COMPARATIVE STUDY OF ETHANOL AND ISOBUTANOL AS GASOLINE BLEND FOR INTERNAL COMBUSTION ENGINE

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COMPARATIVE STUDY OF ETHANOL AND ISOBUTANOL AS GASOLINE BLEND FOR INTERNAL COMBUSTION ENGINE

ABSTRACT

The heavy reliance on petroleum-derived fuels such as gasoline in the transportation sector is one of the major causes of environmental pollution. For this reason, there is a critical need to develop cleaner alternative fuels. The alcohols such as ethanol and isobutanol can be blended with gasoline to produce cleaner alternative fuels because of their favorable physicochemical properties. This study examined the effect of single and dual alcohol of ethanol and isobutanol in gasoline blends on the engine performance and emission characteristics of a spark ignition engine. Six types of fuel blends consist of both alcohols were mixed with unleaded gasoline at different volume rates (E10, E20, iB10, iB20, E5iB5 and E10iB10) and the physicochemical properties of these blends are measured and compared with the pure gasoline. Tests are conducted on a SI engine at wide open throttle position by varying the engine speed ranging from 1000 to 5000 rpm with step of 1000 rpm. Then, a constant- speed test was conducted at 4000 rpm by varying engine torque ranging from 20 to 100 Nm with step of 20 Nm The results show that the fuel blends have a significant increase in the density, viscosity and heat of vaporization, but they are lower in heating value and Reid vapor pressure as compared with pure gasoline. In addition, the E20 blend gives the most significant enhancement for torque, brake power and brake thermal efficiency with an average enhancement of 3.88, 2.60 and 13.61%, respectively, while E10iB10 blend gives the largest improvement of brake specific fuel consumption with an average enhancement of 5.77% than that of pure gasoline. There are no significant changes of exhaust gas temperature between the fuel blends and pure gasoline for both operating conditions. In terms of exhaust emissions, E10iB10 blend results in the lowest CO and HC emissions by varying the engine speeds with an average reduction of 11.21 and 17.13%, respectively, relative to pure gasoline.

By varying the engine torque, E20 and E10iB10 blends result in the lowest CO and HC emissions with an average reduction of 44.02 and 46.32%, respectively, with respect to pure gasoline. However, all the tested fuel blends show higher CO_2 emissions as compared to pure gasoline for both operating conditions. In terms of NO_X emission, there is no significant differences for all fuel blends with pure gasoline for both conditions.

Keywords: ethanol, isobutanol, alternative fuel, spark ignition engine

KAJIAN PERBANDINGAN ETANOL DAN ISOBUTANOL SEBAGAI CAMPURAN GASOLIN UNTUK ENJIN PEMBAKARAN DALAM

ABSTRAK

Kebergantungan tinggi terhadap sumber bahan api petroleum seperti petrol dalam sektor pengangkutan adalah salah satu punca utama berlakunya pencemaran alam sekitar. Oleh sebab ini, terdapat keperluan kritikal untuk membangunkan bahan api alternatif yang lebih bersih. Alkohol seperti etanol dan isobutanol boleh dicampur bersama petrol untuk menghasilkan bahan api alternatif yang lebih bersih kerana sifat-sifat fizikokimia yang baik. Kajian ini menyiasat kesan penggunaan alkohol tunggal dan dual; etanol dan isobutanol dalam campuran petrol terhadap prestasi enjin dan ciri-ciri pelepasan ekzos pada enjin penyalaan cucuh. Enam jenis campuran bahan api terdiri daripada kedua-dua alkohol dicampurkan bersama petrol tanpa plumbum pada kadar isipadu yang berbeza (E10, E20, iB10, iB20, E5iB5 dan E10iB10) dan sifat-sifat fizikokimia campuran tersebut telah diuji dan dibandingkan dengan petrol tulen. Ujian dijalankan pada enjin penyalaan pencucuh dengan mengubah kelajuaan enjin daripada 1000 kepada 5000 putaran per minit (rpm) dengan peningkatan sebanyak 1000 rpm. Kemudian, ujian enjin pada kelajuan malar dijalankan pada kelajuan 4000 rpm dengan mengubah tork enjin daripada 20 kepada 100 Newton meter (Nm) dengan peningkatan sebanyak 20 Nm. Keputusan kajian menunjukkan campuran bahan api menunjukkan peningkatan yang ketara pada nilai ketumpatan, kelikatan dan haba pengewapan, tetapi nilai pemanasan dan tekanan wap Reid adalah lebih rendah berbanding petrol tulen. Tambahan pula, campuran E20 menunjukkan peningkatan yang paling ketara pada keputusan tork enjin, kuasa brek dan kecekapan haba brek dengan peningkatan purata 3.88, 2.60 dan 13.61%, manakala campuran E10iB10 menunjukkan peningkatan paling tinggi pada keputusan penggunaan bahan api tertentu brek dengan peningkatan purata 5.77% berbanding petrol tulen. Tiada perubahan ketara pada keputusan suhu gas ekzos antara campuran bahan api dan petrol

tulen yang diuji untuk kedua-dua keadaan kendalian. Dari segi pelepasan ekzos, campuran E10iB10 menunjukkan keputusan pelepasan karbon monoksida (CO) dan hidrokarbon (HC) yang paling rendah pada kelajuan enjin yang berbeza dengan pengurangan purata 9.67 and 16.06% berbanding petrol tulen. Pada perbezaan tork enjin, campuran E20 dan E10iB10 masing-masing menunjukkan keputusan pelepasan karbon monoksida (CO) dan hidrokarbon (HC) yang paling rendah dengan pengurangan purata 44.02 dan 46.32% berbanding petrol tulen. Walaubaimanapun, semua campuran bahan api yang diuji menunjukkan peningkatan karbon dioksida (CO_2) pada kedua-dua keadaan kendalian. Dari segi pelepasan nitrogen oksida (NO_X) pula, tiada perbezaan yang signifikan bagi semua campuran bahan api yang diuji berbanding petrol tulen untuk kedua-dua keadaan kendalian.

Keywords: etanol, isobutanol, bahan api alternatif, enjin penyalaan cucuh

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LIST OF SYMBOLS AND ABBREVIATIONS

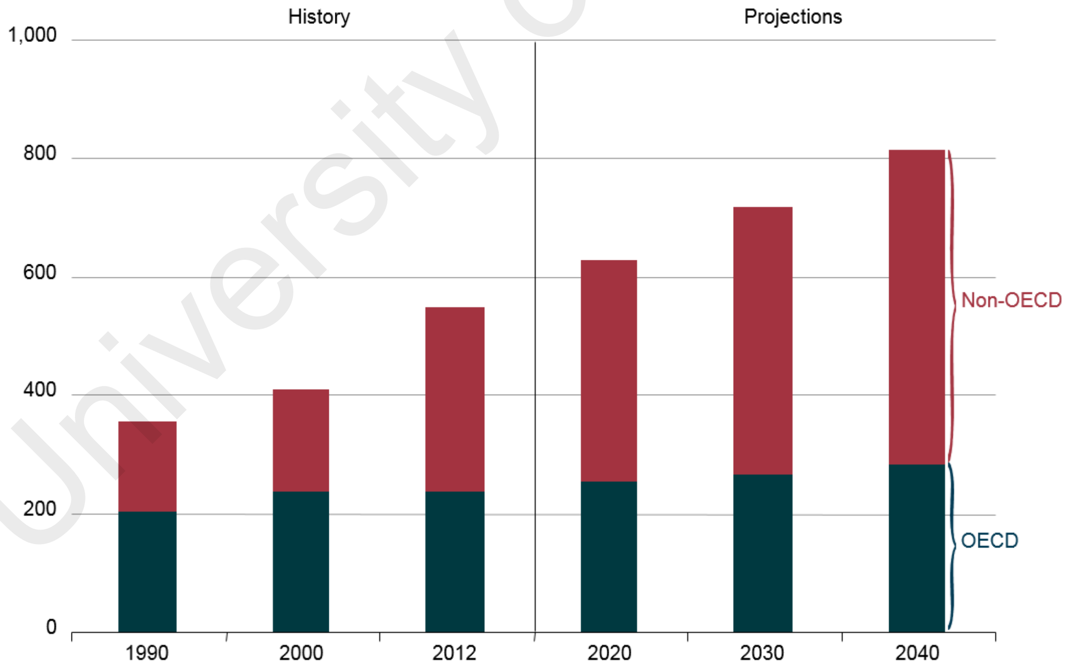
EIA	:	United States Energy Information Administration
OECD	:	Organization for Economic Co-operation and Development
GHG	:	Greenhouse Gases
SI	:	Spark Ignition or Gasoline Engine
FFV	:	Flex Fuel Vehicle
RON	:	Research Octane Number
RVP	:	Reid Vapor Pressure
HHV	:	High Heating Value
LHV	:	Lower Heating Value
HOV	:	Heat of Vaporization
ASTM	:	American Society for Testing and Materials
MPFI	:	Multi-Point Fuel Injection
WOT	:	Wide Open Throttle
DOHC	:	Dual Overhead Camshaft
T	:	Torque
BP	:	Brake Power
BTE	:	Brake Thermal Efficiency
BSFC	:	Brake Specific Fuel Consumption
EGT	:	Exhaust Gas Temperature
VE	:	Volumetric Efficiency
CO	:	Carbon Monoxide
CO_2	:	Carbon Dioxide
HC	:	Hydrocarbon
NO_X	:	Nitrogen Oxides

NO	:	Nitrogen Monoxide
NO_2	:	Nitrogen Dioxide
PM	:	Particulate Matters
E	:	Ethanol
iB	:	Isobutanol
E10	:	Blend containing 10 vol.% of ethanol in gasoline
E20	:	Blend containing 20 vol.% of ethanol in gasoline
iB10	:	Blend containing 10 vol.% of isobutanol in gasoline
iB20	:	Blend containing 20 vol.% of isobutanol in gasoline
E5iB5	:	Blend containing 5 vol.% of ethanol and 5 vol.% of isobutanol in gasoline
E10iB10	:	Blend containing 10 vol.% of ethanol and 10 vol.% of isobutanol in gasoline
PG	:	Pure Gasoline
Btu	:	British thermal unit
rpm	:	revolution per minute

CHAPTER 1: INTRODUCTION

1.1 Overview

Most recently, with the significant growth of populations and economic activities all over the worlds, energy plays an important role for a sustainable development. The demand for energy resources is increasing day by day, and it has been invaluable to human activities, domestic life, transportation, manufacturing process, industrial facilities, lighting, etc. According to United States Energy Information Administration (EIA), the world energy demand increases from 549 quadrillion Btu in 2012 to 629 quadrillion Btu in year 2020 and to 815 quadrillion Btu in 2040 as it presented in **Figure 1.1** (EIA, 2016). Most terrifyingly, the existing amount of fossil fuels i.e. petroleum, coal and natural gas as the primary source of energy is decreasing and it is assumed to be completely diminished for the next 40-50 years (Saidur et al., 2011).



Note: Organization for Economic Co-operation and Development (OECD) is an intergovernmental economic organization with 35 member countries.

Figure 1.1: World energy consumption, year 1990-2040 (EIA, 2016)

Over time, the extensive use fossil fuels also adversely affect environmental pollution as it tends to contribute greenhouse gases i.e. carbon dioxide (CO_2) hence aggravates global warming. The rise of global temperature caused by global warming could leads to extinction of millions natural species and also brings harm to the ecosystem. It is shown that the CO_2 emissions has increased approximately 1.6 times in the last three decades by the anthropogenic activities (Hosseini & Wahid, 2013). The emissions such as CO_2, NO_X, CO and SO_2 are emitted and they are extremely harmful for humans too.

In spite of that, the government seeks into new policies to empower renewable energy to solve environmental issues e.g. Kyoto Protocol (KP) 1997 has mandates any countries that involved in industrial activities must reduce by at least 5% pollutants below 1990 levels (Hosseini & Wahid, 2013). Scientists are looking forward to discover new sustainable and renewable energy sources of energy or known as bio-energy. This bio-energy is created from various natural resources to produce biofuels, which helps to sustain the economic growth and living society for the next generation. Berndes et al. (2003) believes that the bio-energy is able to contribute about 100 EJ/year to 400 EJ/year for the future global energy supply in 2050. Besides that, the government aims new policies to empower renewable energy to solve the environmental issues. For example, Malaysia's National Energy Policy of 1979 targets to have an efficient, safe, clean and environmental friendly of energy supply in the future (Ashnani et al., 2014; Sulaiman et al., 2011). Besides that, Malaysia's Fuel Diversification Policy was set out by the Malaysia Government to develop biomass as the 'fifth fuel' resource of renewable energy, and consequently to reduce dependency on fossil fuels (Mohamed & Lee, 2006).

