG fuel system. The engine was warmed up for around five minutes to reach a steady condition using the original gasoline fuel from the fuel tank of the engine. As the engine was ready to run, the throttle of the engine was adjusted to be in a fully open position to allow more gasoline fuel be supplied into the test engine, thus ensuring the maximum speed. The engine running at maximum speed had been selected as the reference point to compare the performance between gasoline and LPG.

Next, loads were applied to the system by operating the electric bulbs. Different light arrangements were made to investigate various loading conditions. In this experiment, the loads were fixed at 0, 200, 400, and 600 Watts for two-stroke engine as the main application of two-stroke engine are for small personal use and usually loads for 200 to 400 Watts are connected to them while the loads varied from 0 to 1000 Watts for four-stroke engine so that a more extensive coverage of experimental condition can be analyzed. All the data collected which included the engine speed, body temperature, exhaust temperature, voltage, current and concentration of emissions were recorded when steady-state is reached for each set of load values.

After that, the test was performed on the LPG fuel system. Before LPG was allowed to flow into the combustion chamber, the remaining gasoline in the carburetor had to be drained. The LPG tank used was a standard commercial LPG cylinder weighing 14kg. LPG was supplied to the engine through the regulator valve and the engine was allowed to run until it achieves steady state. Then, different sets of load were added to the system to evaluate the engine performance. Again, the data were recorded at steady-state for each set of load values. Throughout the experiment, the throttle of the engine, which controls the value of the required engine speed, was set to maximum to obtain the highest engine speed. All the collected data are then analyzed for comparative performance between gasoline and LPG fuel system. Both two-stroke and four-stroke engine followed the same experimental procedures except pressure sensor and crank encoder were not in used when running the four-stroke engine since the sensors were not available. Therefore, there was no graph showing pressure versus theta for four-stroke engine under the section of discussions and results. Figure 4.3 shows the schematic diagram of the experimental set up used for both two-stroke and four-stroke engine.

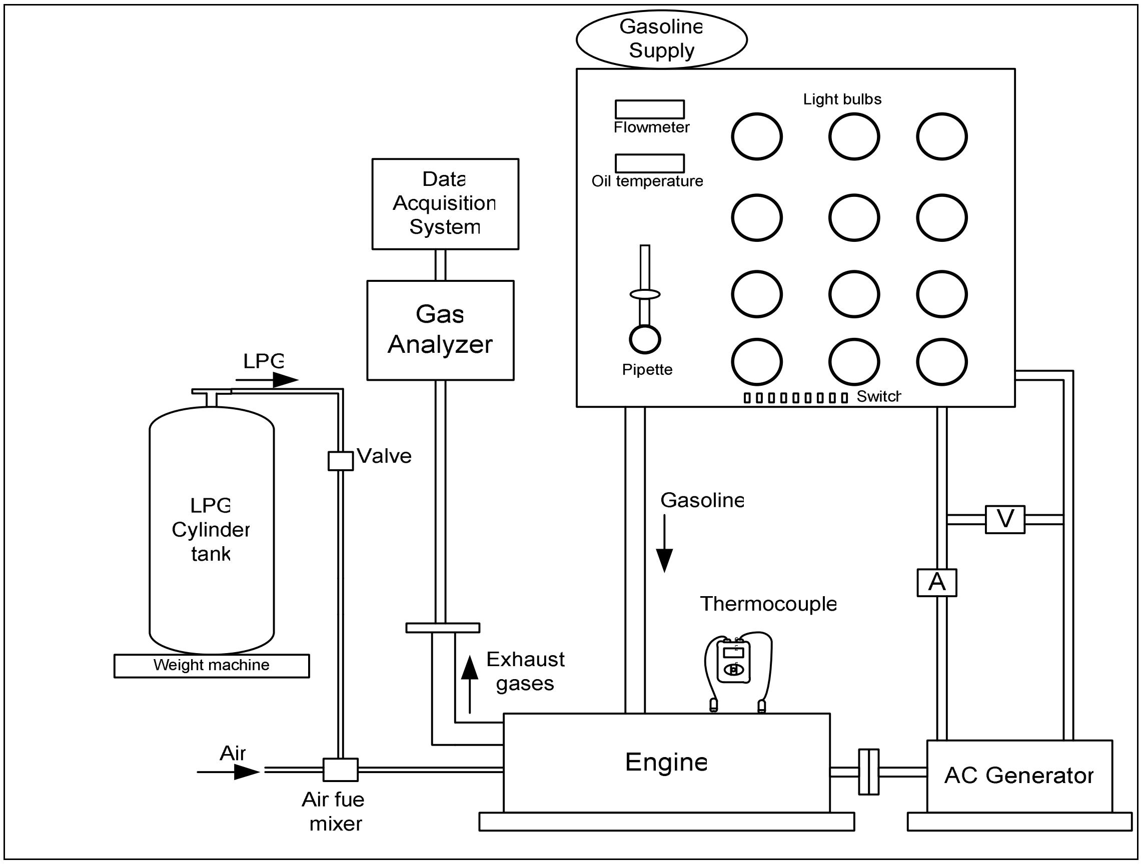

Figure 4.3: Schematic diagram of the experimental set up in UNITEN

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Analysis

Results obtained from experimental investigations for both two-stroke and four-stroke engine using gasoline and LPG fuel system were inserted into Excel spreadsheets. Equations regarding the engine performance were derived and entered into the respective spreadsheets in order to obtain the statistical differences between gasoline and LPG system to analyze the emission and engine efficiency. Most of the discussions emphasize on the comparison of emissions and engine performance between gasoline and LPG fuel system at normal load and maximum load. The journal published by Talal et al. (2004) also produced similar results which showed that the data collected are accurate. The data shown in the journal mentioned above are also used to compare to the data collected for this research project.

5.2 Emissions of Two-stroke Engine

The data of emission gases such as NO_x, CO_2, CO, O_2 and HC were analyzed by the AutoLogic Gas Analyzer. These pollutant emissions were compared for both the gasoline and LPG fuel system. The content of NO_x and HC are measured in parts per million (ppm) while the emission of CO_2, CO and O_2 are in terms of percentage (%). The results obtained from the experiments were comparable with the journal entitled

“LPG is the Best Solution for Improvement of Air Quality in Malaysian Night Market (Pasar Malam)” published by Yusaf, T. et al. during the International Mechanical Engineering Conference And Expo 2004 which was held in Kuwait on 5th to 8th December 2004.

5.2.1 Emission of Nitrogen Oxides (NO_x)

Figure 5.1 shows the emission of NO_x at variable loads for gasoline and LPG fuel system. The graph shows that NO_x emission generated by the LPG fuel system was lower compared to the gasoline system. However, it was found that the level of NO_x emission for LPG fuel at a high load of 600 Watts is closer to the value of emission for gasoline fuel. This is due to the higher air utilization for higher load operations and higher combustion temperature. As more loads are applied on the test bed, a higher amount of fuel is required to generate extra power to supply electricity to the lamp bulbs, and hence leads to higher combustion temperature. The NO_x emission for both the fuel system is low at lower load operations of 200 and 400 Watts.

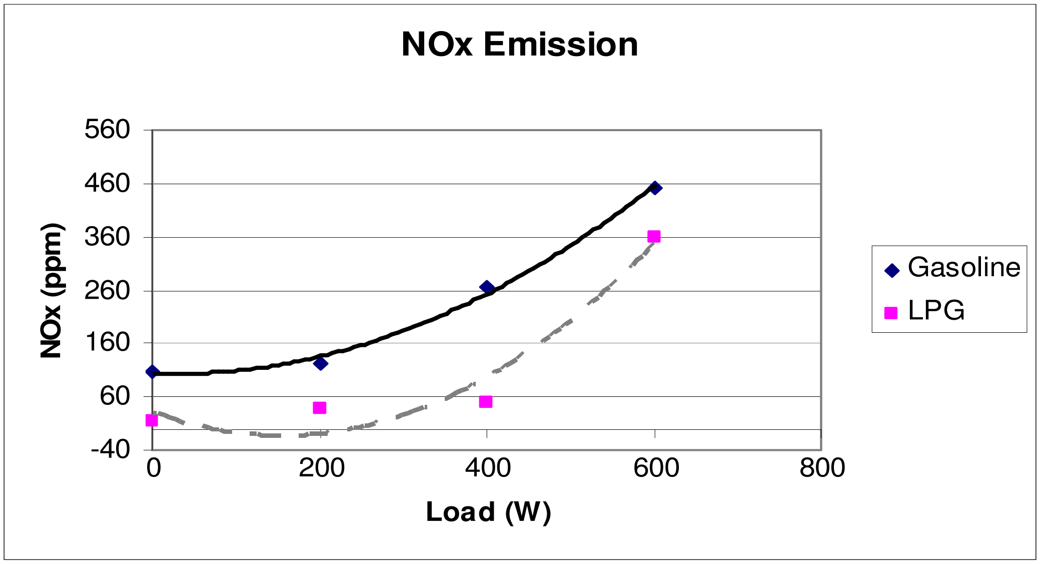

Figure 5.1: Emissions of NOx at variable loads

LPG fuel system demonstrated a good reduction of NO_x with approximately 85% and 20% reduction at 0 and 600 Watts operating conditions respectively. This NO_x emission results also comparable with the results by Talal et al. (2004), where the concentration of NO_x emission is always higher for gasoline fuel system. Air-fuel ratio is one of the factors which affect the formation of NO_x. Therefore the concentration of NOx emission is directly proportional to the value of lambda (λ) which is a measure of air to fuel ratio in the combustion chamber. When the value of lambda is greater than 1, the quality of combustion occurs in lean mode, which results in excess oxygen being supplied to the combustion process. The main drawback of lean burning is the large amount of NO_x generated at higher combustion temperatures. Figure 5.2 shows the lambda values of both gasoline and LPG fuel system. The lambda values of gasoline were much higher than the LPG fuel system as can be seen from Figure 5.2 and this correlates to the emission results of NOx of two-stroke engine for both gasoline and LPG fuel in Figure 5.1.

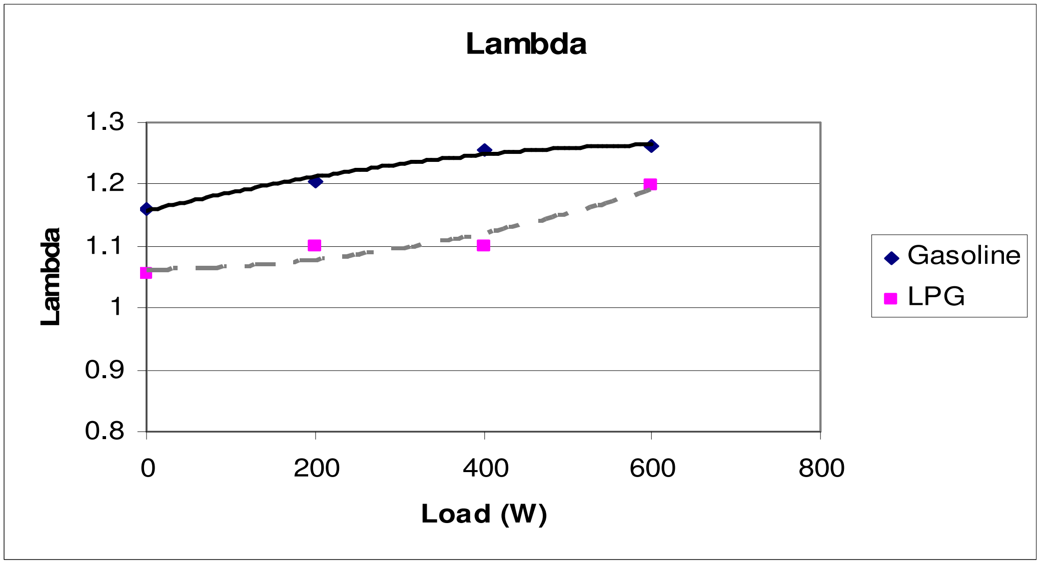

Figure 5.2: Lambda values for gasoline and LPG fuel in two-stroke engine

5.2.2 Emission of Carbon Dioxide (CO_2)

CO_2 is one of the pollutant products produced by the internal combustion engine. It can be seen from Figure 5.3 that the content of CO_2 was much higher in the gasoline system compared to the LPG fuel system. As the load increases, the emission of CO_2 also increases as more fuel is consumed by the engine. The reason for LPG fuel system having lower level of CO_2 emission is due to its less carbon composition compared to gasoline since emissions of CO_2 is directly related to the quality of combustion. LPG fuel operation shows a reduction in the content of CO_2 at an average percentage of 64.1%, demonstrating a good combustion quality in the LPG fuel system.

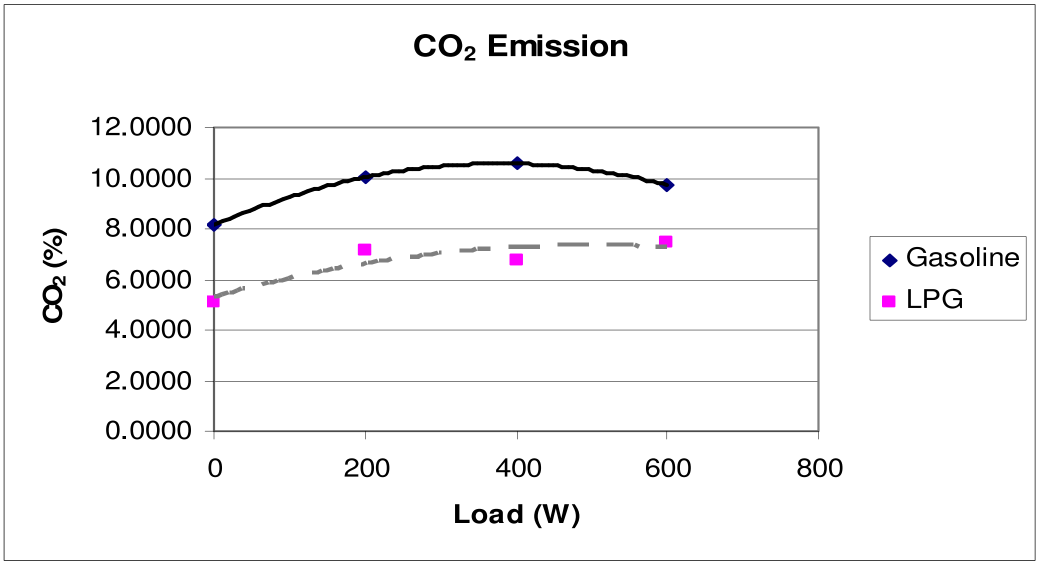

Figure 5.3: Emissions of CO_2 at variable loads

5.2.3 Emission of Carbon Monoxide (CO)

CO is formed by the incomplete combustion of carbon. When there is insufficient air for combustion, the carbon particles in fuel will be converted to CO as the fuel is lacking of air to burn completely. Figure 5.4 shows the emissions of CO for both gasoline and LPG fuel system, and it is clearly shown that the content of CO for gasoline is much higher. The reduction of CO for LPG fuel system ranges from a minimum of 48.7% at 600 Watts to a maximum of 67.4% at 400 Watts in comparison with the conventional gasoline system. The high emission of CO in the gasoline exhaust may be caused by improper operation of the fuel delivery system. The overall result from Figure 5.4 shows that the LPG fuel system has a good indication of combustion quality and LPG fuel is burned completely with the correct chamber temperature and sufficient amount of air. Emissions of CO and O_2 are inversely related since complete combustion produces less CO pollutants and high O_2 emission due to increased air intake for proper combustion. This is in agreement with the result of O_2 emission obtained from Figure 5.5.