1.2 Background

The use of bio based alcohol like ethanol as the alternative fuel is not a new concept as Samuel Morely has developed an engine that ran with ethanol in 1826 and Henry Ford's Model T was built up to run on ethanol in 1908. However, the demand on ethanol was drove up after World War I and then gasoline was dominating the market in 1920s. In 1974, Solar Energy Research, Development, and Demonstration Act of 1974 promoted ethanol as gasoline alternate due to energy crisis. At that time, the ethanol is the most widely used biofuel in transportation due to rising oil price, tremendous risk of climate change, increasing on fuel vehicle demand and also security of energy supply. Therefore, the governments authorize new policies to do research, develop and deploy more sustainable and renewable energy sources. Energy Policy Act of 2005 in United States is most significant steps by mandate the use of ethanol through the Renewable Fuel Standard (RFS) (Demirbas & Balat, 2006). Besides that, the initiation of National Alcohol Fuel Program (Pró-Álcool) in Brazil targets to increase the production of bioethanol in order to substitute the high cost and inadequate standard petroleum-based products (Rasskazchikova et al., 2004).

Figure 1.2 and **Table 1.1** shows the chart and the statistical data for world ethanol fuel production by country or region from year 2007-2015, respectively (RFA, 2016). The global ethanol fuel production reached from 13 billion gallons in year 2007 to more than 25 billion gallons in year 2015 which is the highest ethanol fuel production since 2007. The production is increasing steadily across the nations with regard to reduce oil imports, improve air quality and boost rural economies. In addition, there are 31 countries in international level and 29 provinces which mandate the use of ethanol-gasoline blend in year 2011 (J.L. Sawin et al., 2011). **Table 1.2** listed the usage of ethanol-gasoline fuel blends in different countries (Bajpai, 2013; Janet L Sawin, 2008).

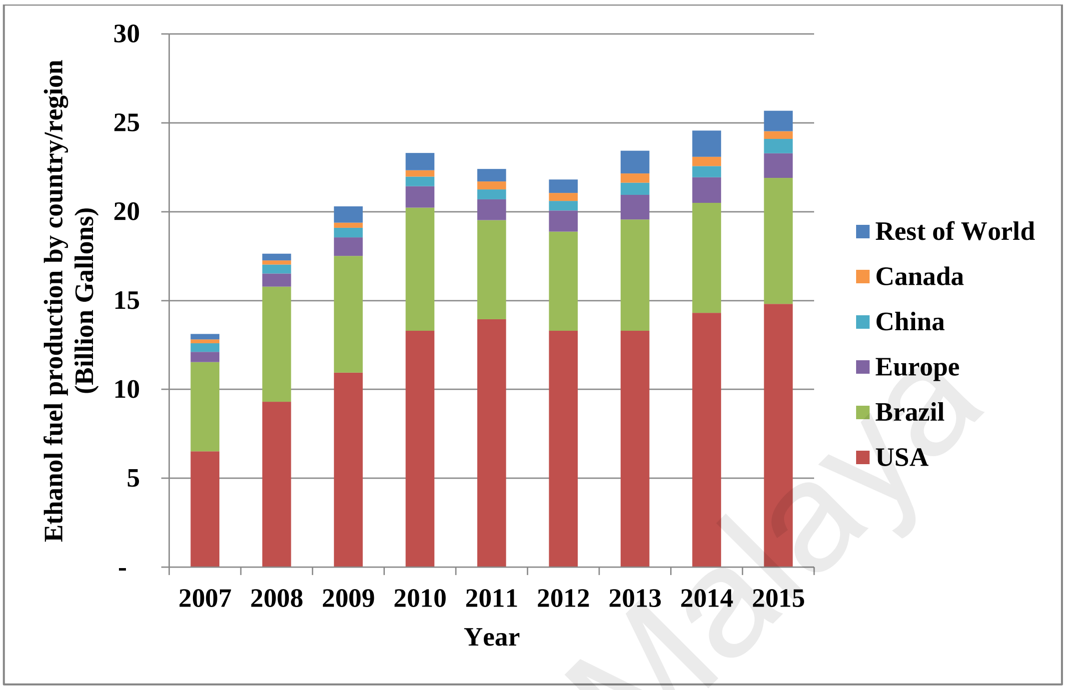


Figure 1.2: Chart for world ethanol fuel production by country/region and year (RFA, 2016)

Table 1.1: Statistical data for world fuel ethanol production by country/region

Country	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
USA	6,521	9,309	10,938	13,298	13,948	13,300	13,300	14,300	14,806
Brazil	5,019	6,472	6,578	6,922	5,573	5,577	6,267	6,190	7,093
Europe	570	734	1,040	1,209	1,168	1,179	1,371	1,445	1,387
China	486	502	542	542	555	555	696	635	813
Canada	211	238	291	357	462	449	523	510	436
Rest of World	315	389	914	985	698	752	1,272	1,490	1,147
WORLD	**13,123**	**17,644**	**20,303**	**23,311**	**22,404**	**21,812**	**23,429**	**24,570**	**25,682**

Source: RFA (2016)

Note: The unit in million gallons

Table 1.2: Ethanol-gasoline fuel blends used in different countries

Country	Bioethanol-gasoline fuel blend
Angola	E10
Argentina	E5
Australia	E4: The blends are used in South wales E5: The blends are used in Queensland
Brazil	E25-E75: Higher blends are used for flex fuel vehicles E100
Canada	E5: The blends are used in National; British Columbia, Alberta & Ontario provinces E7.5: The blends are used in Saskatchewan province E8.5: The blends are used in Manitoba province
Colombia	E8
Costa Rica	E7
Ethiopia	E5
Guatemala	E5
India	E5
Indonesia	E3
Jamaica	E10
Malawi	E10
Malaysia	Not available
Mozambique	E10: The blends are used in 2012-2012 E15: The blends are expected to be used in year 2016-2020 E20: The blends are expected to be used in year 2021 onwards
Paraguay	E24
Peru	E7.8
Philippines	E10
South Africa	E10
South Korea	Not available
Sudan	E5
Thailand	E5
Turkey	E2
United States	E10 (gasohol): The blends used in Missouri, Montana, Florida, Hawaii, New Mexico, Oregon states E70-E85: Blends varies with states
Uruguay	E5: The blends are expected to be used in 2015
Vietnam	E5
Zambia	E10

Source: Bajpai (2013) & J.L. Sawin et al. (2011)

Note:
E2: 2 vol% ethanol-98 vol% gasoline; E3: 3 vol% ethanol-97 vol% gasoline; E4: 4 vol% ethanol-96 vol% gasoline; E5: 5 vol% ethanol-95 vol% gasoline; E7: 7 vol% ethanol-93 vol% gasoline; E7.5: 7.5 vol% ethanol-92.5 vol% gasoline; E7.8: 7.8 vol% ethanol-92.2 vol% gasoline; E8: 8 vol% ethanol-92 vol% gasoline; E8.5: 8.5 vol% ethanol-91.5 vol% gasoline; E10: 10 vol% ethanol-90 vol% gasoline; E15: 15 vol% ethanol-85 vol% gasoline; E20: 20 vol% ethanol-80 vol% gasoline; E25: 25 vol% ethanol-75 vol% gasoline; E75: 75 vol% ethanol-25 vol% gasoline; E85: 85 vol% ethanol-15 vol% gasoline; E100: 100 vol% ethanol or pure ethanol

The investigation on higher carbon chain of alcohols such as butanol as the option for liquid fuel have received much interest recently. Butanol production has long history since it was discovered by Wirtz in 1852 as fusel oil and then Louise Pasteur was clarified the synthesis of butanol at laboratory scale 10 years later in 1861 (Costa & Sodré, 2010; Jin et al., 2011; Ranjan & Moholkar, 2009). Then, the production of acetone-butanol-ethanol (ABE) fermentation of molasses and cereal grains using Clostridium acetobutylicum was achieved in 1912-1916 by the chemist Chaim Weizmann (Shapovalov & Ashkinazi, 2008; Weizmann, 1919). However, the ABE fermentation continuously declined since 1950s, and almost the butanol was produced via petrochemical process due to lower price of petrochemicals and increased food demand of sugar and starchy grains (Jin et al., 2011). The high cost, low-yield and slow fermentations process results the bio based butanol could not compete on a commercial scale thus it is produced synthetically. However, many countries and big oil companies look forward on the bio based butanol again during oil crisis in 1970s as the rising price of petroleum oil and the increase of GHGs in the atmosphere.

Butanol becomes an alternative to ethanol and gasoline as transportation fuels in spark ignition engine due to its advantages in terms of physicochemical properties. Currently, n-butanol and isobutanol are considered as gasoline components to be blended with in higher concentrations without any modification on conventional gasoline engine (Niemistö et al., 2013). Meanwhile, new automobiles FFVs that use 85 vol% ethanol blend (E85) cost a lot of money and quite unaffordable for most car buyers. Therefore, butanol fuel blends are able to replace conventional gasoline in existing cars without modifying the engine’s specifications. Szulczyk (2010) explained that butanol can be blended with gasoline in any percentage up to 100 vol% of butanol in conventional SI engine.

1.3 Problem statement

Ethanol has much higher oxygen content with a value of 34.7 wt.%, which promotes higher complete combustion and lower exhaust emissions. It also has higher research octane number (RON) than gasoline and butanol, which prevents premature ignition that cause knocking which can damage the engine. This higher octane rating also gives advantages in improving the thermal efficiency. However, the combustion of ethanol in gasoline engine gives some inherent problems due to its higher heat of vaporization that leads problems when engine start-up including when running cold engine (Larsen et al., 2009; Patakova et al., 2011) and also promotes higher emissions of organic gases (Chiba et al., 2010). In addition, the low carbon chain alcohol like ethanol gives lower amount of heating value, therefore it provides higher fuel consumption as compared to gasoline. Moreover, ethanol also miscible with water, thus it creates water contamination to the fuel system.

Recent studies focus on the production of higher carbon number alcohols from various renewable sources as the alternative energy. Butanol which is a four carbon alcohol can be used as an alternative fuel to ethanol and gasoline in a spark ignition engine due to its stunning properties. Butanol has slightly lower heating value than gasoline, but it is much higher than ethanol, which can improve fuel consumption. Besides that, butanol has higher auto ignition temperature than ethanol and gasoline, which affect the thermal efficiency and exhaust emissions characteristics. The lower water solubility of butanol can resolve the water contamination problems.

In respect from previous studies, there are numerous valuable studies on ethanol and butanol which can improve engine performances and emissions characteristics. However, there are still lack of research on fuel optimization of single and dual alcohol of ethanol and butanol in gasoline blends on physicochemical properties, engine performances and exhaust emissions since both alcohols have their own advantages.

1.4 Objectives of study

This study is done to compare the single and dual alcohols of ethanol and isobutanol as gasoline blend for an unmodified SI engine. The considered objectives of study are as follows:

1. To characterize the physicochemical properties of single and dual alcohols of ethanol and isobutanol fuel blends and compare with pure gasoline.
2. To investigate the effect of the tested fuel blends on engine performance, i.e. the torque (T), brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT).
3. To evaluate the effect of the tested fuel blends on the exhaust emission characteristics, i.e. carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC) and nitrogen oxides (NO_X).

1.5 Scope of work

This study aims to compare the single and dual alcohols as gasoline blend for a spark ignition engine. The ethanol and isobutanol were used as the blending component with gasoline fuel blends at different volume ratio. The physicochemical properties of tested fuel blends such as oxygen content, higher heating value (HHV), research octane number (RON), density, viscosity, Reid vapor pressure (RVP) and latent heat of vaporization (HOV) were determined and then compared with pure gasoline. Then, the tested fuel blends were examined in a 4-cylinder spark ignition engine to determine their engine performances and exhaust emissions characteristic, then the tested results were comprehensively compared with the pure gasoline.

1.6 Organization of dissertation

This dissertation consists of five chapters. The organization of each chapter is listed as follows:

Chapter 1 presents an overview on energy security, economic developments and environmental needs. This section also discusses on the problems that associated with fossil fuel and enlighten on alcohol as an alternative fuel to gasoline. This is followed by the problems which is related with physicochemical properties of ethanol and butanol fuel blend. Finally, objectives and scopes of this research work are discussed.

Chapter 2 explains in detail the importance of alcohols as the gasoline alternative. The potential sources and the production of ethanol and butanol are discussed. This section also compares the physicochemical properties of gasoline, ethanol and butanol. Then, the effect of ethanol and butanol in gasoline blend on engine performances and exhaust emissions are evaluated. Subsequently, a summary and the research gap of this study are discussed.