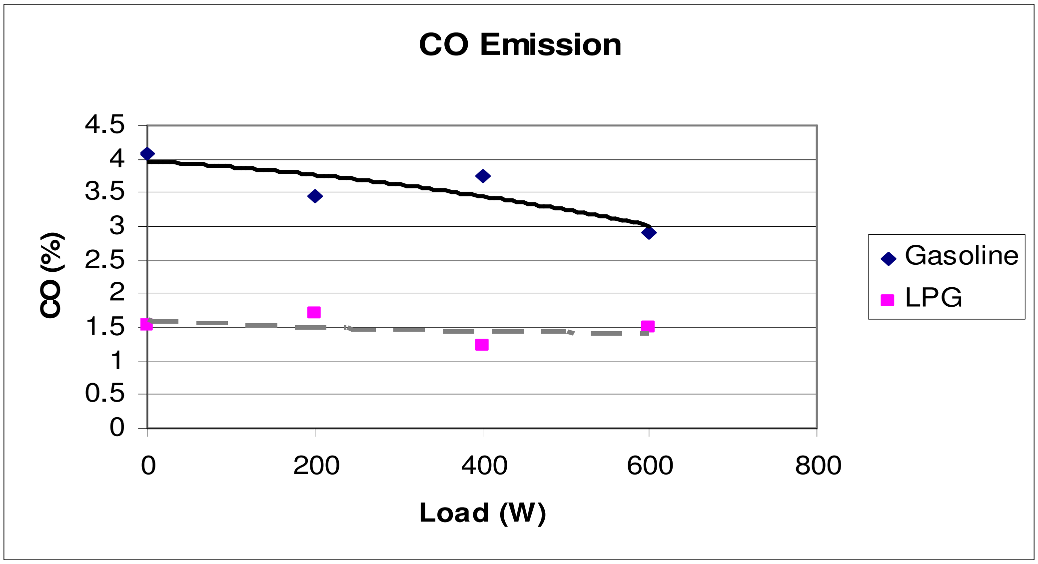

Figure 5.4: Emissions of CO at variable loads

5.2.4 Emission of Oxygen (O_2)

The result of O_2 emission at variable loads is featured in Figure 5.5. The percentage of oxygen from the exhaust of LPG fuel system was higher than gasoline system. For an ideal combustion, the emission of O_2 from the exhaust should be near to zero as all the oxygen is used up during combustion in the engine. As shown in Figure 5.5, LPG fuel system had more excess oxygen in the exhaust which means that The LPG system operates with a leaner combustion compared to gasoline fuel. Although the availability of air, and thus oxygen, is high in the combustion chamber coupled with higher exhaust temperatures in the LPG system, the NO_x level is still low. This may be due to the low residence time of LPG fuel inside the chamber to produce NO and NO_2 particles when the engine is running with a high speed in the range of 3300 rpm. LPG fuel system produced an average of 26.3% more O_2 emission in the exhaust compared to gasoline system. At the load of 200 Watts, the content of O_2 in the gasoline system is approximately 5.6%, showing the lowest emission of O_2 recorded. This reason may be due to the quality of the combustion which was close to stoichiometric. As the loads reach a maximum value, the level of excess O_2 increased as more fuel was supplied to the engine, leading to improper mixing for combustion for both the LPG and gasoline fuel system.

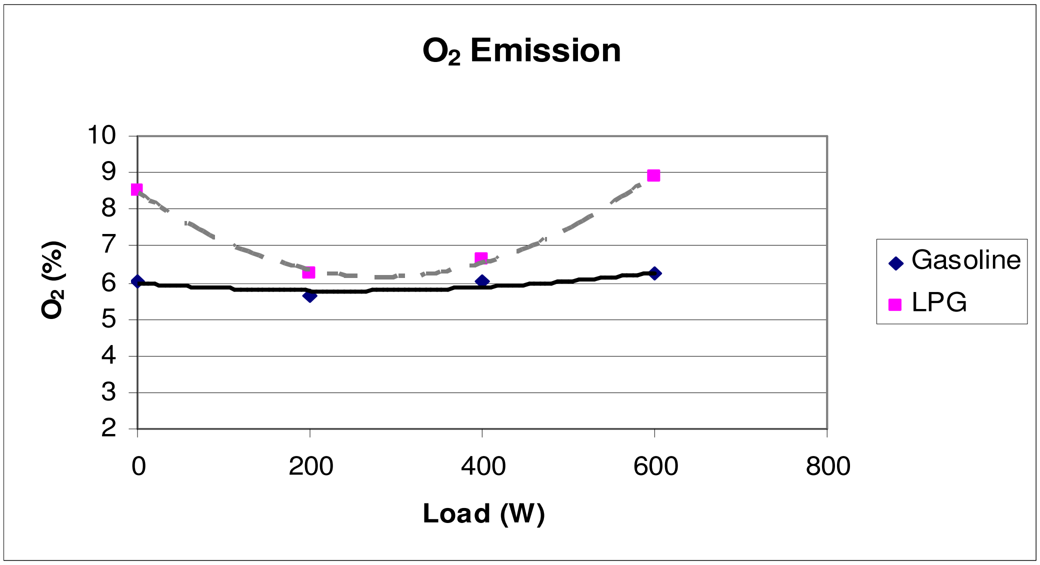

Figure 5.5: Emissions of O_2 at variable loads

5.2.5 Emission of Hydrocarbon (HC)

Figure 5.6 shows the hydrocarbon emissions for both gasoline and LPG fuel system. It is clearly indicated that the HC emission of LPG was much higher than the gasoline system. It was found that LPG fuel system produces HC emission with an average of 81% higher than the gasoline system. High HC emission normally denotes excessive unburned fuel caused by a lack of ignition or by incomplete combustion. As shown in Figure 5.2, the lambda values of LPG fuel system was lower than the gasoline system and this shows that there are insufficient air to produce a proper combustion for LPG fuel system. LPG gas which enters the combustion chamber in gaseous form may be forced out of the exhaust during the engine scavenging process to force exhaust air out so that fresh air can replace them. Some of the unburnt propane may be flushed into the exhaust and causes the HC emission level of LPG system to be high. Besides that, another reason for the high HC emission of LPG fuel system might be due to improper timing or dwelling in the combustion chamber.

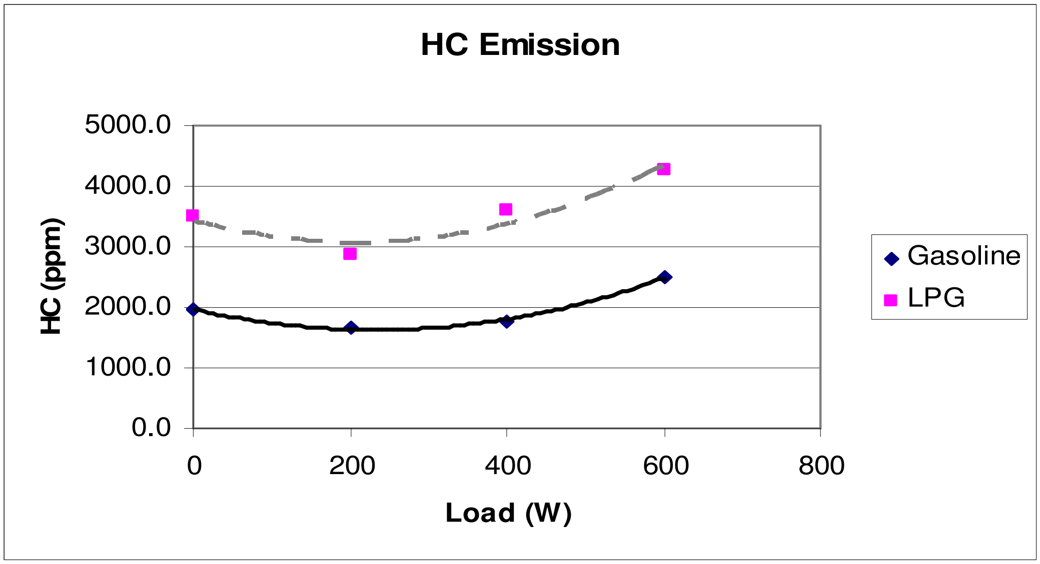

Figure 5.6: Emissions of HC at variable loads

5.3 Engine Performance of Two-stroke Engine

Besides comparing the pollutant emissions of the exhaust for gasoline and LPG fuel systems, engine performance criteria are also important parameters to determine whether LPG is suitable as the alternative fuel to replace the role of conventional fuel in spark ignition engines. The discussions are based on brake specific fuel consumption (bsfc), indicated work and efficiency of the engine.

5.3.1 Brake Specific Fuel Consumption (bsfc)

Figure 5.7 shows the variation of brake specific fuel consumption as the load varies for both fuel systems. The results indicated that the fuel consumption rate of gasoline was lower than LPG fuel system. LPG fuel system showed a higher bsfc because LPG has higher mass flow rate compared to gasoline. The bsfc rates were very high at the lower load of 200 Watts for both systems, which were 2.10 kg/kW.h for LPG fuel system and 1.55 kg/kW.h for gasoline system respectively.

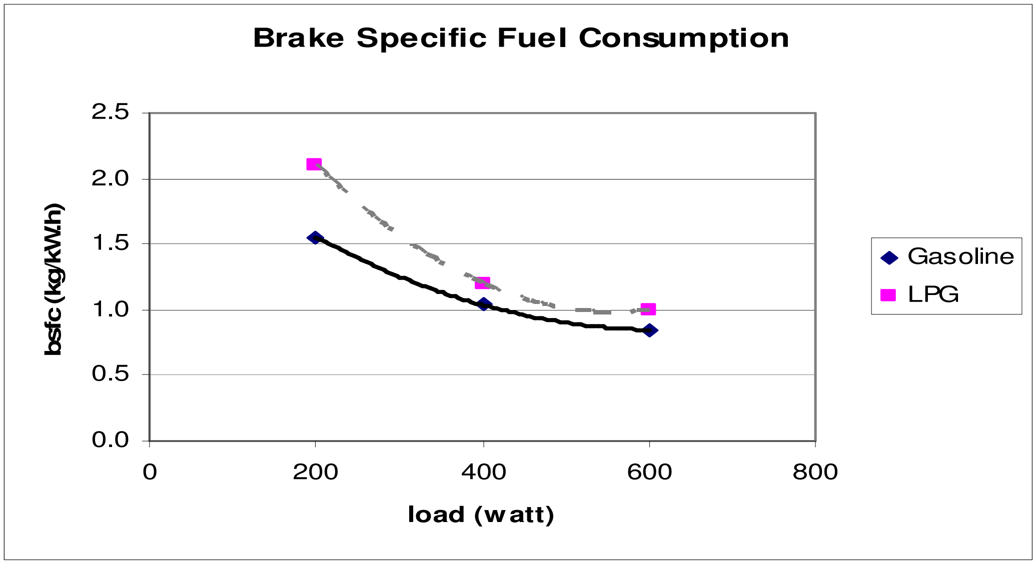

Figure 5.7: Brake specific fuel consumption on variable loads

However the bsfc rates for both systems decreased gradually at higher loads. It can be observed that the bsfc for both systems decreased from 200 Watts and reached a minimum value at 400 Watts. Hence in order to achieve optimum fuel consumption rate in term of economic performance, it is best to operate the two-stroke engine at a load of 400 Watts. Although the bsfc of LPG fuel system is higher than gasoline, LPG fuel system is still the preferable choice of fuel as it reduces the emissions of pollutant gases and most importantly, the cost of LPG is lower than gasoline. Table 5.1 shows the consumer market prices of gasoline and LPG fuel. Gasoline fuel price in most part of Malaysia stands at RM 1.62 (equivalent AUD \$0.56) per litre while the price of LPG is calculated to be RM 0.73 (equivalent AUD \$0.25) per litre. Therefore, the minor differences in bsfc should not be used as the main indicator to evaluate the performance of the fuels as both gasoline and LPG have different heating values and most importantly, LPG fuel provides a significant 55% reduction in costs for consumers.

5.3.2 Indicated Work

The energy given up by the working fluid to the piston of a reciprocating engine is referred to as indicated work. The area under the pressure-crank angle curve represents the indicated work from the combustion chamber. Figures 5.8, 5.9, 5.10 and 5.11 feature the pressure distribution in the combustion chamber of the two-stroke engine running on variable loads. It can be observed that indicated work is still present at 0 Watt load conditions. This is due to the mechanical friction in the engine and work is required to overcome these frictional forces. From the figures shown below, the pressures for LPG fuel system were slightly higher than gasoline system, and thus the indicated work of both systems were comparable.