Chapter 3 describes the research methodology and experimental technique to achieve the research objectives. These includes the selection of alcohol fuels, measurement of physicochemical properties of selected alcohols and their blends, fuel blending preparation for engine testing, engine performance and emissions analysis.

Chapter 4 presents the results that have been obtained from the experimental work. This is followed by providing analysis and detailed discussion. These findings are then compared with the previous studies.

Chapter 5 concludes the research findings and puts forward some recommendations for the future study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Although the gasoline is predominantly used in spark engine vehicles, the world has proposed the use biofuels as the alternative and additive source in liquid transportation fuel. Nowadays, the ethanol is extensively used in many countries as the blend component for spark ignition vehicles. In United States, 10 vol% ethanol in gasoline (E10 or gasohol) has been commercially used as fuel for vehicles. Besides that, the higher concentration of ethanol-gasoline blend such as E85 (85 vol% ethanol, 15 vol% gasoline) have been developed design for new flexible fuel vehicle (FFV) engine. As recorded, almost 90% new cars in Brazil which are sold with FFV engine and the fuel sold contains 20-25 vol% of anhydrous ethanol (Masum et al., 2013; Tavares et al., 2011). Meanwhile, there are nearly 8 million of FFVs on the road in United States with various range of vehicles models (Transport and Air Quality, 2010).

Interestingly, an immense investigation on higher carbon chain of alcohols such as butanol as an option for liquid fuel have received much interest recently. Butanol is believed to be a promising and competitive renewable biofuel in spark ignition vehicles besides the ethanol. There are a few attempts to commercialize the butanol as an alternative transportation fuel by David E Ramey since 1998-2003, however it was not clarified by Department of Energy (DOE) or National Renewable Energy Laboratory. Nonetheless, Ramey et al. (2007) successfully demonstrated pure butanol (Bu100) with unmodified SI engine by moving across America in 2005 and South Dakota in 2007. Besides that, International Clostridia Group has strived to acknowledge butanol fermentation for 25 years but this has been ignored by the fuel producers as they are only focus on ethanol fuel production. Although the biotechnological production of butanol is much complicated than ethanol, it gives far more advantages over ethanol due to its superior physicochemical properties. It can be mixed well with gasoline, higher of its energy content, flash point, boiling point as compared with that ethanol.

The objective of this chapter is to provide a thorough literature review on the current state of oxygenated alcohols in SI engine. The section first describes the physicochemical properties of ethanol, butanol and gasoline. Then a large number of selective literatures are reviewed in order to critically compare the effect of ethanol and butanol in gasoline engine.

2.2 Ethanol and butanol as alternative transportation fuel

The great thing about biofuel is that it can be produced from various sources of raw materials e.g. biomass. Biomass is the oldest source of fuel energy derived from living or organism which can be substituted the commercial fossil derived fuels. Basically, the biofuels production for bio-based ethanol and butanol can be categorized in two main groups; (i) conventional biofuels (first generation) and (ii) advanced biofuels (second and third generation) as illustrated in **Figure 2.1**.

The first generation of biofuels are basically produced from food crops such as sugar rich crops (sugar cane, sugar beet, sweet sorghum) and starch rich crops (corn, milo, wheat, rice, cassava, barley). The production of first generation biofuels can be achieved 50 billion liters per year (Naik et al., 2010). Bioethanol from agricultural food crops e.g. corns are used commercially for the blend component in transportation fuel. However, the feedstock of the first generation appears unsustainable due to the increasing demands of biofuel production. Thus this event causes the rising of food prices and shortage of these edible materials.

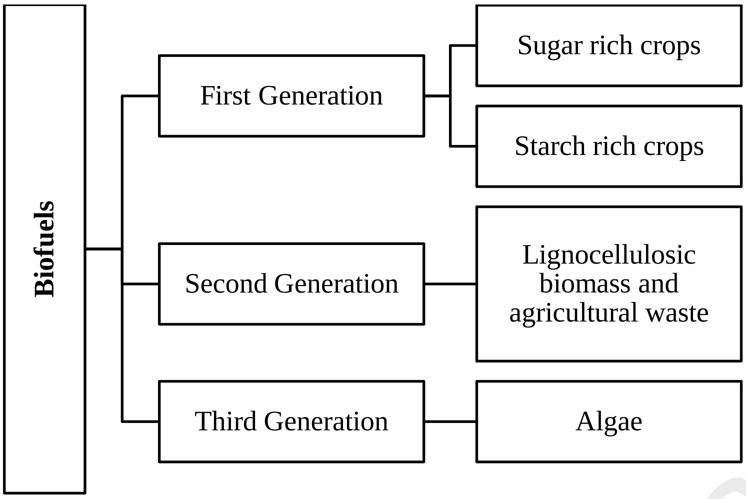


Figure 2.1: First, second and third generation of biofuels feedstocks

2.3 Production of ethanol and butanol

2.3.1 Ethanol

The production routes of bio-based ethanol vary for each feedstock materials as shown in **Table 2.1**. The first generation bioethanol feedstocks e.g. sucrose and starch rich materials can be produced via alcoholic fermentation (Masum et al., 2013; Sims et al., 2008). The starch rich crops contain long chain polymers of glucose have an additional process by mixing and grinding with water to break down into simpler glucose before it is fermented into the ethanol as shown in Equation (2.1) and Equation (2.2). The microorganism e.g. yeast (Saccharomyces sp.), bacteria (Zymomonas sp.) and mold (mycelium) have been widely used for fermentation of ethanol (Naik et al., 2010).

Meanwhile, the lignocellulosic biomass consists of cellulose, hemicellulose and lignin as its main components undergo several steps e.g. pre-treatment, enzymatic and acid hydrolysis, fermentation, distillation and evaporation to produce bio-based ethanol as shown in **Figure 2.2** (Aakko-Saksa et al., 2011; Hahn-Hägerdal et al., 2006). The pre-treatment process of hemicellulose is needed to increase the hydrolysis yield before it is hydrolyzed and fermented into bioethanol. Hamelinck et al. (2005) reported that the hydrolysis with pre-treatment yields over 90% while the hydrolysis without pre-treatment yield less than 20%. The common method of diluted or concentrated acid hydrolysis is used to convert lignocellulose into fermentable sugars, and then the hydrolysate is fermented into bioethanol.

Table 2.1: Bioethanol routes from different raw material of feedstocks

Raw materials	Process
Wood	Acid hydrolysis and fermentation
Wood	Enzymatic hydrolysis and fermentation
Straw	Acid hydrolysis and fermentation
Straw	Enzymatic hydrolysis and fermentation
Wheat	Malting and fermentation
Sugar cane	Fermentation
Sugar beet	Fermentation
Corn grain	Fermentation
Corn stalk	Acid hydrolysis and fermentation
Sweet sorghum	Fermentation

Source: Balat & Balat (2009)

$$\underset{\text{Starch}}{n\,(C_6H_{10}O_5)} + \underset{\text{Water}}{nH_2O} \longrightarrow \underset{\text{Glucose}}{nC_6H_{12}O_6} \qquad \textbf{(2.1)}$$

$$\underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow{\text{yeast}} \underset{\text{Bioethanol}}{2C_2H_5OH} + \underset{\text{Carbon dioxide}}{2CO_2} \qquad \textbf{(2.2)}$$

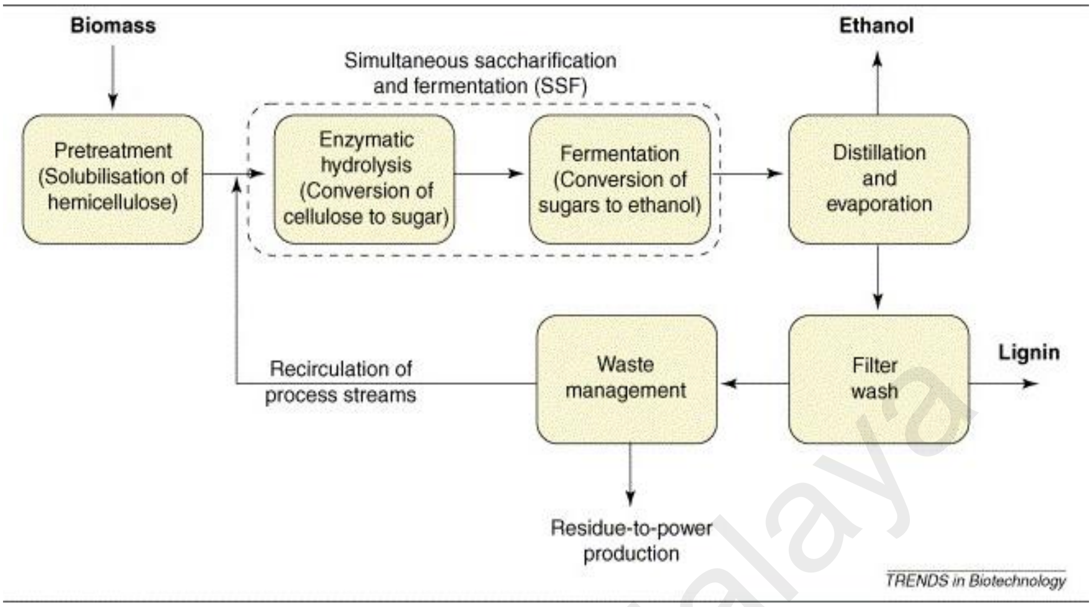


Figure 2.2: Production process for bioethanol from lignocellulosic biomass (Hahn-Hägerdal et al., 2006)

2.3.2 Butanol

Similar to bioethanol, bio based butanol can be produced from the same feedstocks, e.g. sugar crops, starch crops, lignocellulosic biomass and agricultural waste as well. The biological production of biobutanol has been invented decades ago but the process is quite expensive than petrochemical hydration process e.g. oxo-synthesis and aldol concentration. Therefore, almost all modern butanol is produced from petroleum known as petrobutanol. However, due to the depletion of fossil-fuel reserves and environmental issues, the interest on sustainable transportation fuels, especially from non-edible materials, has encourages the technological development in biobutanol fermentation.

Biobutanol can be produced via ABE fermentation where the acetone, butanol and ethanol are the main products of the process. Previously, the cereal grains and sugar feedstocks were utilized for industrial scale by the ABE fermentation process. This production process is the second largest industrial fermentation process after bioethanol by yeast fermentation (Kumar & Gayen, 2011). The difference from ethanol production is primarily in the feedstocks fermentation and also minor changes on distillation process. The process uses C. Acetobutylicum as the substrate to utilize the fermentation process. However, the utilization of these food crops into biobutanol was condemned because of food shortage. Therefore, the researchers focus on the secondary generation biobutanol due to abundant cheaper raw materials as the feedstocks. The process to produce biobutanol from the lignocellulosic feedstocks is illustrated in **Figure 2.3**.

The lignocellulosic biomass undergoes several steps to produce biobutanol i.e. pre-treatment, detoxification, fermentation and recovery. Fermentation process of the biomass feedstocks can be done via different modes i.e. batch fermentation, fed-batch fermentation and continuous fermentation processes, free cell continuous fermentation, immobilized cells continuous fermentation, and cells recycling and bleeding. **Table 2.2** shows the comparison of the biomass feedstocks via different fermentation process and their potential butanol yield/ productivity.

Interestingly, biobutanol also can be derived from algae which is the third generation biofuel. Algae provides several advantages, as it capable to produce an outstanding yields with lower resource inputs than other feedstocks. In fact, algae that has high amount of starch can yield as high as 20,000 gallons of biofuel per acre and the yields are ten times higher than the second generation biofuels, according to US Department of Energy. Presently, the developers i.e. Butamax Advanced Biofuels LLC, Swiss Butalco GmbH, American Gevo Inc., ButylFuel LLC and Advanced Biofuels LLC are developing their own fermentation process towards an economical synthesis of biobutanol (Aakko-Saksa et al., 2011).