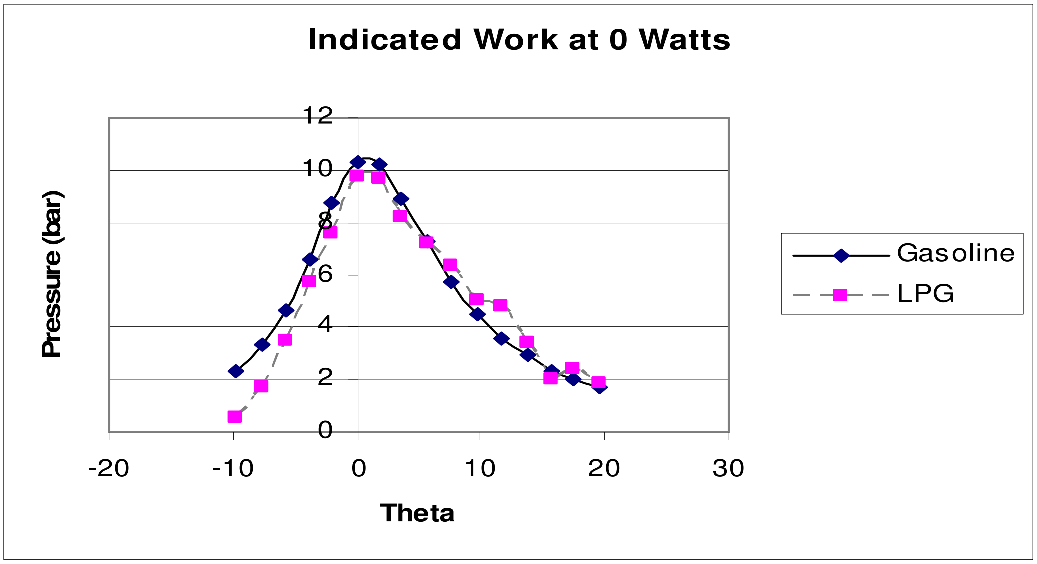

Figure 5.8: Indicated work for gasoline and LPG fuel system at 0 Watts

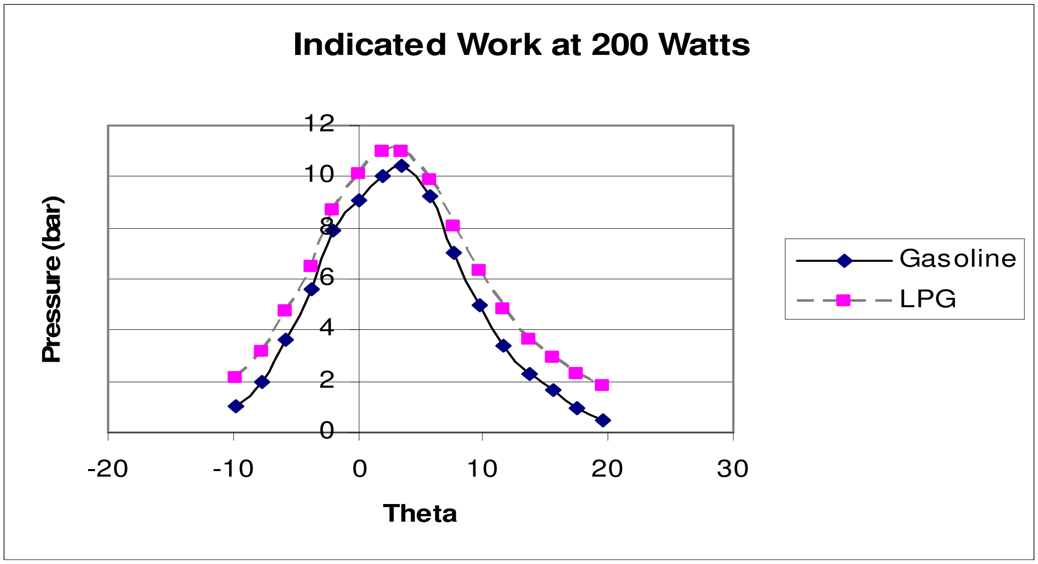

Figure 5.9: Indicated work for gasoline and LPG fuel system at 200 Watts

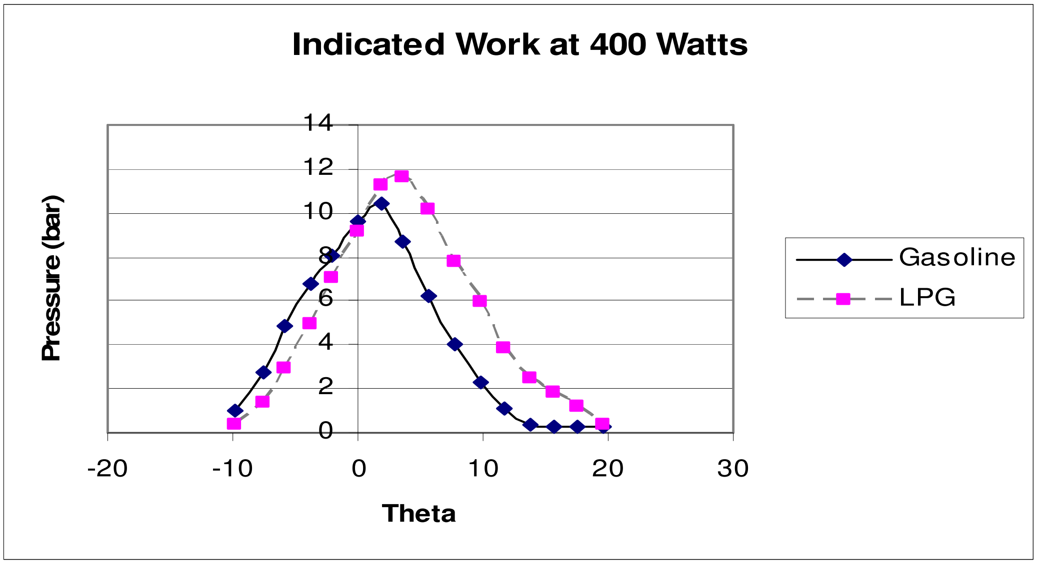

Figure 5.10: Indicated work for gasoline and LPG fuel system at 400 Watts

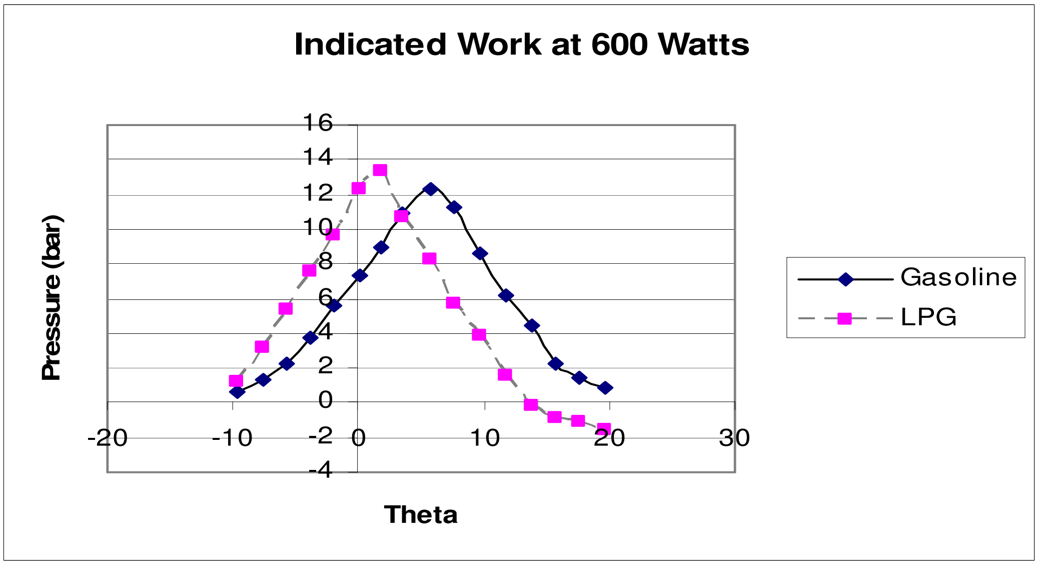

Figure 5.11: Indicated work for gasoline and LPG fuel system at 600 Watts

The higher heating value of LPG fuel is the main reason which contributes to higher values of indicated work for LPG fuel system especially when loads are applied to the engine. This also exhibits the greater amount of available energy for use in the engine for LPG system. From the figures, we can also see that the maximum pressure of gasoline stays nearly constant as the loads are increased, while the maximum pressure of LPG fuel system increases steadily as the loads are progressively added. This is due to the unavailability of fuel injection control in the LPG fuel system to control the desired amount of LPG to be injected into the cylinder before the combustion process starts. As a result, a large amount of LPG will be consumed once the combustion process begins and the pressure rise in the cylinder will be greater in comparison to the gasoline system. Hence, the pressure of LPG fuel system is directly proportional to the increase of loads.

5.3.3 Engine Efficiency

Figure 5.12 shows that the engine efficiency for two-stroke engine running on LPG fuel system is slightly lower than gasoline system. The engine efficiency increases slowly at higher load conditions. The lower efficiency of LPG fuel system is compensated by the savings in LPG fuel cost compared to the increasing gasoline price. The decrease in engine overall efficiency by an average of 2.0% in the LPG fuel system will not be apparent in many applications.

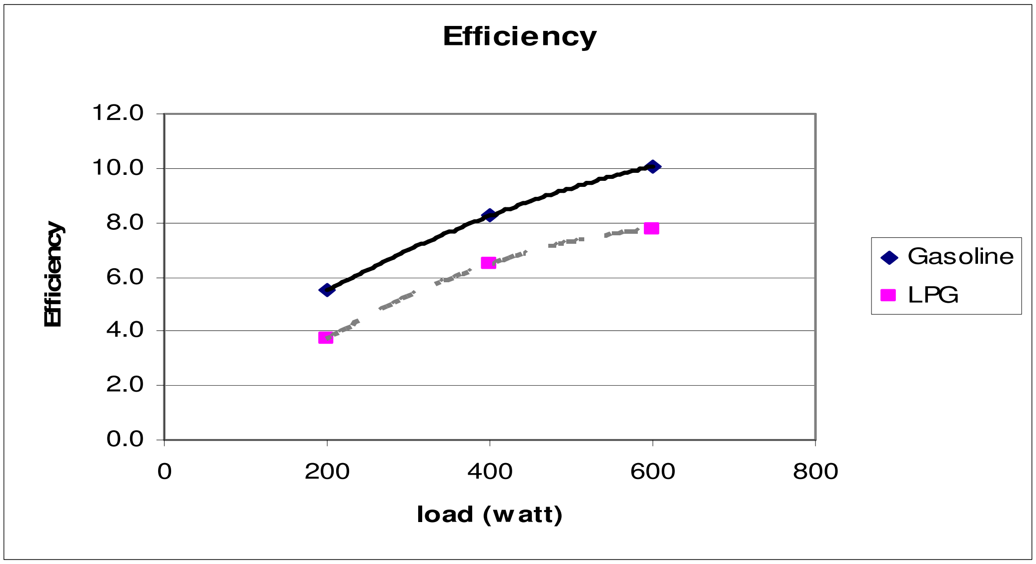

Figure 5.12: Comparison of engine efficiency of gasoline and LPG fuel system

5.4 Temperatures of Two-stroke Engine

Figure 5.13 and 5.14 shows the exhaust and engine body temperature for the two-stroke engine respectively. It can be observed that the exhaust and engine body temperature for the two-stroke engine increased gradually as loads were added for both fuel systems. This was due to reason that more fuel is needed for the engine as the loads are increased from 0 to 600 Watts, resulting in a higher steady-state temperature. As shown in Figure 5.13 and 5.14, both exhaust temperature and engine body temperature of LPG fuel system were higher compared to gasoline system. The reason for this may be due to the lack of lubrication oil in LPG system to ease the friction acting on the pistons, whereas conventional two stroke engine lubrication oil was used in the gasoline system to reduce the friction between pistons and cylinder and hence allowing a lower exhaust and engine body temperature. Apart from that, the higher recorded temperatures for LPG fuel system corresponds to the lower CO emission gas found in the exhaust as higher temperatures promote better combustion and lowers the rate of CO formation.

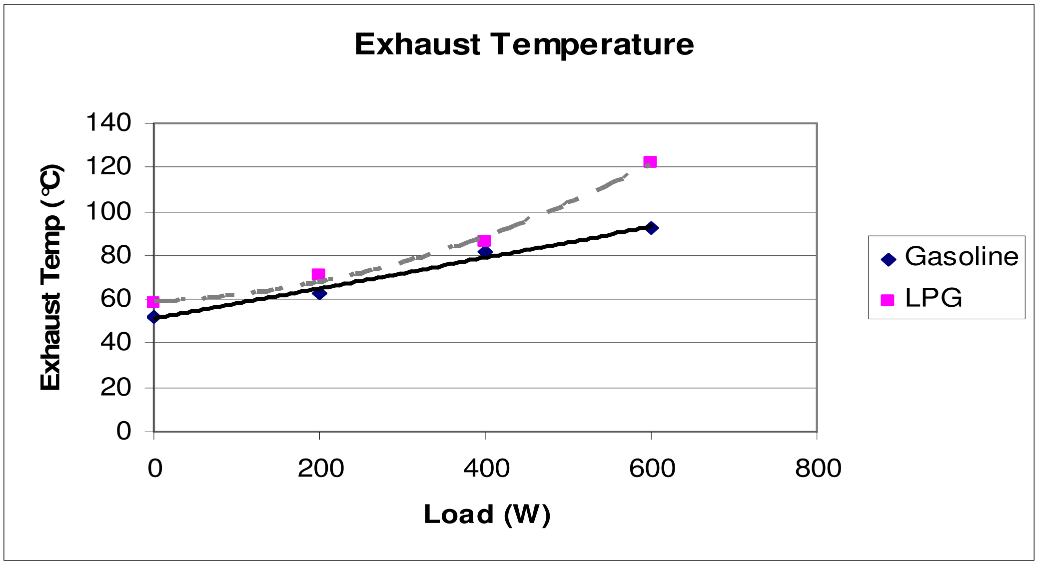

Figure 5.13: Exhaust temperature of two-stroke engine

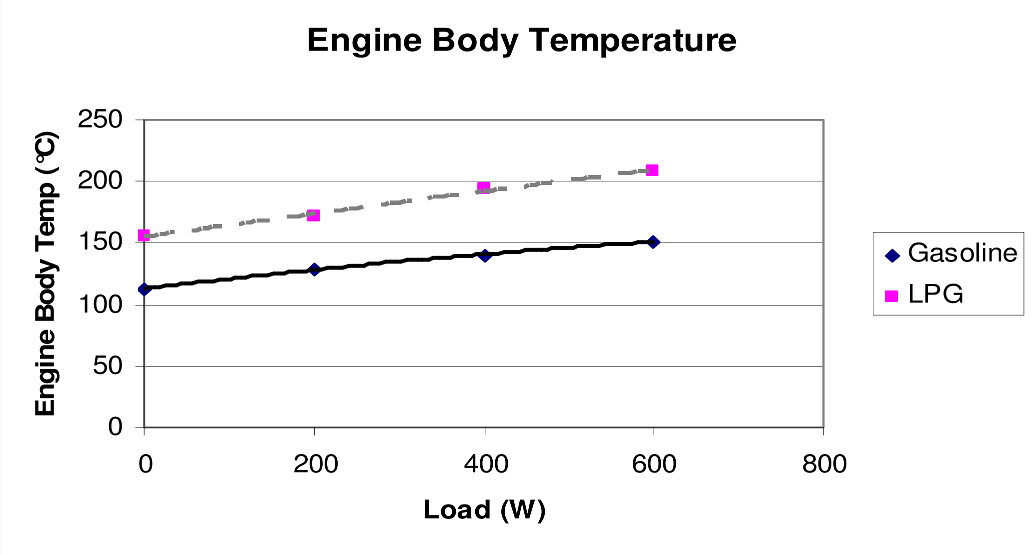

Figure 5.14: Body temperature of two-stroke engine

5.5 Emissions of Four-stroke Engine

The combustion products which contribute mostly to air pollution in the exhaust of the four-stroke engine consists of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) and oxides of nitrogen (NO_x). On the other hand, excess oxygen (O_2) from the exhaust is not a pollutant but the concentration of O_2 acts as an indicator of lean or rich mixture. These pollutant emissions were compared for both the gasoline and LPG fuel system. The content of NO_x and HC are measured in parts per million (ppm) while CO_2, CO and O_2 are in term of percentage (%), similar to the two-stroke engine.