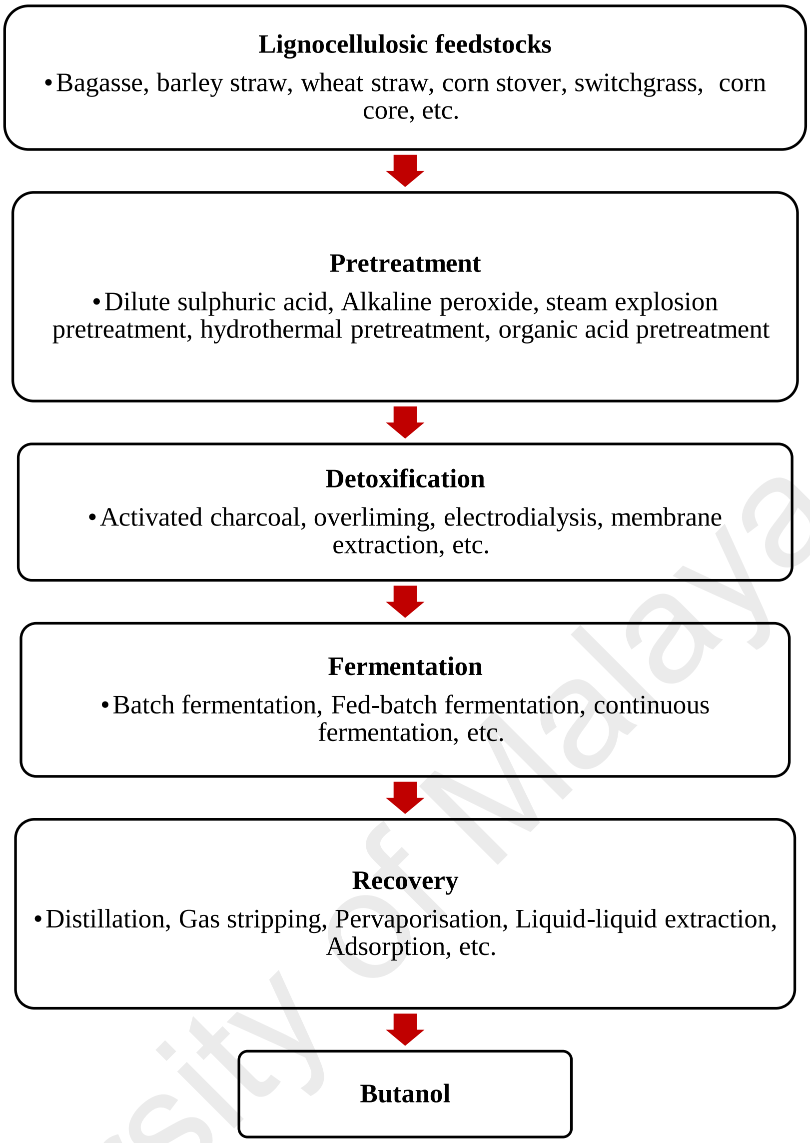


Figure 2.3: Production process for biobutanol from lignocellulosic feedstocks (Ezeji & Blaschek, 2008; H. Liu et al., 2013)

Table 2.2: Comparison of biomass feedstocks and their potential biobutanol yield/ productivity via different fermentation process

Feedstocks or substrates	Fermentation process	Strain used	Yield (g/g)/ productivity (g/ L.h)	Maximum titer of ABE (g/L)
Barley straw	Batch fermentation	C. beijerinkii P260	0.43/ 0.39	26.64
Wheat straw	Batch fermentation	C. beijerinkii P260	0.41/ 0.31	21.42
	Fed-batch fermentation	C. beijerinkii P260	-/ 0.36	16.59
Corn fibres	Batch fermentation	C. beijerinkii BA101	0.36-0.39/ 0.10	9.3
Corn stover & switchgrass (1:1)	Batch fermentation	C. beijerinkii P260	0.43/ 0.21	21.06
Switchgrass	Batch fermentation	C. beijerinkii P260	0.37/ 0.09	14.61
Sago starch	Free cell continuous fermentation	C. saccharobutylicum DSM13864	0.29/ 0.85	9.1
Degermed corn	Free cell continuous fermentation	C. beijerinkii BA101	-/ 0.29-0.30	14.28
Whey permeate	Immobilized cells continue fermentation	C. acetobutylicum P262	3.5-3.6/ 0.36-1.10	8.6
Corn	Immobilized cells continue fermentation	C. acetobutylicum ATCC 55025	0.42/ 4.6	12.50 (butanol)
Sugar beet juice		C. beijerinkii CCM 6182	0.37/ 0.40	-

Sources: Kumar & Gayen (2011) and (Patakova et al., 2011)

2.4 Physicochemical properties of ethanol and butanol

Table 2.3 summarizes the comparison of physical and chemical properties of respective gasoline, ethanol and butanol. The significant fuel properties are discussed below.

Table 2.3: Comparison of physicochemical properties of gasoline, ethanol and butanol isomers

Properties	Gasoline	Ethanol	n-butanol	sec-butanol	tert-butanol	Isobutanol
Chemical formula	~$C_8H_{15.6}$	C_2H_5OH	C_4H_9OH	C_4H_9OH	C_4H_9OH	C_4H_9OH
Oxygen content (wt. %)	0	34.7	21.6	21.6	21.6	21.6
LHV (MJ/kg)	43.46	26.8	33.2	32.9	32.7	33.1
RON	88-98	109	98	105	105	105
MON	80-88	90	85	93	89	90
Density at 15 ºC (kg/m^3)	750.8	794.6	812.6	810.5	787.3	805.6
Kinematic viscosity at 20 ºC (mm^2/s)	0.51698	1.50663	3.5528	4.5797	-	4.9751
Dynamic viscosity at 20 ºC (MPa.s)	0.3860	1.1936	2.8823	3.6935	-	3.9898
RVP at 37.8 ºC (kPa)	63.9	17	2.2	5.3	12.2	3.3
Latent HoV (kJ/kg)	352	920	707.9	671.1	527.2	686.4
Flash point (ºC)	-43	13	29	24	11	28
Boiling point (ºC)	27-225	78	117.7	99.6	82.4	107.9
Auto-ignition temperature (ºC)	257	363	343	405	478	415
Specific gravity at 20 ºC	0.69-0.79	0.794	0.810	0.808	0.791	0.802
Solubility of compound in water at 20 ºC (wt. %)	negligible	miscible	7.7	12.5	miscible	8.7

Source: Yanowitz et al. (2011)

2.4.1 Ethanol

Ethanol with formula C_2H_5OH as illustrated in **Figure 2.4** is an alcohol which is colourless liquid, transparent, neutral, volatile, flammable, miscible in both water and non-polar solvents and oxygenated liquid hydrocarbons, which has a pungent odour and sharp burning taste (Ganguly et al., 2012; Masum et al., 2013). Ethanol has much higher oxygen content with value of 34.7 wt.%, which promotes higher complete combustion and lower exhaust emissions. It also has higher octane number than gasoline and butanol that can prevent premature ignition that cause knocking which can damage the engine. This higher octane rating also gives an advantage in improving the thermal efficiency.

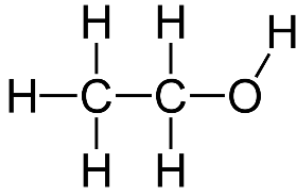


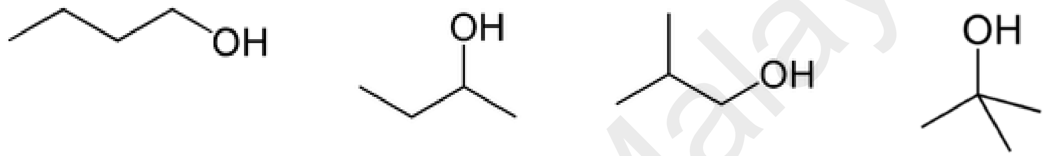
Figure 2.4: Structural formula of ethanol

However, ethanol has lower Reid vapor pressure (RVP) than gasoline, thus it brings problems when starting a cold engine especially during cold weather (Bajpai, 2013; Szulczyk et al., 2010). However, the low carbon chain alcohol likes ethanol gives lower amount of lower heating value (LHV). The energy content of ethanol is approximately 65% of gasoline energy, therefore it has a higher fuel consumption as compared to gasoline. Ethanol also has higher density than the gasoline which results in enhancing the volumetric fuel economy. The viscosity of ethanol is higher than gasoline, which can adversely affect the fuel injection system due to higher flow resistance especially at lower temperature (Patakova et al., 2011).

Moreover, ethanol has higher heat of vaporization (HOV) than gasoline, thus reducing the air-fuel mixture temperature during intake stroke. Higher HOV improves knock resistance and achieves better volumetric efficiency of the engine. However, higher HOV of ethanol leads to problems during engine start-up including when running cold engine (Larsen et al., 2009; Patakova et al., 2011) and also promotes higher emissions of organic gases (Chiba et al., 2010). The flash point, boiling point and auto-ignition temperature of ethanol are 13 ºC, 78 ºC and 363 ºC, respectively.

2.4.2 Butanol

Butanol or butyl alcohol exists with four different isomers with respect to the location of –OH and carbon chain structure as shown in **Figure 2.5**. It has 21.6% of oxygen content which can enhance complete combustion. The isomers have the similar chemical properties but can be distinguished by their structures that affect their properties as shown in **Table 2.3**.



n-butanol **sec-butanol** **Isobutanol** **tert-butanol**

Figure 2.5: Structural formulae of butanol isomers

Butanol isomers have different solubility despite it has similar molecular weight and same functional group. N-butanol and isobutanol have less water solubility; sec-butanol has significantly greater water solubility while tert-butanol is fully miscible with water but less soluble than ethanol. The high hydrophobic nature of n-butanol and isobutanol can reduce water contamination, which can damage the engine's fuel system.

Besides that, the isomers have lower LHV and RVP than gasoline but much higher than ethanol. The significantly lower RVP of butanol as compared to gasoline, results in cold engine start-up problem especially during winter season. The isomers also have higher RON and HOV than gasoline, but lower than ethanol. The auto-ignition of butanol isomers are higher than ethanol and gasoline which can affect the thermal efficiency and exhaust emissions.

2.5 Effect of ethanol and butanol addition in gasoline on engine performances

Gasoline engine is an internal combustion engine with spark-ignition (known as Spark Ignition engine), designed to run on gasoline and other similar volatile fuels. The engine was invented by Nikolaus August Otto in 1876 in Germany. Though gasoline engine is developed for gasoline, alcohols have been used intensively as a fuel blend or additives since its invention. Many researchers have been carried out experimental studies on SI engine fueled with various concentration of alcohols in gasoline blends to determine engine performances i.e. torque (T), brake power (BP), brake specific fuel consumption (BSFC), volumetric efficiency (VE), brake thermal efficiency (BTE) and exhaust gas temperature (EGT) (Yusoff et al., 2015).

Masum, Kalam, Masjuki, Palash, et al. (2014) examined different alcohols fuel blends i.e. 20 vol% of methanol, ethanol, propanol and butanol in gasoline (denoted as M20, E20, Pr20 and Bu20, respectively) on a MPFI- SI engine at wide open throttle by varying engine speed. The results showed that the alcohol fuel blends gave better performances on torque and brake thermal efficiency (BTE) than the pure gasoline. However, the brake specific fuel consumption (BSFC) of alcohols much higher than the gasoline due to their lower energy content, resulting more fuel blended were needed to yield same power output. The BSFC of Bu20 and E20 are higher than the gasoline with 1.95% and 5.17% respectively.

Besides that, Ozsezen & Canakci (2011) studied the effect of ethanol and methanol with 5 vol% and 10 vol% in gasoline (denoted as E5, E10, M5 and M10) at wide open throttle and different vehicle speeds on a chassis dynamometer. It was showed that the vehicle fueled with the alcohol blends increased the peak wheel power, fuel consumption and combustion efficiency. The E10 blend provided the highest combustion efficiency at 60 km/h and 100 km/h. Further investigation was done by Canakci et al. (2013) on a vehicle equipped with 4 cylinders SI engine fueled with the same alcohol-gasoline blends on a chassis dynamometer at different vehicle speeds and wheel powers. The result showed that E10 gave the highest BSFC among the blends at 80 km/h and 100 km/h with 3.6% and 1.5% respectively as compared to pure gasoline. The alcohol fuel blends also showed reduction in EGT due to their higher latent HOV than the gasoline.

Moreover, Koç et al. (2009) experimentally studied the ethanol-gasoline blends i.e. 0 vol%, 50 vol% and 85 vol% (denoted as E0, E50 and E85) on a single cylinder 4-stroke SI engine at wide open throttle and varying engine speed. The addition of oxygenated fuel likes ethanol in gasoline blend produced higher T, BP and BSFC. Furthermore, Najafi et al. (2009) also experimentally examined the ethanol-gasoline fuel blends of 0 vol%, 5 vol%, 10 vol%. 15 vol% and 20 vol% (denoted as E0, E5, E10, E15 and E20 respectively) on 4 cylinder KIA 1.3L engine with the aid of artificial neural network. It was reported that the gasoline blended with ethanol (derived from potato waste) increased the T, BP, BTE, VE and BSFC as compared to pure gasoline. Substantial experimental studies have been done by other researchers (Celik, 2008; Dhaundiyal, 2014; Elfasakhany, 2014; Hsieh et al., 2002; Saridemir, 2012) to evaluate the effect of ethanol- gasoline blends on SI engine performances.