5.5.1 Emission of Nitrogen Oxides (NO_x)

Figure 5.15 shows the emission of NO_x at variable loads for gasoline and LPG fuel system from the exhaust of the four-stroke engine. The graph shows that NOx emission generated by the gasoline system was higher compared to the LPG fuel system. The NO_x emissions for both the fuel system are low at low load operations from 0 to 200 Watts. LPG fuel system demonstrated a good reduction of NO_x as high as 93% at no load operating conditions. However, it was found

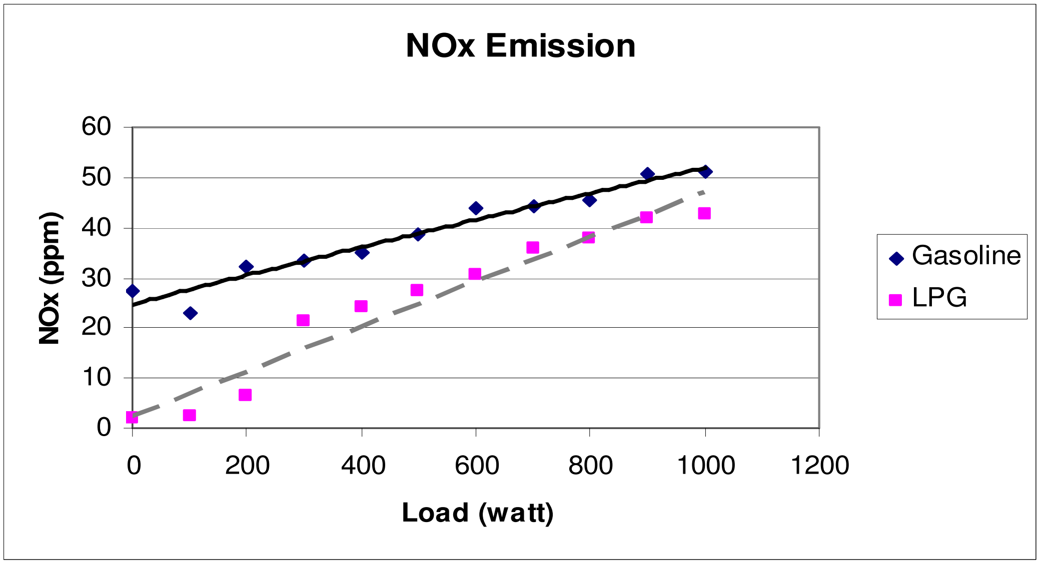

Figure 5.15: Emissions of NO_x at variable loads

that the level of NO_x emission for LPG fuel increases when loads are applied at a higher rate than gasoline fuel, but nevertheless still at a lower level. This is due to the higher air utilization for higher load operations and higher combustion temperature achieved. As more loads are applied on the test bed, more fuel is required to generate more power to supply electricity to the light bulbs, and this leads to higher combustion temperatures. The formation of NO_x is directly related to the air-fuel ratio. The combustion process occurs in lean combustion when the value of lambda is higher than 1. This indicates that excess oxygen was supplied to the combustion chamber and causes more NO_x to be generated and released through the exhaust. Figure 5.16 shows the lambda values for both gasoline and LPG fuel system. The lambda values for the LPG fuel system are much lower than the gasoline system as seen in Figure 5.16, and this corresponds to the result of emissions of NO_x for the four-stroke engine both gasoline and LPG fuel system in Figure 5.15. For LPG, the increasing air to fuel ratio as the load increases produces a leaner mixture and hence produces more NO_x. On the other hand, although lambda values decrease slightly as the load is increased for the gasoline system, the high combustion temperatures as can be shown from the measured engine body and exhaust temperature by a thermocouple produces an increasing amount of NO_x at a much slower rate compared to LPG system.

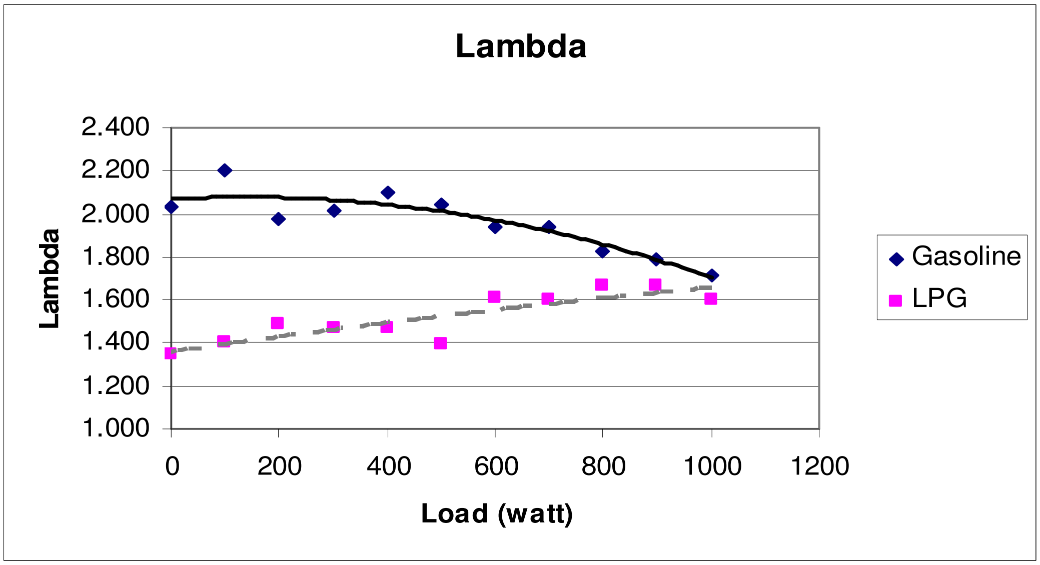

Figure 5.16: Lambda values for gasoline and LPG fuel in four-stroke engine

5.5.2 Emissions of Carbon Dioxide (CO_2)

CO_2 is the main contributor of greenhouse gases which cause global warming and hazardous to the environment and people. It can be seen from Figure 5.17 that the emission of CO_2 is much lower in the LPG fuel system compared to gasoline. As the load increases, the emission of CO_2 also increases as more fuel as the engine consumes more fuel. The reason for LPG fuel system having a lower level of CO_2 is due to the less carbon composition of LPG which consists of mostly propane, compared to gasoline. Emissions of CO_2 are also related to the quality of combustion and with a reduction of CO_2 emission from a range of 5.7% to 19.4% shows a good indication of the combustion quality of LPG fuel system.

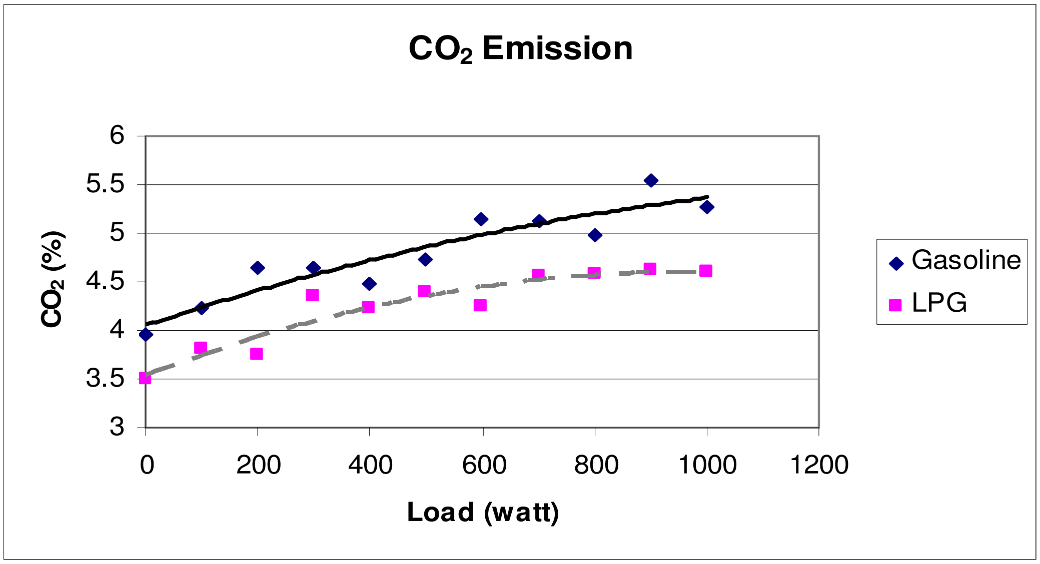

Figure 5.17: Emissions of CO_2 at variable loads

5.5.3 Emissions of Carbon Monoxide (CO)

CO is the major component produced in a rich combustion where the fuel is in excess compared to the air intake. Figure 5.18 shows the emissions of CO for both gasoline and LPG fuel system and it is found that the CO emission of LPG fuel system is much higher compared to gasoline system undoubtedly. The reduction of CO percentage for LPG fuel system ranges from a minimum of 23.0% at a load of 1000 Watts to a maximum of 54.5% at a load of 700 Watts compared to the gasoline system. High CO emissions commonly indicate an

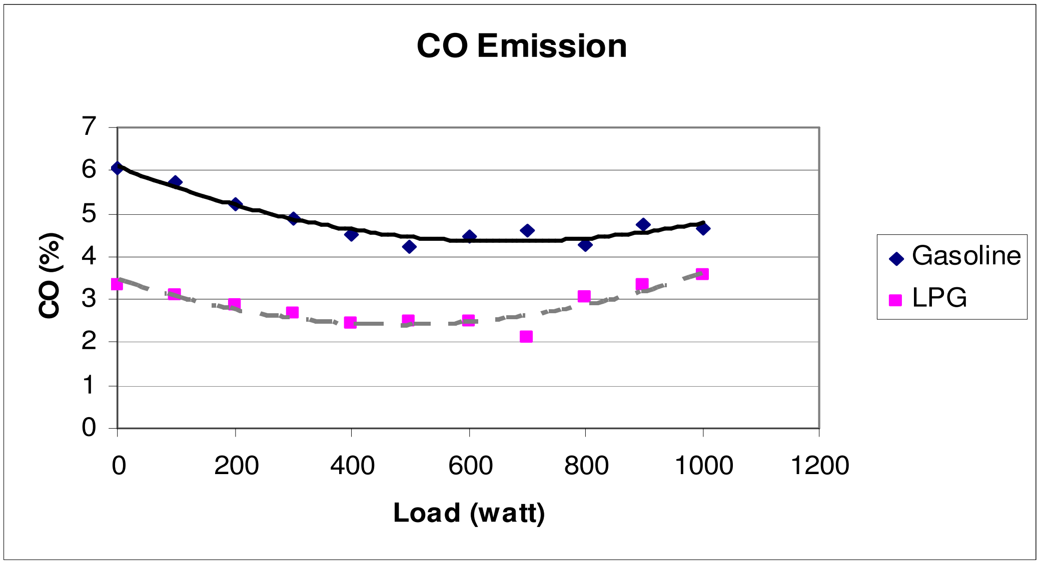

Figure 5.18: Emissions of CO at variable loads

incomplete combustion in the gasoline fuel system. The reasons for this might be an improper float setting in the carburetor, dirty or restricted air filters and excessively dirty or contaminated oil in the engine. Similar with the two-stroke engine, LPG fuel system shows a good indication of combustion quality in the four-stroke engine and produces less toxic CO emission.

5.5.4 Emissions of Oxygen (O_2)

The result of O_2 emissions at variable loads of the four-stroke engine is featured in Figure 5.19, which reflects the amount of oxygen gas remaining in excess in the exhaust after the combustion process had taken place in the combustion chamber. Figure 5.19 shows that the percentage of oxygen recorded from the gasoline exhaust system is higher than LPG fuel system. The gasoline system contains an average of 22.5% more O_2 content in the exhaust compared to the LPG fuel system. High O_2 emission indicates a very lean air-fuel ratio. As shown in the Figure 5.19, the gasoline system contains more excess oxygen in the exhaust as the lambda values for

LPG fuel in engine is lower compared with gasoline as can be seen from Figure 5.16. The higher air to fuel ratio of the gasoline system causes excess air or oxygen gas to be present for combustion and hence most of the oxygen is not used up. High readings of O_2 in the exhaust might also be due to vacuum leaks and ignition related problems causing misfires.