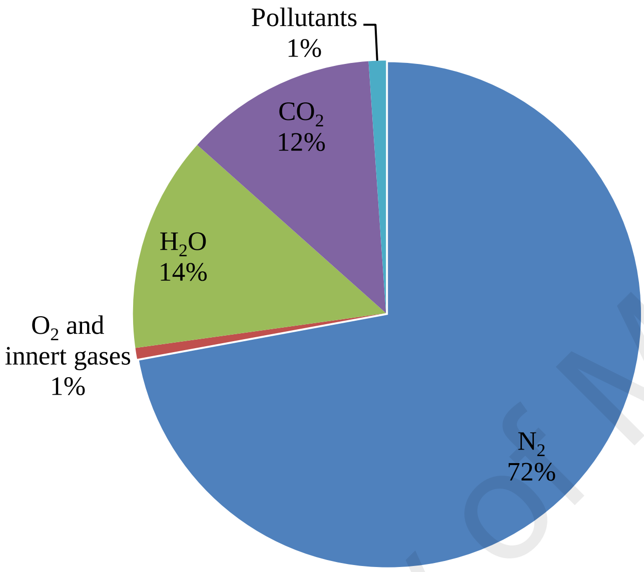
Rigorous studies have been done by researchers to study the effect of butanol in gasoline blend on engine performances. S. B. Singh et al. (2015) examined the effect of various concentration rate of butanol in gasoline blend i.e. 5 vol%, 10 vol%, 20 vol%, 50 vol% and 75 vol% on a 4 cylinder MPFI medium duty SI engine. It showed that butanol-gasoline blends produced lower BTE and EGT but slightly higher BSFC than the pure gasoline. Furthermore, Elfasakhany (2015) studied the effect of hybrid isobutanol in gasoline blend i.e. 3 vol%, 7 vol% and 10 vol% isobutanol in gasoline blends (denoted as iBu3, iBu7, iBu10 respectively) on a SI engine. The addition of butanol in gasoline blend reduced the torque T, BP, VE, EGT and in-cylinder pressure than pure gasoline without engine optimization.

Besides that, Elfasakhany (2016b) also compared the effect of dual butanol blend (n-butanol and isobutanol) with single butanol (iso-butanol or n-butanol) and baseline gasoline on SI engine performances at different volume rates (3-10 vol%) and engine conditions. The 10 vol% of n-butanol/isobutanol in gasoline (niBu10) gives the best performances among the tested dual and single butanol blends. However, the dual butanol blends give reduction on VE, BP, T and EGT compared to the pure gasoline. Other researchers (Dernotte et al., 2009; Pukalskas et al., 2009; Xialong et al., 2009) also observed the effect of butanol addition in gasoline blends on SI engine performances.

2.6 Effect of ethanol and butanol addition in gasoline on exhaust emissions

Exhaust emission is an undesirable element i.e. flue gas that is emitted and discharged into the air as a result of fuel combustion in the internal combustion engine. Excessive release of the undesirable foreign substances into the air will aggravate the air quality, which can cause acid rain, health problems and also cause damage to the ecosystem. Caiazzo et al. (2013) observed that road transportation contributes up to 53000 premature deaths per year in United States due to exhaust emissions. In United Kingdom, the pollution experts from MIT, Massachusetts have observed almost 5000 premature deaths per year are caused by exhaust emission from vehicles, which is more than twice that from traffic accidents (Pease, 2012).

The combustion gases consist of non-toxic gases, i.e. nitrogen (N_2), water vapor (H_20) and also carbon dioxide (CO_2) that contributes to global warming. The other little parts of unpleasant gases which are toxic and very harmful such as carbon monoxide (CO) discharged from incomplete combustion, hydrocarbon (HC) exhibits from unburned fuel, nitrogen oxides, NO_X reveals from extra combustion temperatures, ozone (O_3) and also particulate matters (PMs), i.e. soot. **Figure 2.6** shows the proportion data of exhaust emissions produced by SI engine (Soruşbay, 2015). In spite of that, the amounts of these emissions varies depending on the engine design including its operating condition.



Pollutants	(%)
PM	0.0008
NO_X	0.13
HC	0.09
CO	0.90

Figure 2.6: The proportion data of exhaust emissions produced by SI engine (Soruşbay, 2015)

An experimental study was done by E. Singh et al. (2014) to examine the exhaust emissions of ethanol and n-butanol in gasoline blends at volume concentration of 10 vol% (denoted as E10 and nBu10, respectively) on a single cylinder SI engine by varying load at a constant speed of 3000 rpm. The results showed that nBu10 gives the lowest CO_2 emission than E10 and pure gasoline. The nBu10 also produces slightly comparable NO emission to gasoline but much lower than E10 due to its identical properties to gasoline. However, E10 emits the lowest CO and HC emissions than nBu10 and gasoline at all loads. Besides that, Farkade & Panthre (2012) investigated the effect of different volume concentration of methanol, ethanol and butanol in gasoline blends on exhaust emission characteristics of a Greaves MK-25 engine. These oxygenate alcohols in the gasoline blends give a significant reduction in HC and CO emissions especially the 30 vol% methanol in gasoline (M30) that emits the lowest HC and CO emissions at all operating conditions.

Moreover, Lin et al. (2010) studied different ratios of ethanol in gasoline blended fuels (E0, E3, E6 and E9) on a small engine generator under different loadings. Addition of ethanol increases the oxygen content in fuel, results in lower CO, HC and NO_X at each engine loading. F. Liu et al. (2012) studied 10 vol% and 20 vol% of ethanol in gasoline blends (denoted as E10 and E20) in a three cylinders PFI gasoline engine. The increasing ethanol fraction in fuel blends showed reduction in HC, CO_2 and NO_X than pure gasoline.

Yücesu et al. (2006) studied different volume concentration of ethanol in gasoline blends i.e. E10, E20, E40 and E60 compared with gasoline in a single cylinder SI engine at different engine speed and compression ratio. It showed that the higher ratio of ethanol-gasoline blends i.e. E40 and E60 reduced more HC and CO than the gasoline. In other experiment, Koç et al. (2009) investigated the effect of ethanol in gasoline blends at different ratios of E0, E50 and E85 on a single cylinder SI engine at wide open throttle and varying engine speed on emissions characteristic. The addition of ethanol as oxygenates reduces HC emissions as a result of the leaning effect, but HC emission increased at higher compression ratio due to higher surface to volume ratio. Also, adding ethanol in gasoline blends emitted lower NO_X due to high latent HOV of ethanol.

Furthermore, there are also several studies that observed the emissions characteristics of butanol in gasoline blends. Feng et al. (2015) studied the effect of n-butanol–gasoline blend on a single cylinder SI motorcycle engine at 6500 rpm and 8500 rpm of speed under full load and partial load conditions. The results showed that 35 vol% of n-butanol in gasoline (nBu35) with optimized ignition timing released lower HC, CO and O_2 emissions amount compared to 30 vol% n-butanol in gasoline (nBu30). However, NO_X and CO_2 emissions are much higher than pure gasoline. Typical results were observed by Deng et al. (2013) as 35 vol% in gasoline (Bu35) with optimum ignition timing produced lower HC and CO emissions with decrease of 22% and 49.5% on average respectively, but the NOx emission largely increases with 190% on average relative to that pure gasoline. Similar investigation was achieved by Feng et al. (2013) as the 35 vol% of n-butanol in gasoline (nBu35) with 1 vol% H_2O addition, in combine with optimized ignition timing is performed on the similar engine parameters. The tested blend gives lower amount of CO and HC emissions nevertheless NO_X and CO_2 emissions are higher than gasoline.

In addition, Wallner & Frazee (2010) studied the effect of three different alcohol isomers; ethanol, n-butanol and isobutanol on the regulated and unregulated emissions on a SIDI engine with disable EGR. The results showed that both n-butanol and isobutanol increase the formaldehyde and acetaldehyde emissions compared to ethanol; butanol increased propene, 1, 3-butadiene and acetylene emissions, while HC and NO_X emissions are lower with higher alcohol contents. Wallner et al. (2010) also examined the unregulated emissions characteristics on a SIDI engine at constant load, speed and power. The amount of formaldehyde emission is higher for isobutanol fuel blends as compared to ethanol fuel blends for most operating conditions. But, the acetaldehyde emissions increase for both ethanol and isobutanol blends.

2.7 Summary and research gap

The heavy reliance on petroleum-derived fuels such as gasoline in the transportation sector is one of the major causes of environmental pollution. For this reason, there is a critical need to develop cleaner alternative fuels. Numerous researchers have conducted the use of ethanol in gasoline blends. To date, 10 vol% ethanol in gasoline (E10 or gasohol) has been commercially used as fuel for vehicles in many countries. The higher concentration of ethanol-gasoline blend such as E85 (85 vol% ethanol, 15 vol% gasoline) have been developed design for new FFV engine. Interestingly, investigation on higher alcohol such as butanol as the option for liquid fuel have received much interest recently. Butanol is believed to be a promising and competitive renewable biofuel which can be blended with gasoline in spark ignition vehicles to produce cleaner alternative fuels because of their favourable physicochemical properties compared to ethanol. In respect from the previous experimental studies, there are numerous valuable studies on ethanol and butanol in gasoline blend which can affect the engine performances and exhaust emissions as summarized in **Table 2.4**.

However, there are still limited information to acknowledge the effect of single alcohol and dual alcohols of ethanol and isobutanol in gasoline blends since both alcohols have their own advantages and disadvantages. Therefore, this research will focus on the effect of dual ethanol-isobutanol and single ethanol and isobutanol in gasoline blends on physicochemical properties, engine performances and exhaust emissions in a spark ignition engine.

Table 2.4: Research study on alcohol fuel for past few years

No	Authors	Type of engine		Operating condition		Alcohol used				Engine performances					Exhaust emissions			
		Single cylinder	**Multi-cylinder**	**Varying speed**	**Varying torque**	**Methanol**	**Ethanol**	**Butanol**	**Dual alcohols**	**Torque**	**BP**	**BTE**	**BSFC**	**EGT**	**CO**	**CO_2**	**HC**	**NO_X**
1	a		X	X		X	X	X		X		X	X	X	X	X	X	X
2	b	X		X			X			X	X		X		X		X	X
3	c		X	X			X			X	X	X	X		X	X	X	X
4	d		X	X		X	X				X			X	X	X	X	X
5	e		X	X		X	X						X	X	X	X	X	X
6	f	X		X			X			X			X	X	X	X	X	
7	g	X		X				X		X	X			X	X	X	X	X
8	h	X		X				X		X	X			X	X	X	X	
9	i	X		X		X	X	X	X	X	X				X	X	X	
10	j	X		X					X	X	X			X	X		X	
11	k		/	/	/		/	/	/	/	/	/	/	/	/	/	/	/

Ref.

a. Masum, Kalam, Masjuki, Palash, et al. (2014)
b. Koç et al. (2009)
c. Najafi et al. (2009)
d. Ozsezen & Canakci (2011)
e. Canakci et al. (2013)
f. Elfasakhany (2014)
g. Elfasakhany (2015)
h. Elfasakhany (2016b)
i. Elfasakhany (2016c)
j. Elfasakhany (2016a)
k. This study

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this chapter, the research methodology and approaches of the entire study for achieving objectives have been discussed. These includes the selection of alcohol fuels, measurement of physicochemical properties of selected alcohols and their blends, fuel blending preparation for engine testing, engine performance and emissions analysis. **Figure 3.1** presents a summary of the work practice for this research.

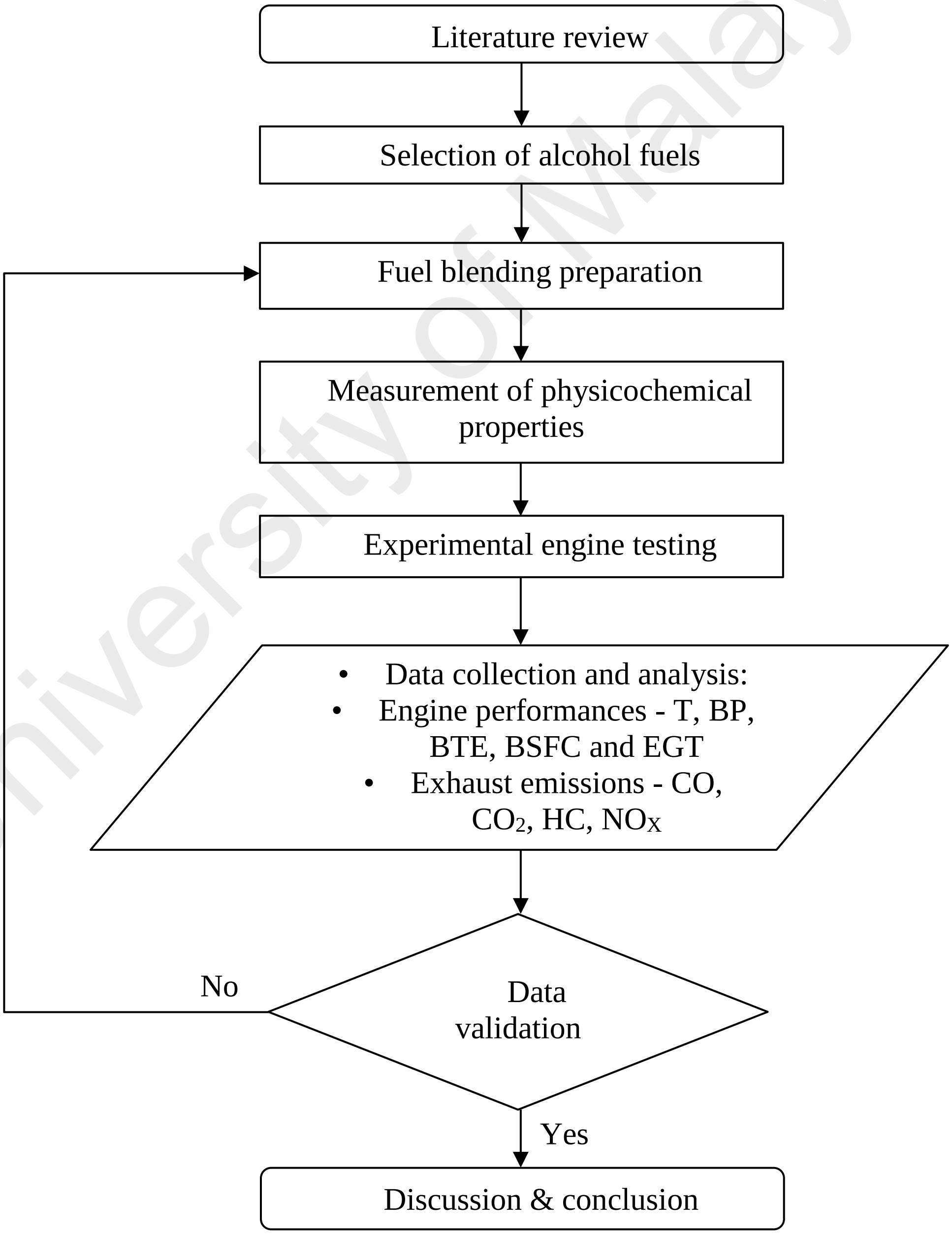


Figure 3.1: Flowchart of the research methodology

3.2 Selection of alcohol fuels

There are two types of alcohols to be used in this study, i.e. ethanol and isobutanol. The ethanol (purity 99.8%) was procured from Chemical Industries (Malaya) Sdn. Bhd., Malaysia and the isobutanol (purity ≥ 99%) was obtained from Merck Sdn. Bhd., Malaysia. Meanwhile, Primax95 unleaded gasoline with Research Octane Number 95 was acquired from Petronas, Malaysia.

3.3 Fuel blending preparation

Six types of fuel blends consist of single and dual alcohol fuel blends of ethanol and butanol were mixed with unleaded gasoline at different volume rates as tabulated in **Table 3.1**. All the fuel mixtures were blended on a shaker machine (IKA KS130 basic) for 30 minutes at 400 rpm prior to the engine testing for every run as illustrated in **Figure 3.2**. The mixtures were blended in closed bottle as the alcohols and gasoline easily evaporate at ambient temperature.

Table 3.1: Composition of ethanol, butanol and gasoline for blending

Sample Name	Volume of ethanol (% vol.)	Volume of isobutanol (% vol.)	Volume of gasoline (% vol.)
E10	10	-	90
E20	20	-	80
iB10	-	10	90
iB20	-	20	80
E5iB5	5	5	90
E10iB10	10	10	80
PG	-	-	100

Note: E= ethanol, iB= isobutanol, PG= pure gasoline (baseline)

Figure 3.2: IKA KS130 basic shaker machine

3.4 Measurement of physicochemical properties

The physicochemical properties indicates the quality of fuel to be combusted in SI engine (Masum et al., 2013). These includes heat of vaporization (HOV), higher heating value (HHV), Reid vapor pressure (RVP), density, viscosity and research octane number (RON). In this section, the properties of all the tested fuel blends were observed using different equipment and recommended standard method as listed in **Table 3.2**.

Table 3.2: Equipment and standard method used for testing fuel properties

Property	Equipment	Manufacturer	Standard method	Accuracy
Heat of vaporization	Heat Flux DSC 4000	Perkin Elmer, US	-	-
Higher heating value	C2000 basic Calorimeter- automatic	IKA, UK	ASTM D240	±0.1%
Reid vapour pressure at 37.8°C	Setavap 2 Automatic Vapour Pressure Tester	Paragon Scientific Ltd., UK	ASTM D5191	±0.1 KPa
Density at 15°C	DM40 LiquiPhysics™ Density Meter	Mettler Toledo, US	ASTM D4052	0.0001 g/cm^3
Kinematic and dynamic viscosity at 20°C	SVM3000 Stabinger Viscometer	Anton Paar, UK	ASTM D445	±0.35%

3.4.1 Heat of vaporization

Latent heat of vaporization also known as enthalpy of vaporization is the energy required by a substance to change the state from liquid to vapor at a constant – temperature. Heat flux DSC 4000 is used to measure the energy necessary at nearly zero temperature difference between a pan containing a sample and an empty reference pan in a single furnace, as both pans are subjected to an identical temperature regimes in an environment heated or cooled at a controlled rate. At first, the computer, Pyris software, DSC system, purge gas regulator and sub ambient cooling device system is turned on accordingly. The purge gas flow rate of nitrogen is applied at 20 – 25 psi. Then, a fuel sample typically 5-15 mg is weighed in a specific pan. Once the empty reference pan and sample pan are put inside the furnace, the method editor is used to set up method for sample run.

3.4.2 Higher heating value

The heating value (or calorific value or energy value) is the quantity of heat produced by the complete combustion of a specific amount of fuel at constant pressure and under standard conditions. The higher heating value (HHV) or gross energy of the tested fuels are measured using constant-volume type of IKA C2000 bomb calorimeter according to ASTM D240. At first, a fuel sample of 0.5g is weighted on a micro balance and it is then poured into crucible. The crucible which is carrying the fuel sample is located in the bomb and the ignition wire is tied to the terminal electric. Afterwards, the top of the bomb is screwed down tightly and closed into the calorimeter. Then, 30 bar of oxygen is admitted slowly before the ignition is occurred. The change in water temperature surrounding the calorimeter is used to calculate the energy content of the sample fuel. The heating value comes to the digital display automatically.

3.4.3 Reid vapor pressure

Reid vapor pressure (RVP) is defined as the absolute vapor pressure exerted by the liquid at 37.8 °C (100 °F) temperature, determined by Setavap 2 automatic vapor pressure tester according to the test method of ASTM D5191. This convenient alternative mini measurement of vapor pressure is used with proven correlation to ASTM D323. The analysis is carried out at a vapor to liquid ratio is 4:1 using 3 mL of fuel sample which is injected through a septum into a fixed vacuum chamber. The vacuum chamber is maintained at 37.8 ± 0.1 °C and its internal pressure is monitored by a low volumetric displacement transducer. The test results are displayed and the instrument automatically drains the sample and then shifted the instrument ready for the next test. The results shown in total pressure (P_{tot}), dry vapor pressure equivalent (DVPE), EPA, or Reid using pre-programmed correlation equations, and may be printed via the integral RS232 port and optional 81000-2 printer. The value of each sample was recorded.

3.4.4 Density

Density is the mass per unit volume of fuel. The density of the fuel blends are measured using DM40 LiquiPhysics™ Density Meter, US according to ASTM D4052. To measure the density, the temperature is set at 15^{o}C. Then, approximately 3mL of fuel sample is injected to the equipment before the measurement is started. The sample fuel is injected 3 times for subsequent measurement until the result is valid.

3.4.5 Kinetic and dynamic viscosity

Viscosity is the measure of the flow resistance of a fluid fuel. Both kinematic viscosity and dynamic viscosity are measured using SVM3000 Stabinger Viscometer, UK according to ASTM D445. To measure the viscosity, the equipment is set at mode of M0: PRECISE and the temperature of 20^{o}C. Then, 3mL of fuel sample is injected to the equipment before the measurement is started. The sample fuel is injected 2-3 times for subsequent measurement until the results of dynamic and kinematic viscosity comes out on the display.

3.4.6 Research octane number

Research octane number (RON) is a rating used to measure a fuel's knocking resistance in gasoline engines. RON for the tested fuels were computed on a molar basis using the following equation (Anderson et al., 2010; Masum et al., 2015).

$$ON_{blend} = (1-X_{alc})\, ON_{base} + (X_{alc})\, bON_{mol,\, alc} \qquad \textbf{(3.1)}$$

Where,

ON_{blend} : ON of the alcohol-gasoline blend

ON_{base} : ON of the base gasoline

$bON_{mol,\, alc}$: Blending ON of the alcohol in the base gasoline

X_{alc} : Molar alcohol fraction

3.5 Engine test setup and engine performance analysis

The experiment was conducted on a 1.6L four cylinder PROTON CamPro engine at Faculty of Engineering, University of Malaya as illustrated in **Figure 3.3**. The details of the engine are presented in **Table 3.3**.

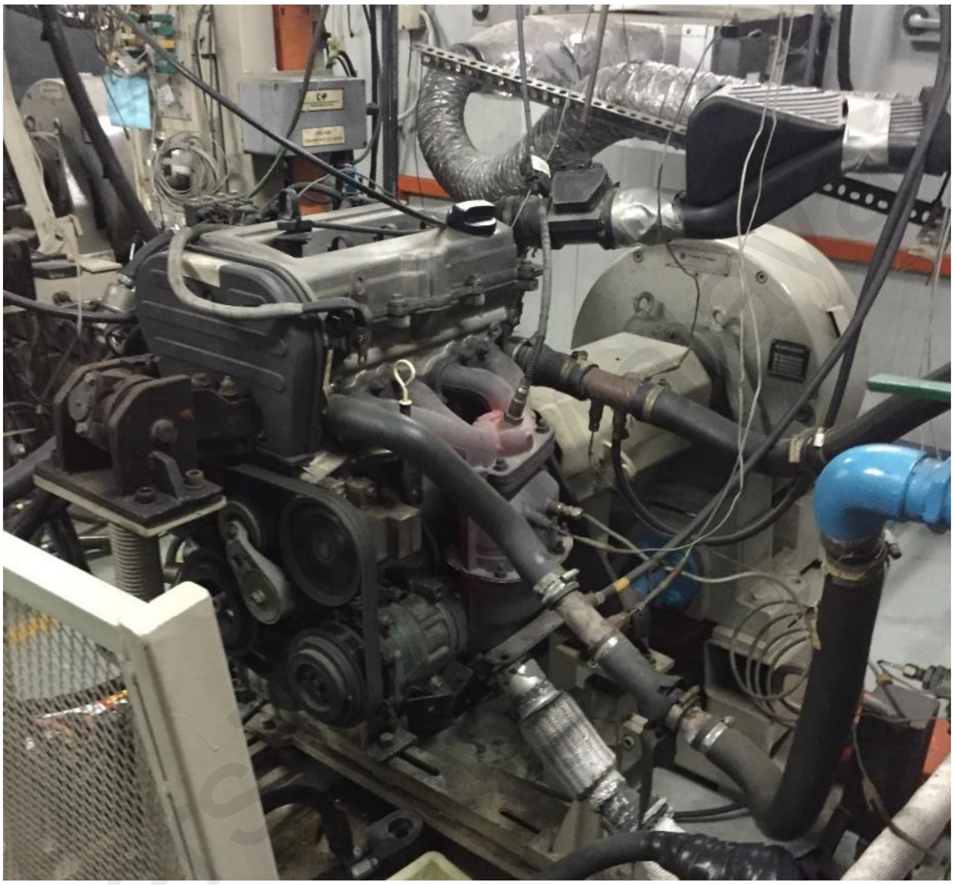


Figure 3.3: 1.6L Proton CamPro engine

Table 3.3: Characteristics of the tested engine

Engine parameter	Value
Model	PROTON CamPro
Number of cylinders	4
Valve mechanism	16-valve DOHC
Displacement volume	1597 cc
Bore	76 mm
Stroke	88 mm
Compression ratio	10:1
Fuel system	Multi-point fuel injection (MPFI) system
Max output	82 kW at 6000 rpm
Max torque	148 N/m at 4500 rpm

Figure 3.4 presents the schematic diagram of engine test bed. The tested engine was directly coupled with an eddy current dynamometer (Froude Hofmann AG150, UK) at maximum power of 150 kW. It was connected to a data acquisition system, which automatically collects and processes the signals throughout the experiment. The data acquisition system was connected to the computer, where the data was monitored, controlled and analyzed using CADET V12 software.