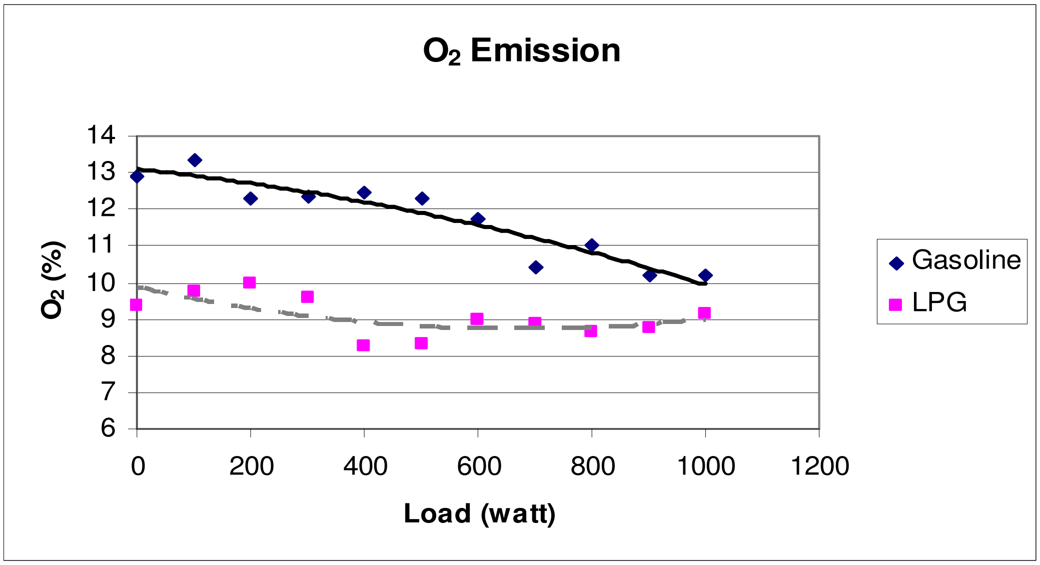

Figure 5.19: Emissions of O_2 at variable loads

5.5.5 Emissions of Hydrocarbons (HC)

Figure 5.20 shows the hydrocarbon emission for both gasoline and LPG fuel system. It is clear that the HC emission of the LPG fuel system is much higher than gasoline at lower loads. It is also found that the LPG fuel system emits HC with an average of almost two and a half time more compared to gasoline system from 0 to 600 Watts of load. However, the HC emission of LPG fuel system gradually decreases to a minimal value when more loads are added. This might be due to a better fuel distribution and mixture to give a more complete combustion for the LPG system at high loads. Incomplete combustion is one of the factors which cause high HC emission. Referring back to Figure 5.16, the lambda values of LPG fuel system is lower than gasoline and this represents a lower air to fuel ratio at loads ranging from 0 to 600 Watts. There is insufficient air to produce a complete combustion in the chamber and this factor contributes mainly to the high HC emission as shown in Figure 5.19. Other factors which might contribute to the higher HC emission of LPG fuel are low quality combustions due to fouled spark plugs, vacuum leaks and poor compression due to the lack of optimization of the gasoline engine to accept a gaseous fuel.

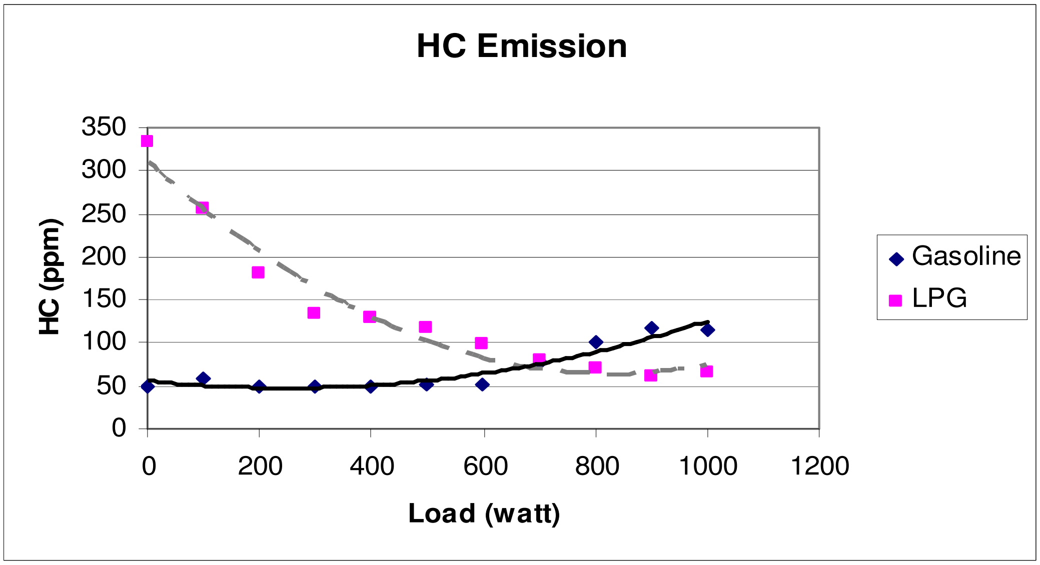

Figure 5.20: Emissions of HC at variable loads

5.6 Engine Performance of Four-stroke Engine

The discussions on engine performance of four-stroke engine are based on brake specific fuel consumption (bsfc) and engine efficiency. Indicated work data is not included in the discussion due to the unavailability of pressure sensor and crank encoder of the four-stroke engine in the laboratory.

5.6.1 Brake Specific Fuel Consumption (bsfc)

Figure 5.21 shows the variation of brake specific fuel consumption for four-stroke engine utilizing gasoline and LPG as the load varies. The results indicate that the fuel consumption rate of LPG fuel system is higher than the gasoline system for most engine loads. LPG fuel system showed higher bsfc readings because LPG uses higher mass flow rate compared to gasoline to produce the same unit of power output. The bsfc rates are very high at the lower loads for both systems, recording at 3.21 kg/kW.h for LPG and 3.0 kg/kW.h for gasoline fuel system respectively when the load applied is 100 Watts.

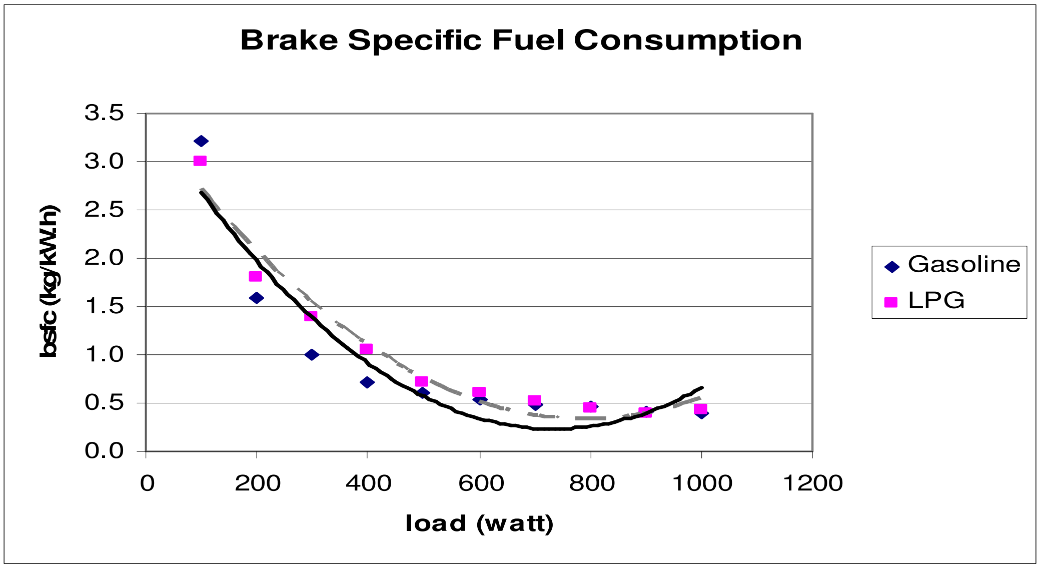

Figure 5.21: Brake Specific Fuel Consumption on variable loads

However the bsfc rates for both systems decreased gradually at as the loads are increased. It can be found that bsfc for LPG decreases from 200 Watts and reaches the minimum value at 900 Watts while the bsfc of gasoline reaches a minimum value at 700 Watts from the gasoline curve in Figure 5.21. At higher engine loads, knocking begins to occur with high combustion pressure and temperature and thus causes the bsfc value to increase above its minimum point. Beyond the load values of 1000 Watts, the bsfc increases tremendously due to increased amount of engine knocking and the engine stalls for both fuel systems. Again, LPG is still the preferable choice of fuel as it reduces the emissions of pollutant gases and most importantly, the cost of LPG is lower than gasoline. Tables 5.1, 5.2 and 5.3 show the updated price differences between gasoline and LPG in Malaysia.

5.6.2 Engine Efficiency

Figure 5.22 shows the engine efficiency comparison between the LPG and gasoline fuel system for four-stroke engine running on various loads. We can see that the efficiency of the LPG fuel system is slightly lower compared to the gasoline system, showing a similar trend as the two-stroke engine. The LPG system recorded an efficiency of 2.4% lower on average compared to the gasoline system. At higher engine loads, the efficiency for both LPG and gasoline increases steadily since the combustion temperatures increase with load to provide a higher fuel conversion efficiency to produce more output power.

Figure 5.22: Comparison of engine efficiency of gasoline and LPG fuel system

5.7 Temperature of Four-stroke Engine

Figures 5.23 and 5.24 show the exhaust and engine body temperatures for four-stroke engine at different loads. It can be found that engine body temperature for four-stroke engine increases gradually as loads are progressively increased for both fuel systems.

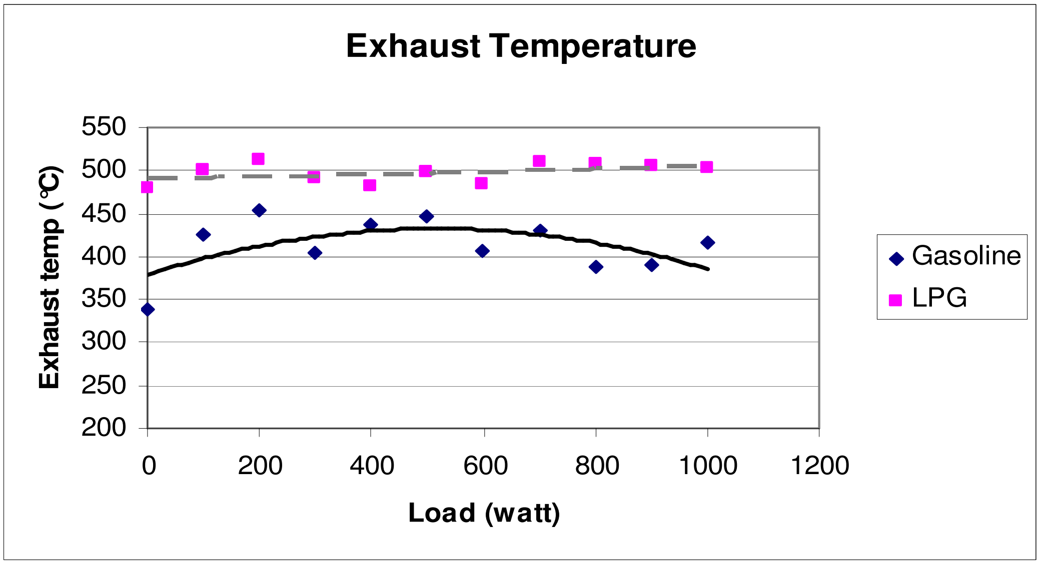

Figure 5.23: Exhaust temperature of four-stroke engine

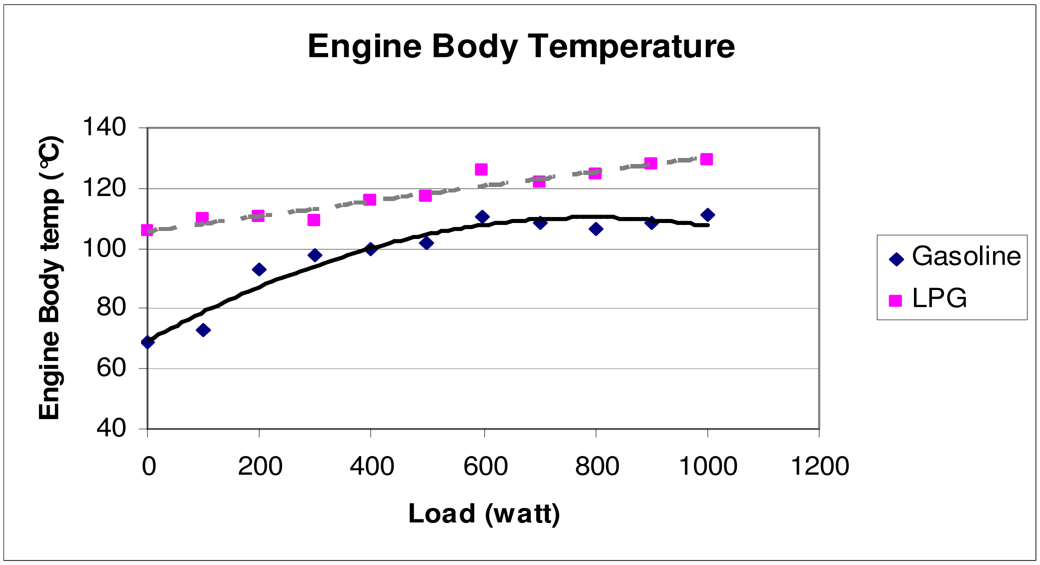

Figure 5.24: Engine body temperature of four-stroke engine

More fuel is needed for the engine to support the increasing loads and this result in a higher body temperature of the engine. The result is similar to Figure 5.14 for the two-stroke engine where the engine body temperature increases gradually for both fuels. By monitoring Figures 5.23 and 5.34, a significant difference is observed compared to the exhaust and body temperatures of the two-stroke engine. The temperatures begin to drop at a load of 800 Watts for the gasoline fuel system. This can be directly linked with the lower air to fuel ratio as depicted in Figure 5.16 for the four-stroke engine. A richer combustion produces less heat and causes both the engine exhausts and body temperatures to drop. As shown in Figures 5.23 and 5.24, both the exhaust and engine body temperatures of LPG fuel system were higher compared to gasoline system. The lack of lubrication oil for LPG system proves to be the main reason for the temperature increase in both two and four-stroke engines.

5.8 Concluding Discussions

Tables 5.1 to 5.4 show the average emission gases and engine performance for two-stroke and four-stroke engines. From the tables shown below, both two- stroke and four-stroke engine showed a similar trend where LPG fuel is fully capable of reducing the harmful emission gases such as nitrogen oxides, carbon dioxide and carbon monoxide. For two-stroke engine, the NO_x emissions were reduced by an average of 64.11% and 41.65% for the four-stroke engine. LPG fuel system also achieved an average reduction of 31.23% and 11.46% in carbon dioxide for both two-stroke and four-stroke engine accordingly. There are 51.19% reduction in carbon monoxide for the two-stroke engine and 40.67% for four-stroke engine as shown in the tables 5.1 and 5.3. However there is a slight setback where the LPG fuel operated engine showed a decrease in the engine thermal efficiency compared to gasoline operated engine. On the other hand, the hydrocarbon emissions for engine running on LPG fuel has increased by 81.2% and 145.02% respectively for both two-stroke and four-stroke engine. This can be solved by using a catalytic aftertreatment technique to control the high amount of hydrocarbon emissions from spark-ignition engines (Turns 1996). Engines running on LPG fuel system also showed a higher brake specific fuel consumption rate, which are 25.21% and 10.21% more than gasoline fuel system for two-stroke and four-stroke engines respectively. In contrast, LPG still remains a competitive alternative fuel to replace conventional gasoline as the price of LPG is less than half of the price of gasoline in the Malaysian market. The price differences between LPG and gasoline are shown in tables 5.5, 5.6 and 5.7.

Emission Gases	Gasoline	LPG	Reduction in %
Nitrogen oxides (NO_x)	237.03	115.80	64.11
Carbon dioxide (CO_2)	9.61	6.62	31.23
Carbon monoxide (CO)	3.55	1.49	57.19
Oxygen (O_2)	5.98	7.57	-26.33
Hydrocarbon (HC)	1973.08	3559.60	-81.20

Table 5.1: Average emission gases for two-stroke engine

Engine Performance	Gasoline	LPG	Reduction in %
Brake specific fuel consumption (bsfc)	0.86	1.08	-25.21
Efficiency	5.96	4.48	2.48

Table 5.2: Average engine performance for two-stroke engine

Emission Gases	Gasoline	LPG	Reduction in %
Nitrogen oxides (NO_x)	38.67	24.83	41.65
Carbon dioxide (CO_2)	4.80	4.24	11.46
Carbon monoxide (CO)	4.85	2.86	40.67
Oxygen (O_2)	11.75	9.06	22.33
Hydrocarbon (HC)	70.05	138.71	-145.02

Table 5.3: Average emission gases for four-stroke engine

Engine Performance	Gasoline	LPG	Reduction in %
Brake specific fuel consumption (bsfc)	0.85	0.94	-10.21
Efficiency	12.51	10.35	1.73

Table 5.4: Average engine performance for four-stroke engine

5.9 Justifications of Lower LPG Engine Efficiency

The tables below show the price comparisons between gasoline and LPG fuel in Peninsular Malaysia and East Malaysia. The prices of LPG are usually quoted in kilograms and tables 5.5 to 5.7 included a converted price unit for LPG fuel to aid comparison with the gasoline price quoted in litres. The last column of the tables shows the equivalent prices of both the fuels in Australian dollars. Although a minor drop in engine efficiency and rise in fuel consumption by fractions, LPG fuel is still more economical due to its low price and remains a high potential alternative fuel. According to the New Straits Times (2005), fuel prices had gone up effective from July 31st 2005 by between five and ten cents per litre to overcome the impact of rising crude oil prices and to cut back on subsidies paid by the Malaysian Government. The current prices of LPG referring to the tables below are still much lower than gasoline as the cost of LPG per litre is less than half the price of the equivalent volume of gasoline in all parts of Malaysia.

Fuel (per litre)	June 2005 prices in Peninsular Malaysia (Ringgit Malaysia)	New prices effective July 31 2005 (Ringgit Malaysia)	Equivalent new prices in Australia dollars
Gasoline RON 97	1.52	1.62	0.55
Gasoline RON 92	1.48	1.58	0.54
LPG (per kg)	1.40	1.45	0.49
LPG (per litre)	0.71	0.73	0.25

Table 5.5: The prices of fuel in Peninsular Malaysia

Fuel (per litre)	June 2005 prices in Sabah, Malaysia (Ringgit Malaysia)	New prices effective July 31 2005 (Ringgit Malaysia)	Equivalent new prices in Australia dollars
Gasoline RON 97	1.50	1.60	0.54
Gasoline RON 92	1.48	1.58	0.54
LPG (per kg)	1.48	1.53	0.52
LPG	0.75	0.77	0.26

Table 5.6: The prices of fuel in Sabah, Malaysia

Fuel (per litre)	June 2005 prices in Sarawak, Malaysia (Ringgit Malaysia)	New prices effective July 31 2005 (Ringgit Malaysia)	Equivalent new prices in Australia dollars
Gasoline RON 97	1.51	1.61	0.55
Gasoline RON 92	1.48	1.58	0.54
LPG (per kg)	1.48	1.53	0.52
LPG	0.75	0.77	0.26

Table 5.7: The prices of fuel in Sarawak, Malaysia

CHAPTER 6

CONCLUSION

6.1 ACHIEVEMENT OF OBJECTIVES

Small utility engines that are used frequently in Malaysia consume gasoline as the main fuel to generate power for different applications. The main aim of this research project is to analyze and prove the reduction of nitrogen oxides using LPG in spark ignition engines. The data for other emission gases are also collected and compared. Besides that, this project also intends to investigate the engine performance for both gasoline and LPG fuel system for both the two-stroke and four-stroke engine. From the results obtained in the experiments, it was found that the feasibility of LPG fuel to replace conventional gasoline is very high as it reduces the major pollutant emission gases such as nitrogen oxides, carbon monoxide and carbon dioxide.

The pollution level of the environment and the health of people are of prime concern in this research project. According to the data collected from the experiments, LPG demonstrated a good average reduction of NO_x as high as 64.11% for two-stroke engine and 41.65% for four-stroke engine. On the other hand, carbon dioxide which is a strong greenhouse gas and acts as the main contributor to the global warning effect is reduced by using the LPG fuel system by an average of 31.23% and 11.46% for two-stroke and four-stroke engine respectively. Apart from that, the experiments also indicated that the level of CO had been reduced by up to 57.19% for two-stroke engine and 40.61% for four-stroke engine. However, the level of emission for HC was not encouraging as LPG fuel showed an increased of 81.20% and 145.02% for both the two-stroke and four-stroke engines respectively. The high level of HC emission can be controlled by an oxidation catalyst to reduce the level of HC produced and also to minimize the emission of CO to a safety level of 30 ppm set by the government.

The performance of LPG operated engine is also comparable to gasoline operated engine as proven by the experiments. Although the results showed that the engine efficiency of LPG is slightly lower for both the two-stroke and four-stroke engines by an average of 2%, this is not a main factor of concern as high power is generally not required in small utility engines thus the effect will not be noticeable. Fuel consumption plays an important role in terms of cost to the consumers. The research indicated that the fuel consumption rate of gasoline fuel system is slightly lower compared to LPG fuel system. However, LPG is more economical where its cost per litre equivalent is much lower compared with the price of gasoline as shown in the tables 5.5, 5.6 and 5.7. The world's crude oil prices have increased at a rapid rate and were as high as US$64 (RM243.20) per barrel. In Malaysia, fuel prices had also gone up effective from 31st July 2005 to curb the increase in subsidies paid by the Malaysia government in the face of protracted soaring crude oil prices. This was the third fuel price hike in Malaysia this year. With the newly announced prices, the price of LPG was fixed at RM0.73 compared to gasoline at RM1.45, which offered a great savings in fuel costs of more than 50%.

As a conclusion, LPG proves to be a competitive alternative fuel to replace gasoline in spark ignition engines since the price of LPG is less than half the price of gasoline and LPG produces less pollutant emissions including oxides of nitrogen (NO_x) which are investigated in this research. Although this experiment produced encouraging results, the use of LPG has not gained popularity among consumers due to the unavailability of the engine conversion kits and lack of publicity in the Malaysian market to create awareness among vehicle consumers in Malaysia.

6.2 RECOMMENDATION AND FUTURE WORK

This project researches on the potential of LPG to replace the role of conventional gasoline fuel and the data obtained from experiments yield an encouraging and promising result. However, more research has to be done to improve the design of the LPG fuelled gasoline engine to gain better engine performance. As shown in Figures 5.12 and 5.22, the thermal efficiency of engine running on LPG fuel is slightly lower than gasoline operated engine. Therefore, future researches should be concentrated in this area to increase the engine efficiency of LPG operated engine.

The engine can be further enhanced by modifying the components in the engine to achieve optimum engine performances. This can be done through simulation software such as FLUENT to develop and improve the existing design of the engines available in the market. With the aid of the software program, design process becomes easier and large financial commitments can be avoided without having to build the prototype of the design product to test its performances. The simulations can be performed in more detail on the distribution of heat transfer in the combustion chamber so that a deeper understanding on the combustion process can be developed. For instance, the heat transfer model can be used to simulate heat losses from the compressed gas to the walls or to detect the possible fuel residuals left after the combustion process.

Besides that, other emission gases from the engine exhaust such as particular matters (PM) and sulfur dioxide (SO_2) should also be measured using a more advanced gas analyzer in order to increase the coverage of pollutant emission gases analyzed for both gasoline and LPG fuel engines so that any byproducts of using LPG fuel can be determined and controlled.

In addition, more campaigns and advertisements on the benefits of using LPG fuel should be implemented in Malaysia to create awareness among Malaysians to reduce the pollutant emission gases associated with conventional fuels not just to protect the environment but the health of the public in general. Since LPG produces less toxic emissions and cost less than half of the price of gasoline, LPG should strongly be encouraged to be used among Malaysian consumers.

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APPENDIX A

PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	CHAN, Lai Kuan
TOPIC:	REDUCTION OF NITROGEN OXIDES (NO_X) USING LPG (LIQUIFIED PETROLEUM GAS) IN SI (SPARK IGNITION) ENGINE
SUPERVISORS:	Dr. Harry Ku (USQ) Dr. Fok Sai Cheong (USQ) Dr. Talal Yusaf (UNITEN)
ENROLMENT:	ENG 4111 – S1, X, 2005 ENG 4112 – S2, X, 2005
PROJECT AIM:	The main objective of this project is to investigate the reduction of NOx percentage using LPG (Liquid Petroleum Gas) in SI (Spark Ignition) engine.
PROGRAMME:	**Issue A, 10th March 2005**

1. Conduct a detailed study on the history, properties and usage of LPG as an alternate fuel, and the factors and effects of NO_x emission.

2. Measure the concentration of emission gases such as NOx, CO2, CO and hydrocarbons from the two-stroke engine which using both the gasoline and LPG as the main fuel.

3. Evaluate the data collected from the experiment conducted for both gasoline and LPG in the two-stroke engine for different set of load conditions and engine speeds.

4. Comparative study of the use of conventional fuel and LPG in term of pollutants and feasibility of using LPG fuel as a suitable alternative in CI engines.

As time permits,

5. Construct a Matlab program to simulate and verify the emission data collected from the experiment.

AGREED:

________________ (Student) _______________ , _______________ (Supervisors)

__ / __ / __ __ / __ / __ __ / __ / __

APPENDIX B

TABULATION OF DATA FOR TWO-STROKE ENGINE

EMISSION GASES

Gasoline System

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	8.12	4.060	2015	6.20	115	1.15
2	8.12	4.058	2019	6.17	114	1.15
3	8.11	4.048	2000	6.11	112	1.15
4	8.10	4.046	1965	6.06	110	1.15
5	8.10	4.042	1987	6.03	107	1.16
6	8.12	4.065	1954	6.02	107	1.16
7	8.13	4.071	1920	5.97	107	1.17
8	8.13	4.075	1905	5.88	105	1.17
9	8.17	4.194	1935	5.90	105	1.17
10	8.17	4.112	1930	5.89	104	1.16
Total	81.27	40.771	19630	60.23	1086	11.6
Min	8.127	4.0771	1963	6.023	108.6	1.159

Table B1: Emissions at 0 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	9.88	3.554	1690	5.66	122	1.20
2	9.93	3.550	1685	5.66	122	1.20
3	9.93	3.488	1679	5.67	122	1.20
4	9.98	3.476	1672	5.68	123	1.21
5	10.04	3.359	1663	5.65	123	1.21
6	10.06	3.359	1655	5.65	123	1.21
7	10.09	3.497	1647	5.65	123	1.21
8	10.09	3.466	1633	5.65	124	1.21
9	10.11	3.424	1629	5.63	123	1.20
10	10.11	3.395	1625	5.62	123	1.20
Total	100.22	34.568	16578	56.52	1228	12.05
Min	10.022	3.4568	1657.8	5.652	122.8	1.205

Table B2: Emissions at 200 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	10.49	3.720	1812	5.97	257	1.25
2	10.52	3.720	1808	5.95	257	1.25
3	10.52	3.812	1800	5.92	262	1.25
4	10.55	3.718	1779	5.87	262	1.25
5	10.56	3.695	1775	5.95	267	1.25
6	10.60	3.690	1773	5.99	267	1.26
7	10.63	3.719	1770	6.04	267	1.26
8	10.63	3.725	1770	6.04	270	1.26
9	10.63	3.888	1768	6.14	272	1.26
10	10.64	3.922	1764	6.16	272	1.26
Total	105.77	37.609	17819	60.03	2653	12.55
Min	10.577	3.7609	1781.9	6.003	265.3	1.255

Table B3: Emissions at 400 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	9.73	2.958	2488	6.22	455	1.25
2	9.73	2.936	2469	6.23	451	1.25
3	9.73	2.936	2471	6.24	445	1.26
4	9.72	2.922	2501	6.24	442	1.26
5	9.72	2.918	2501	6.24	452	1.26
6	9.72	2.905	2495	6.20	448	1.26
7	9.72	2.889	2495	6.21	444	1.27
8	9.72	2.889	2495	6.21	465	1.27
9	9.71	2.882	2491	6.24	460	1.27
10	9.71	2.863	2490	6.25	452	1.27
Total	97.21	29.098	24896	62.28	4514	12.62
Min	9.721	2.9098	2489.6	6.228	451.4	1.262

Table B4: Emissions at 600 Watts

LPG Fuel System

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.14	1.568	3275	8.52	17	1.06
2	5.14	1.568	3275	8.52	17	1.06
3	5.13	1.540	3468	8.46	17	1.06
4	5.13	1.536	3468	8.44	16	1.05
5	5.13	1.524	3485	8.40	16	1.05
6	5.12	1.536	3570	8.45	16	1.05
7	5.12	1.560	3578	8.45	15	1.05
8	5.12	1.560	3595	8.53	15	1.05
9	5.13	1.569	3656	8.53	15	1.06
10	5.13	1.575	3689	8.61	17	1.06
Total	51.29	15.536	35059	84.91	161	10.6
Min	5.129	1.5536	3505.9	8.491	16.1	1.055