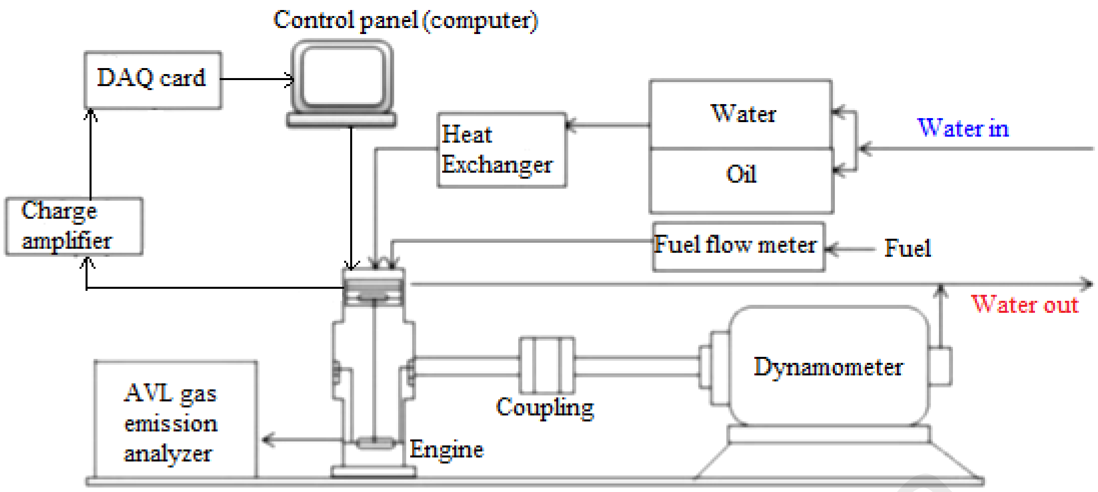


Figure 3.4: Schematic diagram of engine test set-up

At first, the engine was warm up for 15 minutes with pure gasoline to ensure the engine operating condition is perfectly stable. The fuel was then switched to different fuel blends, where sufficient amount of blends were consumed to ensure the removal of residual gasoline from the fuel lines. In this study, a constant-throttle test was operated at full throttle position by varying the engine speed ranging from 1000 to 5000 rpm with an increment of 1000 rpm. Then, a constant speed test was conducted at 4000 rpm by varying engine torque ranging from 20 to 100 Nm with an increment of 20 Nm.

Both test conditions were performed to establish engine performance and emissions characteristics and to determine the best mixture blends. The engine performances parameters such as torque (T), brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) were determined. The test on performances were repeated for three times for each fuel blending to get an average data of the experiment.

In addition, several important procedure were taken into consideration before operating with engine test bed.

i. The water supply from the cooling tower was opened.

ii. The water level inside the water tank was sufficient during engine testing.

iii. The engine oil level was checked using the dipstick indicator.

3.6 Exhaust emission analysis

The exhaust emissions such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_X), oxygen (O_2) and hydrocarbon (HC) were measured using AVL DICOM 4000 exhaust emission analyzer as shown in **Figure 3.5**. The specifications for the emission analyser is presented in **Table 3.4**. The sample line hose of the emission analyser was put to the exhaust tailpipe 1.5 meter away from exhaust port to ensure sufficient mixing of the exhaust emissions. The emissions results were then recorded for every increment of engine speed ranging from 1000 to 5000 rpm at full throttle position and also for every increment of engine torque ranging from 20 to 100Nm at constant 4000 rpm engine speed.

Figure 3.5: AVL DICOM 4000 exhaust emission analyzer

Table 3.4: Specifications of the exhaust emission analyzer

Model	Measuring Element	Measurement range	Resolution
AVL DICOM 4000	CO	0 – 10 vol.%	±0.01 vol.%
	CO_2	0 – 20 vol.%	±0.1 vol.%
	HC	0 – 20000 ppm vol.	1 ppm
	NO_X	0 – 5000 ppm vol.	1 ppm
	O_2	0 – 25 vol.%	±0.01 vol.%

3.7 Uncertainty analysis

The experimental uncertainties are related to various factors such as the selection, condition and calibration of the instruments, test conditions, observation and data collection techniques, as well as experimental planning and design. The uncertainties calculation for the engine performance and exhaust emission parameters are presented in Appendix A. The overall uncertainty was determined using the following equation (How et al., 2014):

Overall experimental uncertainty = square root of [(uncertainty of T_{speed})^2 + (uncertainty of BP_{speed})^2 + (uncertainty of BTE_{speed})^2 +(uncertainty of BTE_{torque})^2 + (uncertainty of $BSFC_{speed}$)^2 + (uncertainty of $BSFC_{torque}$)^2 + (uncertainty of EGT_{speed})^2 + (uncertainty of EGT_{torque})^2 + (uncertainty of CO_{speed})^2 + (uncertainty of CO_{torque})^2 + (uncertainty of CO_{2_speed})^2 + (uncertainty of CO_{2_torque})^2 + (uncertainty of HC_{speed})^2 + (uncertainty of HC_{torque})^2 + (uncertainty of NO_{X_speed})^2 + (uncertainty of NO_{X_torque})^2]

= square root of [$(0.79)^2 + (0.99)^2 + (1.09)^2 + (1.01)^2 + (1.10)^2 + (1.01)^2 + (1.40)^2 + (0.65)^2 + (0.68)^2 + (1.22)^2 + (0.46)^2 + (0.22)^2 + (0.92)^2 + (1.72)^2 + (1.80)^2 + (0.75)^2$]

= ±4.27%

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The results from all analysis is presented and discussed in this chapter. The first part of this chapter presents the physicochemical properties of the of respective fuel blends of ethanol, isobutanol and gasoline. The engine performance and exhaust emission characteristics of spark ignition engine fueled with those blends were then presented and compared with pure gasoline.

4.2 Physicochemical properties of ethanol-butanol-gasoline fuel blends

Measurement of physical and chemical properties is the only way to assess the quality of fuel. In this study, the physicochemical properties were measured for each fuel blend using various instruments, as listed in **Table 3.2**. The physicochemical properties of the fuel blends tested are summarized in **Table 4.1** below.

Table 4.1: Physicochemical properties of tested ethanol-butanol-gasoline fuel blends

Properties	Gasoline	E10	E20	iB10	iB20	E5iB5	E10iB10
HHV (MJ/kg)	43.46	42.00	40.55	42.68	41.90	42.34	41.22
Latent HoV (kJ/kg)	352	409	466	385	419	397	442
RVP (kPa)	63.9	59.7	55.5	58.9	53.7	59.3	54.6
Density (kg/m^3)	750.8	757.2	760.9	759.3	763.2	754.4	761.3
Kinematic viscosity (mm^2/s)	0.52633	0.57351	0.64849	0.59485	0.70333	0.56405	0.64512
Dynamic viscosity (MPa.s)	0.39262	0.43131	0.49096	0.44875	0.53549	0.42446	0.48661
RON	95	99.5	104.0	97.7	100.4	98.9	102.7

As can be seen clearly in **Table 4.1**, the fuel blends have significantly lower HHV than pure gasoline. The increasing of oxygen content of the alcohols linearly reduces the heating value of the tested fuel blends. It can be seen that the blends of E10, E20, iB10, iB20, E5iB5 and E10iB10 showed the reduction of heating value with 3.4, 6.7, 1.8, 3.6, 2.6 and 5.1% respectively as compared with pure gasoline. In comparison with ethanol, isobutanol which has more carbon-carbon bonds increases the change in enthalpy during combustion, which results in higher energy content (Smith, 2013). The lower of heating value gives higher fuel consumption and also effects on engine performances and emissions (Masum et al., 2015).

Latent heat of vaporization (HOV) of the tested fuels containing ethanol and butanol are significantly higher than pure gasoline. For comparison, the HOV of ethanol, isobutanol and gasoline are 920, 686.4 and 352 kJ/kg respectively. The fuel blends of E10, E20, iB10, iB20, E5iB5 and E10iB10 showed 16.1, 32.3, 9.5, 19, 12.8 and 25.6% higher HOV respectively as compared with pure gasoline. The significantly higher HOV results in a temperature reduction inside the engine intake system of port fuel injection, as the energy taken from the intake air is needed to evaporate the fuel.

Reid vapor pressure (RVP) is determined to evaluate the volatility of gasoline and other fuel blends. The results showed that the addition of ethanol and isobutanol in gasoline blends reduce the RVP values, where ethanol and butanol have 17 and 3.3 kPa respectively. Indeed, the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend reduce the RVP with 6.5, 13.2, 7.9, 15.9, 7.2 and 14.5% respectively. A lower RVP is desirable for evaporative emissions, however too low of a RVP can cause cold start problem and an increase in hydrocarbon emission (Kito-Borsa et al., 1998).

The addition of ethanol and butanol increase the fuel density values to the tested fuel blends, where the density of ethanol and isobutanol are 791.61 and 802.1 kg/m^3 respectively. The E10, E20, iB10, iB20, E5iB5 and E10iB10 blend increase the density with 0.9, 1.3, 0.7, 1.1, 1.7, 0.5 and 1.4% respectively as compared with pure gasoline. Therefore, the higher fuel density value, the higher mass of fuel that can be stored in the tank and the higher the mass of the fuel that can be pumped to the engine via a pump.

The viscosity of the tested fuels containing the alcohols are significantly higher than pure gasoline. The kinematic viscosity of E10, E20, iB10, iB20, E5iB5 and E10iB10 are higher than pure gasoline with 9.0, 23.2, 13.0, 33.6, 7.2 and 22.6% respectively. The fuel viscosity has not technically been an issue in their gasoline applications, as it is not operating at much higher pressure as compared to diesel fuel pumps, therefore the viscosity requirements for the gasoline are much lower as compare to diesel fuel (Agudelo et al., 2011).

RON of the tested fuels containing ethanol and isobutanol are significantly higher than pure gasoline. For comparison, the RON for gasoline, ethanol and isobutanol are 95, 107.4 and 105.1 respectively. The fuel blends of E10, E20, iB10, iB20, E5iB5 and E10iB10 increase the RON with 4.7, 9.0, 2.9, 5.7, 4.2 and 8.1% respectively as compared with pure gasoline. The significantly higher value of RON can prevent premature ignition that causes engine knocking. This higher octane rating also gives an advantage in improving the thermal efficiency.

4.3 Engine performance

Engine performance of a SI engine is usually described in terms of engine torque (T), brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) under different engine operating conditions, i.e. varying speed and engine torque. In this study, three readings were recorded for each experiment test point for all tested fuel blends. The uncertainty value for each parameter were determined and presented in the graph.

4.3.1 Engine torque

Figure 4.1 shows the variation of engine torque for the tested fuel blends as a function of the engine speed. It can be observed that the engine torque increases steadily up to 4000 rpm and decreases thereafter for all fuel blends. The maximum engine torque recorded at 4000 rpm is 111.8, 113.3, 112.3, 112.5, 111.4 and 112.6 and 111.0 Nm for the E10, E20, iB10, iB20, E5iB5, E10iB10 blend and pure gasoline (PG), respectively. As the engine speed increases to 4000 rpm, the amount of air intake into the engine cylinders increases the engine torque and volumetric efficiency simultaneously. Therefore, the increase in the engine torque is attributed to the volumetric efficiency and engine speed (Al-Hasan, 2003). However, the engine torque decreases at an engine speed higher than 4000 rpm due to fuel choking as a consequence of reduced air intake. Fuel choking occurs when insufficient charge being supplied into the combustion chamber due to short air intake time at high engine speed. Furthermore, there is only a slight increase in the engine torque at 3000 rpm, followed by an abrupt increase up to an engine speed of 4000 rpm. This phenomenon is known as torque dip or torque loss which naturally occurs in DOHC CamPro engines manufactured by PROTON, Malaysia, or any other SI engines that caused by designed intake manifold geometry and valve timing to compromise the maximum engine torque and achieve the desired emission levels (Mohiuddin et al., 2008). The low-end engine torque is not smooth and it typically occurs within an engine speed range of 2500–3500 rpm.

In general, blending ethanol and butanol with gasoline improves the engine torque. Indeed, the E10, E20, iB10, iB20, E5iB5, E10iB10 blend has higher engine torque, with an average enhancement of 2.33, 3.88, 2.56, 3.06, 1.06 and 3.77%, respectively, relative to PG. At a constant engine speed, the engine torque varies from one fuel blend to another because of the fuel properties. The engine torque enhancement is due to the high HOV of the fuel blends, whereby the fuel vaporizes in the intake manifold and combustion chamber (Masum et al., 2015). This higher HOV is due to the decrease in the charge temperature as the alcohols evaporate. Moreover, alcohols provide more oxygen to the gasoline, which results in a leaner mixture as compared to PG. This increases the fuel burning efficiency while concurrently improves the engine torque (Koç et al., 2009; Masum, Kalam, Masjuki, Rahman, et al., 2014).