Table B5: Emissions at 0 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	7.18	1.809	2912	6.32	38	1.10
2	7.18	1.805	2903	6.32	38	1.10
3	7.17	1.788	2875	6.28	38	1.10
4	7.17	1.785	2850	6.28	36	1.11
5	7.17	1.750	2900	6.25	36	1.09
6	7.17	1.669	2900	6.25	37	1.09
7	7.16	1.666	2855	6.20	37	1.10
8	7.16	1.666	2845	6.18	37	1.10
9	7.16	1.620	2840	6.15	36	1.10
10	7.16	1.612	2838	6.15	38	1.10
Total	71.68	17.17	28718	62.38	371	10.99
Min	7.168	1.717	2871.8	6.238	37.1	1.099

Table B6: Emissions at 200 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	6.74	1.245	3580	6.85	51	1.11
2	6.74	1.238	3580	6.82	50	1.11
3	6.74	1.238	3597	6.82	50	1.11
4	6.75	1.232	3597	6.70	49	1.09
5	6.75	1.227	3592	6.65	48	1.09
6	6.73	1.222	3577	6.62	48	1.10
7	6.73	1.215	3580	6.62	50	1.10
8	6.73	1.215	3589	6.54	50	1.09
9	6.74	1.211	3589	6.50	49	1.09
10	6.74	1.203	3600	6.46	49	1.11
Total	67.39	12.246	35881	66.58	494	11.00
Min	6.739	1.2246	3588.1	6.658	49.4	1.100

Table B7: Emissions at 400 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	7.47	1.543	4262	8.55	325	1.190
2	7.47	1.540	4262	8.55	325	1.190
3	7.47	1.524	4262	8.58	350	1.190
4	7.46	1.535	4270	9.02	374	1.190
5	7.46	1.537	4270	8.99	378	1.200
6	7.46	1.498	4275	8.92	370	1.200
7	7.45	1.487	4275	9.87	359	1.200
8	7.45	1.464	4279	8.87	372	1.210
9	7.45	1.410	4283	8.85	372	1.210
10	7.46	1.397	4288	8.90	381	1.200
Total	74.6	14.935	42726	89.10	3606	11.98
Min	7.46	1.4935	4272.6	8.91	360.6	1.198

Table B8: Emissions at 600 Watts

COMPILE EMISSION GASES DATA

Gasoline system

Load (Watt)	Exhaust temp (℃)	Body temp (℃)	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
0	52.4	112.4	8.1270	4.0771	1963.0	6.023	108.6	1.159
200	62.6	128.8	10.022	3.4568	1657.8	5.652	122.8	1.205
400	81.4	140.2	10.577	3.7609	1781.9	6.003	265.3	1.255
600	92.2	151.0	9.721	2.9098	2489.6	6.228	451.4	1.262

Table B9: Compile emission gases data for gasoline system

LPG fuel system

Load (Watt)	Exhaust temp (℃)	Body temp (℃)	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
0	58.2	155.8	5.129	1.5360	3505.9	8.491	16.1	1.055
200	70.8	171.2	7.168	1.7170	2871.8	6.238	37.1	1.099
400	86.0	194.6	6.739	1.2246	3588.1	6.658	49.4	1.100
600	122.2	208.6	7.46	1.4935	4272.6	8.910	360.6	1.198

Table B10: Compile emission gases data for LPG fuel system

INDICATED WORK DATA FOR TWO-STROKE ENGINE

Theta	Gasoline Pressure (Bar)	LPG Pressure (Bar)
-9.72	0.99	2.12
-7.80	1.98	3.14
-5.88	3.60	4.72
-3.78	5.64	6.48
-1.87	7.92	8.67
-0.09	9.11	10.12
1.56	10.06	10.94
3.49	10.42	10.99
5.42	9.24	9.85
7.51	7.01	8.08
9.46	4.98	6.31
11.34	3.43	4.81
13.46	2.27	3.63
15.36	1.68	2.90
17.46	0.98	2.27
19.38	0.48	1.85

Table B11: Raw data of indicated work at 200 Watts

	Gasoline Pressure (Bar)	LPG Pressure (Bar)
-9.73	2.33	0.53
-7.62	3.30	1.72
-5.77	4.65	3.48
-3.74	6.60	5.70
-2.01	8.77	7.58
0.03	10.26	9.74
1.88	10.19	9.71
3.57	8.89	8.18
5.75	7.30	7.16
7.67	5.76	6.35
9.74	4.51	5.05
11.69	3.56	4.78
13.74	2.92	3.40
15.66	2.35	2.05
17.52	2.01	2.42
19.65	1.72	1.87

Table B12: Raw data of indicated work at 0 Watts

Theta	Gasoline Pressure (Bar)	LPG Pressure (Bar)
-8.07	1.01	0.39
-5.97	2.73	1.41
-4.07	4.83	2.93
-2.17	6.76	4.94
-0.78	8.06	7.08
1.69	9.59	9.14
3.62	10.42	11.26
5.53	8.72	11.64
7.47	6.20	10.12
9.36	4.00	7.81
11.47	2.31	5.93
13.35	1.14	3.87
15.37	0.35	2.49
17.29	0.31	1.81
19.87	0.28	1.19
21.64	0.24	0.39

Table B13: Raw data of indicated work at 400 Watts

Theta	Gasoline Pressure (Bar)	LPG Pressure (Bar)
-9.72	0.59	1.20
-7.79	1.28	3.21
-5.88	2.29	5.34
-3.93	3.73	7.59
-2.21	5.57	9.65
-0.29	7.36	12.26
1.23	8.99	13.36
3.15	10.96	10.65
4.89	12.28	8.25
6.81	11.28	5.67
8.73	8.58	3.83
10.65	6.16	1.54
12.57	4.44	-0.19
14.49	2.22	-0.88
16.41	1.40	-1.07
18.33	0.83	-1.62

Table B14: Raw data of indicated work at 600 Watts

ENGINE PERFORMANCE

Gasoline system

Load (watt)	Engine Speed (rpm)	Torque (N.m)	Brake Power (kW)	Time for 10ml fuel (s)	Density	Mass Flow Rate (kg/h)	bsfc (kg/kW.h)	Engine efficiency
0	3780.88	0.0000	0.0000	132	748.92	0.2043	0.00	0.00
200	3635.40	0.5253	0.2000	87	748.92	0.3099	1.55	5.52
400	3635.40	1.0506	0.4000	65	748.92	0.4148	1.04	8.25
600	3500.22	1.6367	0.6000	53	748.92	0.5087	0.85	10.09

Table B15: Engine performance for gasoline system

LPG fuel system

Load (watt)	Engine Speed (rpm)	Torque (N.m)	Brake Power (kW)	Weight consumed in 1 min (kg)	Mass Flow Rate (kg/h)	bsfc (kg/kW.h)	Engine efficiency
0	3888.56	0.0000	0.0000	0.005	0.300	0.00	0.0000
200	3800.75	0.5024	0.2000	0.007	0.420	2.10	3.6970
400	3800.75	1.0049	0.4000	0.008	0.480	1.20	6.4697
600	3635.33	1.5759	0.6000	0.010	0.600	1.00	7.7636

Table B16: Engine performance for LPG fuel system

APPENDIX C

TABULATION OF DATA FOR FOUR-STROKE ENGINE

EMISSION GASES

Gasoline System

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	3.99	6.152	48	13.10	28	2.07
2	3.99	6.158	48	13.10	28	2.07
3	3.98	6.158	48	13.02	27	2.03
4	3.95	6.155	49	12.96	27	2.03
5	3.95	6.095	50	12.94	27	2.03
6	3.95	6.019	50	12.94	27	2.03
7	3.95	6.019	51	12.89	27	2.02
8	3.96	5.996	52	12.82	28	2.00
9	3.96	5.887	52	12.71	28	2.01
10	3.96	5.997	54	12.73	27	2.01
Total	39.64	60.636	502	129.21	274.00	20.3
Min	3.964	6.0636	50.2	12.921	27.4	2.03

Table C1: Emissions at 0 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.05	5.756	48	13.50	23	2.23
2	4.12	5.629	49	13.43	22	2.21
3	4.12	5.629	51	13.38	23	2.15
4	4.18	5.634	51	13.38	23	2.14
5	4.26	5.647	52	13.34	22	2.17
6	4.27	5.649	67	13.29	22	2.20
7	4.27	5.658	67	13.29	23	2.20
8	4.30	5.669	69	13.29	24	2.20
9	4.32	5.882	69	13.29	24	2.25
10	4.38	5.967	68	13.30	24	2.26
Total	42.27	57.12	591	133.49	230	22.01
Min	4.227	5.712	59.1	13.349	23	2.201

Table C2: Emissions at 100 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.62	5.243	47	12.75	30	2.04
2	4.62	5.244	47	12.71	30	2.04
3	4.62	5.247	48	12.52	32	2.02
4	4.62	5.250	48	12.52	32	2.02
5	4.63	5.255	49	12.40	32	2.01
6	4.66	5.256	50	12.08	33	1.94
7	4.67	5.260	50	12.08	33	1.94
8	4.70	5.266	51	11.96	33	1.93
9	4.70	5.089	51	11.96	34	1.93
10	4.71	5.089	52	11.91	34	1.92
Total	46.55	52.199	493	122.89	323	19.79
Min	4.655	5.2199	49.3	12.289	32.3	1.979

Table C3: Emissions at 200 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.96	4.587	47	12.00	36	1.93
2	4.93	4.587	48	12.11	35	1.95
3	4.93	4.850	48	12.11	35	1.95
4	4.67	5.105	49	12.39	34	2.02
5	4.58	5.173	50	12.56	33	2.08
6	4.48	5.173	50	12.60	32	2.07
7	4.50	4.816	51	12.47	32	2.05
8	4.47	4.728	51	12.44	33	2.05
9	4.47	4.833	51	12.44	33	2.05
10	4.49	4.833	52	12.42	32	2.04
Total	46.48	48.685	497	123.54	335	20.19
Min	4.648	4.8685	49.7	12.354	33.5	2.019

Table C4: Emissions at 300 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.43	4.276	48	12.76	34	2.16
2	4.44	4.250	49	12.62	34	2.12
3	4.44	4.345	49	12.62	34	2.12
4	4.45	4.524	49	12.51	35	2.11
5	4.46	4.544	50	12.44	35	2.1
6	4.46	4.544	50	12.44	35	2.1
7	4.50	4.538	50	12.33	36	2.08
8	4.52	4.747	51	12.30	36	2.07
9	4.56	4.757	52	12.26	36	2.07
10	4.59	4.789	53	12.24	36	2.06
Total	44.85	45.314	501	124.52	351	20.99
Min	4.485	4.5314	50.1	12.452	35.1	2.099

Table C5: Emissions at 400 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.72	3.996	50	12.49	38	2.06
2	4.72	4.124	50	12.49	38	2.06
3	4.72	4.124	50	12.37	38	2.05
4	4.72	4.277	51	12.30	38	2.04
5	4.72	4.339	51	12.27	39	2.01
6	4.72	4.319	51	12.26	39	2.01
7	4.72	4.319	51	12.26	39	2.01
8	4.73	4.332	51	12.23	39	2.07
9	4.74	4.329	52	12.23	39	2.07
10	4.74	4.325	53	12.24	39	2.06
Total	47.25	42.484	510	123.14	386	20.44
Min	4.725	4.2484	51	12.314	38.6	2.044

Table C6: Emissions at 500 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.02	4.438	50	12.24	41	2.01
2	5.02	4.438	50	12.07	42	2.00
3	5.02	4.445	50	12.07	42	2.00
4	5.03	4.448	50	11.95	43	1.99
5	5.04	4.457	52	11.84	43	1.98
6	5.07	4.457	52	11.64	44	1.92
7	5.07	4.457	52	11.64	44	1.92
8	5.10	4.460	54	11.45	45	1.90
9	5.59	4.472	54	11.33	47	1.86
10	5.59	4.478	55	11.33	47	1.86
Total	51.55	44.55	519	117.56	438	19.44
Min	5.155	4.455	51.9	11.756	43.8	1.944

Table C7: Emissions at 600 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.10	4.650	75	10.43	42	1.98
2	5.10	4.650	75	10.43	42	1.98
3	5.10	4.671	76	10.48	43	1.95
4	5.10	4.686	77	10.40	42	1.95
5	5.11	4.642	78	10.40	44	1.95
6	5.13	4.635	79	10.42	45	1.94
7	5.13	4.635	79	10.38	45	1.92
8	5.16	4.630	80	10.38	45	1.9
9	5.17	4.549	80	10.35	47	1.90
10	5.20	4.302	80	10.30	47	1.90
Total	51.3	46.05	779	103.97	442	19.37
Min	5.13	4.605	77.9	10.397	44.2	1.937

Table C8: Emissions at 700 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.06	4.248	98	10.20	50	1.84
2	4.66	4.248	99	10.88	46	1.84
3	4.68	4.262	99	11.20	44	1.85
4	4.68	4.262	99	11.20	44	1.85
5	4.68	4.288	100	11.35	44	1.83
6	4.72	4.295	100	11.42	43	1.82
7	4.75	4.295	100	11.29	45	1.84
8	5.54	4.312	101	11.07	45	1.82
9	5.55	4.318	101	11.07	45	1.82
10	5.55	4.327	102	10.41	48	1.79
Total	49.87	42.855	999	110.09	454	18.3
Min	4.987	4.2855	99.9	11.009	45.4	1.83

Table C9: Emissions at 800 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.52	4.597	115	10.30	52	1.78
2	5.53	4.627	116	10.28	52	1.78
3	5.54	4.816	117	10.19	51	1.80
4	5.54	4.816	117	10.19	51	1.80
5	5.55	4.661	117	10.18	49	1.82
6	5.55	4.701	118	10.25	51	1.81
7	5.55	4.756	118	10.25	51	1.81
8	5.54	4.769	118	10.12	50	1.79
9	5.54	4.769	119	10.12	50	1.78
10	5.54	4.768	119	10.11	52	1.75
Total	55.4	47.28	1174	101.99	509	17.92
Min	5.54	4.728	117.4	10.199	50.9	1.792

Table C10: Emissions at 900 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	5.22	4.765	111	10.01	51	1.75
2	5.22	4.624	112	10.02	51	1.75
3	5.22	4.624	112	10.02	51	1.72
4	5.23	4.536	113	12.07	51	1.72
5	5.23	4.573	114	10.02	53	1.74
6	5.25	4.707	115	10.01	52	1.70
7	5.25	4.707	115	10.01	51	1.70
8	5.25	4.754	115	9.97	51	1.69
9	5.28	4.779	116	9.88	51	1.68
10	5.60	4.574	117	9.91	50	1.65
Total	52.75	46.643	1140	101.92	512	17.1
Min	5.275	4.6643	114	10.192	51.2	1.71

Table C11: Emissions at 1000 Watts

LPG Fuel System

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	3.51	3.222	324	9.24	1	1.33
2	3.51	3.222	325	9.29	1	1.33
3	3.51	3.383	325	9.29	1	1.33
4	3.51	3.364	342	9.31	2	1.33
5	3.51	3.358	337	9.40	2	1.34
6	3.51	3.358	335	9.41	2	1.35
7	3.51	3.325	335	9.41	2	1.35
8	3.50	3.345	335	9.50	2	1.36
9	3.50	3.365	336	9.48	3	1.36
10	3.50	3.345	336	9.48	3	1.36
Total	35.07	33.287	3330	93.81	19.00	13.4
Min	3.507	3.3287	333	9.381	1.9	1.34

Table C12: Emissions at 0 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	3.88	3.033	258	9.60	2	1.39
2	3.85	3.063	256	9.86	2	1.42
3	3.85	3.300	256	9.86	2	1.42
4	3.84	3.289	256	9.86	2	1.42
5	3.82	3.157	255	9.83	2	1.42
6	3.78	3.032	254	9.81	2	1.41
7	3.77	3.037	254	9.76	3	1.41
8	3.77	3.037	254	9.67	3	1.41
9	3.75	3.300	254	9.67	2	1.38
10	3.75	2.804	253	9.61	3	1.38
Total	38.06	31.052	2550	97.53	23	14.06
Min	3.806	3.1052	255	9.753	2.3	1.406

Table C13: Emissions at 100 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	3.76	2.786	183	10.14	6	1.50
2	3.75	2.778	182	10.08	6	1.49
3	3.75	2.760	182	10.00	7	1.49
4	3.75	2.760	182	9.95	6	1.48
5	3.75	2.768	182	9.95	6	1.48
6	3.75	2.921	182	9.92	6	1.48
7	3.75	2.936	181	9.87	6	1.48
8	3.75	2.928	181	9.78	7	1.48
9	3.75	2.928	181	9.93	7	1.47
10	3.75	2.939	180	9.93	6	1.50
Total	37.51	28.504	1816	99.55	63	14.85
Min	3.751	2.8504	181.6	9.955	6.3	1.485

Table C14: Emissions at 200 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.23	2.784	135	10.22	20	1.56
2	4.23	2.755	135	10.22	20	1.56
3	4.30	2.755	134	9.99	21	1.51
4	4.32	2.700	134	9.56	22	1.44
5	4.32	2.533	135	9.06	21	1.39
6	4.36	2.639	135	9.06	21	1.39
7	4.52	2.665	135	9.16	22	1.44
8	4.45	2.701	135	9.46	23	1.47
9	4.42	2.701	135	9.45	23	1.46
10	4.40	2.708	135	9.45	22	1.46
Total	43.55	26.941	1348	95.63	215	14.68
Min	4.355	2.6941	134.8	9.563	21.5	1.468

Table C15: Emissions at 300 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.22	2.363	131	9.69	24	1.53
2	4.20	2.481	130	9,75	24	1.54
3	4.22	2.481	129	9.73	25	1.53
4	4.23	2.456	129	9.40	23	1.48
5	4.23	2.470	129	9.35	23	1.47
6	4.24	2.470	129	9.35	24	1.47
7	4.22	2.492	129	9.16	22	1.46
8	4.22	2.483	129	8.89	25	1.42
9	4.24	2.463	130	8.64	25	1.40
10	4.26	2.465	131	8.44	26	1.38
Total	42.282	24.624	1296	82.65	241	14.68
Min	4.2282	2.4624	129.6	8.265	24.1	1.468

Table C16: Emissions at 400 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.32	2.478	116	9.44	25	1.52
2	4.33	2.478	116	8.92	25	1.46
3	4.33	2.483	115	8.92	27	1.46
4	4.33	2.527	117	8.39	27	1.4
5	4.38	2.620	118	8.24	27	1.38
6	4.40	2.619	119	7.94	28	1.36
7	4.40	2.619	119	7.94	28	1.36
8	4.45	2.339	120	7.86	28	1.35
9	4.47	2.333	122	7.73	30	1.34
10	4.47	2.372	122	7.73	30	1.34
Total	43.88	24.868	1184	83.11	275	13.97
Min	4.388	2.4868	118.4	8.311	27.5	1.397

Table C17: Emissions at 500 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.35	2.414	99	8.53	28	1.57
2	4.35	2.375	99	9.16	28	1.65
3	2.45	2.375	98	9.32	29	1.65
4	4.38	2.382	98	9.32	30	1.64
5	4.40	2.388	98	9.51	30	1.64
6	4.45	2.597	98	9.21	32	1.64
7	4.48	2.597	98	8.77	32	1.58
8	4.52	2.554	98	8.77	32	1.58
9	4.55	2.401	98	8.54	33	1.56
10	4.59	2.401	98	8.62	34	1.57
Total	42.524	24.484	982	89.75	308	16.08
Min	4.2524	2.4484	98.2	8.975	30.8	1.608

Table C18: Emissions at 600 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.46	1.996	77	9.46	33	1.67
2	4.46	2.003	78	9.32	33	1.66
3	4.52	2.019	79	9.17	34	1.60
4	4.53	2.019	79	9.17	36	1.60
5	4.53	2.156	79	8.88	36	1.60
6	4.58	2.165	80	8.75	36	1.59
7	4.60	2.157	80	8.61	37	1.57
8	4.60	2.144	81	8.56	37	1.57
9	4.65	2.144	81	8.56	38	1.57
10	4.68	2.135	81	8.42	40	1.56
Total	45.61	20.938	795	88.9	360	15.99
Min	4.561	2.0938	79.5	8.89	36	1.599

Table C19: Emissions at 700 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.46	2.989	68	8.97	35	1.65
2	4.66	3.022	69	8.95	35	1.65
3	4.66	3.030	69	8.88	35	1.65
4	4.45	3.033	70	8.69	36	1.65
5	4.52	3.019	70	8.58	38	1.66
6	4.56	3.015	70	8.58	39	1.66
7	4.56	3.122	70	8.55	40	1.68
8	4.60	3.125	70	8.58	40	1.68
9	4.62	3.125	70	8.42	40	1.68
10	4.64	3.128	70	8.37	41	1.68
Total	45.73	30.608	696	86.57	379	16.64
Min	4.573	3.0608	69.6	8.657	37.9	1.664

Table C20: Emissions at 800 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.55	3.210	58	8.58	40	1.68
2	4.55	3.218	59	8.60	40	1.68
3	4.58	3.218	59	8.60	40	1.66
4	4.60	3.346	62	8.72	39	1.65
5	4.65	3.350	62	8.75	42	1.65
6	4.65	3.335	63	8.80	42	1.65
7	4.64	3.348	63	8.84	45	1.66
8	4.66	3.352	63	8.86	44	1.67
9	4.70	3.455	63	9.02	44	1.69
10	4.73	3.457	60	9.02	44	1.68
Total	46.31	33.289	612	87.79	420	16.67
Min	4.631	3.3289	61.2	8.779	42	1.667

Table C21: Emissions at 900 Watts

no	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
1	4.41	3.458	62	8.88	39	1.60
2	4.47	3.520	66	8.98	42	1.60
3	4.48	3.536	66	9.02	42	1.60
4	4.56	3.536	66	9.10	42	1.61
5	4.60	3.550	65	9.15	42	1.61
6	4.60	3.567	65	9.15	41	1.60
7	4.68	3.578	64	9.22	44	1.62
8	4.70	3.585	64	9.25	45	1.60
9	4.75	3.670	64	9.34	45	1.60
10	4.83	3.899	67	9.47	46	1.59
Total	46.08	35.899	649	91.56	428	16.03
Min	4.608	3.5899	64.9	9.156	42.8	1.603

Table C22: Emissions at 1000 Watts

COMPILE EMISSION GASES DATA

Gasoline system

Load (Watt)	Exhaust temp (℃)	Body temp (℃)	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
0	338.6	69.1	3.964	6.0636	50.2	12.921	27.4	2.030
100	425.1	73.1	4.227	5.7120	59.1	13.349	23.0	2.201
200	453.1	93.3	4.655	5.2199	49.3	12.289	32.3	1.979
300	403.2	97.9	4.648	4.8685	49.7	12.354	33.5	2.019
400	437.8	99.6	4.485	4.5314	50.1	12.452	35.1	2.099
500	446.7	101.8	4.725	4.2484	51.0	12.314	38.6	2.044
600	406.9	110.3	5.155	4.4550	51.9	11.756	43.8	1.944
700	430.4	108.6	5.130	4.6050	77.9	10.397	44.2	1.937
800	387.8	106.4	4.987	4.2855	99.9	11.009	45.4	1.830
900	389.6	108.3	5.540	4.7280	117.4	10.199	50.9	1.792
1000	415.3	110.9	5.275	4.6643	114.0	10.192	51.2	1.710

Table C23: Compile emission gases data for gasoline system

LPG fuel system

Load (Watt)	Exhaust temp (℃)	Body temp (℃)	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_x (ppm)	Lambda
0	479.6	105.9	3.507	3.3287	333.0	9.381	1.9	1.344
100	500.5	109.8	3.806	3.1052	255.0	9.753	2.3	1.406
200	512.2	110.6	3.751	2.8504	181.6	9.955	6.3	1.485
300	491.8	108.8	4.355	2.6941	134.8	9.563	21.5	1.468
400	481.1	115.9	4.228	2.4624	129.6	8.265	24.1	1.468
500	499.2	117.3	4.388	2.4868	118.4	8.311	27.5	1.397
600	484.9	125.7	4.252	2.5065	98.2	8.975	30.8	1.608
700	508.9	122.2	4.561	2.0938	79.5	8.890	36.0	1.599
800	507.8	124.8	4.573	3.0608	69.6	8.657	37.9	1.664
900	505.6	128.2	4.631	3.3289	61.2	8.779	42.0	1.667
1000	502.3	129.5	4.608	3.5899	64.9	9.156	42.8	1.603

Table C24: Compile emission gases data for LPG fuel system

ENGINE PERFORMANCE

Gasoline system

Load (watt)	Engine Speed (rpm)	Torque (N.m)	Brake Power (kW)	Time for 10ml fuel (s)	Density	Mass Flow Rate (kg/h)	bsfc (kg/kW.h)	Engine efficiency
0	2775	0.00	0.00	71	748.92	0.3797	0.00	0.00
100	2646	0.36	0.10	84	748.92	0.3210	3.21	2.66
200	2543	0.75	0.20	85	748.92	0.3172	1.59	5.39
300	2479	1.16	0.30	90	748.92	0.2996	1.00	8.56
400	2363	1.62	0.40	95	748.92	0.2838	0.71	12.05
500	2298	2.08	0.50	88	748.92	0.3064	0.61	13.96
600	2262	2.53	0.60	84	748.92	0.3210	0.53	15.99
700	2237	2.99	0.70	80	748.92	0.3370	0.48	17.76
800	2209	3.46	0.80	74	748.92	0.3643	0.46	18.78
900	2183	3.94	0.90	72	748.92	0.3745	0.42	20.55
1000	2155	4.43	1.00	69	748.92	0.3907	0.39	21.88

Table C25: Engine performance for gasoline system

LPG fuel system

Load (watt)	Engine Speed (rpm)	Torque (N.m)	Brake Power (kW)	Weight consumed in 1 min (kg)	Mass Flow Rate (kg/h)	bsfc (kg/kW.h)	Engine efficiency
0	3125	0.00	0.00	0.005	0.3000	0.00	0.00
100	3094	0.31	0.10	0.005	0.3000	3.00	2.59
200	3085	0.62	0.20	0.006	0.3600	1.80	4.31
300	3072	0.93	0.30	0.007	0.4200	1.40	5.55
400	3074	1.24	0.40	0.007	0.4200	1.05	7.39
500	3055	1.56	0.50	0.006	0.3600	0.72	10.78
600	3054	1.88	0.60	0.006	0.3600	0.60	12.94
700	3042	2.20	0.70	0.006	0.3600	0.51	15.10
800	3031	2.52	0.80	0.006	0.3600	0.45	17.25
900	3044	2.82	0.90	0.006	0.3600	0.40	19.41
1000	3049	3.13	1.00	0.007	0.4200	0.42	18.48

Table C26: Engine performance for LPG fuel system

APPENDIX D

CALCULATION OF DATA

CALCULATION OF ENGINE PARAMETERS

- **Torque**

$$\tau = \frac{60P}{2\pi N}$$

Where τ = Torque (Nm)
P = Power developed by engine (W)
π = 3.142
N = Engine speed (rpm)

- **Mass Flow Rate for Gasoline**

$$\dot{m} = \frac{\rho \times V}{t}$$

Where $\dot{m}$ = Mass flow rate (kg/h)
ρ = Density of gasoline (kg/m^3)
V = Volume of gasoline (ml)
t = Time (s)

- **Mass Flow Rate for LPG**

$$\dot{m} = \frac{m}{t}$$

Where $\dot{m}$ = Mass flow rate (kg/h)
m = Mass of LPG consumed (kg)
t = Time (s)

- **Brake Specific Fuel Consumption**

$$bsfc = \frac{\dot{m}}{BP}$$

Where bsfc = Brake specific fuel consumption rate (kg/kW.h)

$\dot{m}$ = Mass flow rate (kg/h)

BP = Brake power (kW)

- **Engine Efficiency**

$$\eta_f = \frac{3.6}{(bsfc) \times Q_{HV}} \tag{3.10}$$

Where η_f = Engine efficiency

Q_{HV} = Lower calorific value of fuel (MJ/kg)

$bsfc$ = Brake specific fuel consumption (kg/kWh)

Where

$Q_{HV_{Gasoline}}$ = 42.1 MJ/kg

$Q_{HV_{LPG}}$ = 46.37 MJ/kg