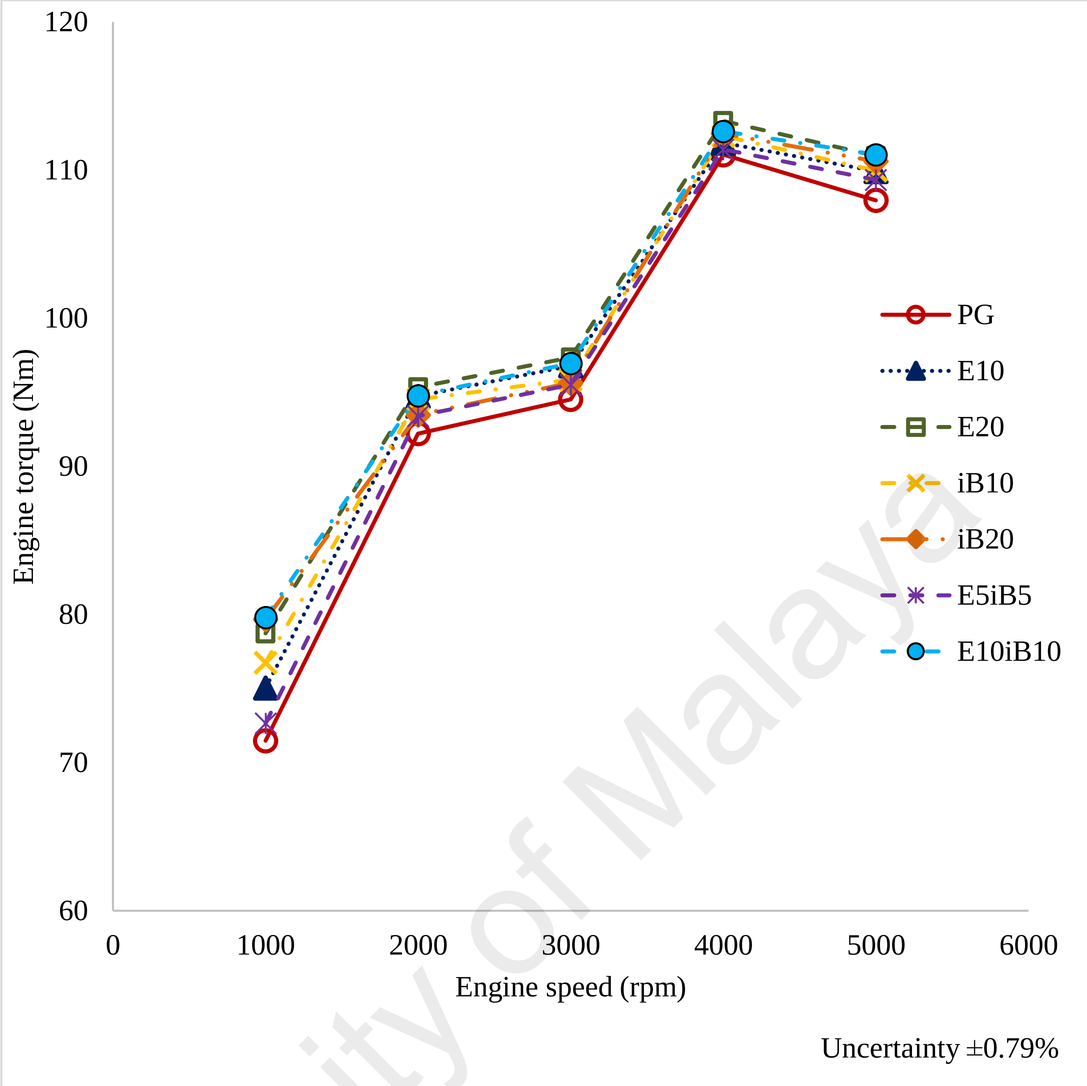


Figure 4.1: Variation of engine torque as a function of engine speed for all tested fuel blends

4.3.2 Brake power

Figure 4.2 shows the variation of brake power for the tested fuel blends as a function of the engine speed. It can be seen that the brake power increases in an almost linear fashion when the engine speed is increased from 1000 to 5000 rpm. The higher volume ratio of the alcohol blends of E20, iB20, E10iB10 and blend has higher brake power enhancement with respect to PG, with average increase of 2.60, 2.57 and 2.22% respectively. This is followed by the lower volume ratio of alcohol blends of iB10, E10 and E5iB5, with an average brake power enhancement of 1.92, 1.64 and 0.95%, respectively. Since the ethanol and isobutanol are essentially oxygenates, blending these alcohols with gasoline increases the octane rating of the blends, making them less prone to auto-ignition and eventually increasing the brake power. Moreover, both ethanol and isobutanol have higher latent HOV than gasoline, which increases the fuel-air charge cooling. This in turn, increases the intake air density, which boosts the engine power (Najafi et al., 2009).

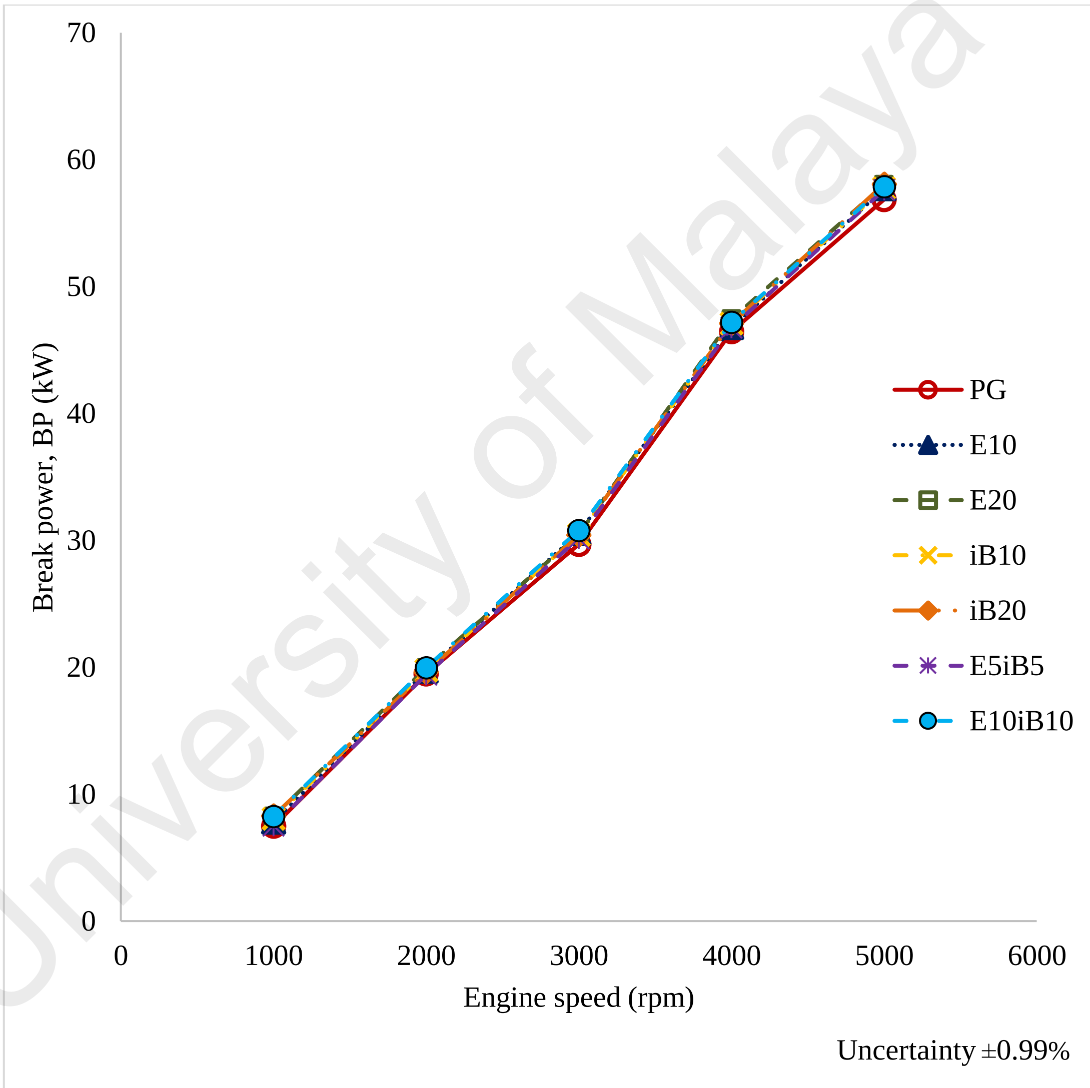
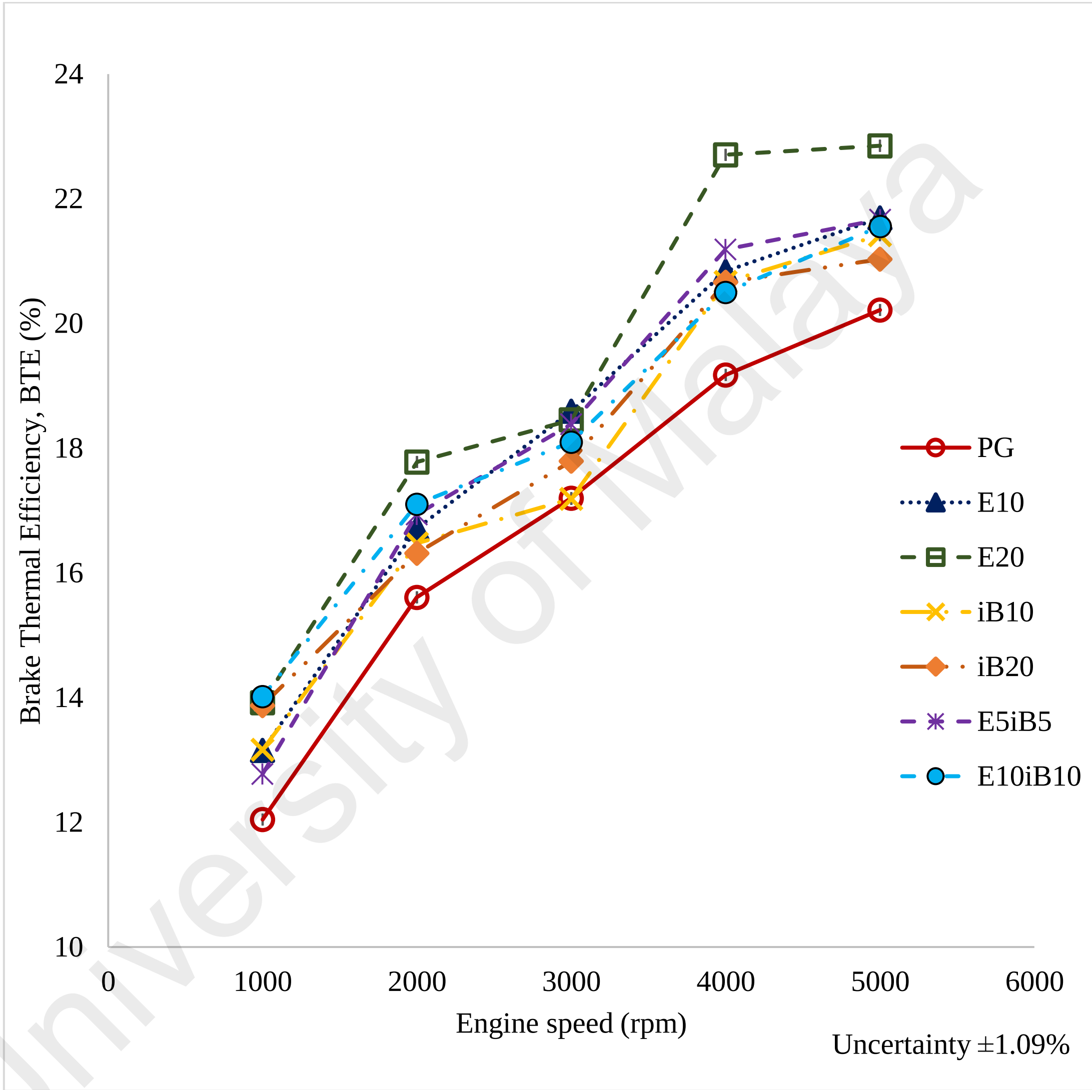


Figure 4.2: Variation of brake power as a function of engine speed for all tested fuel blends

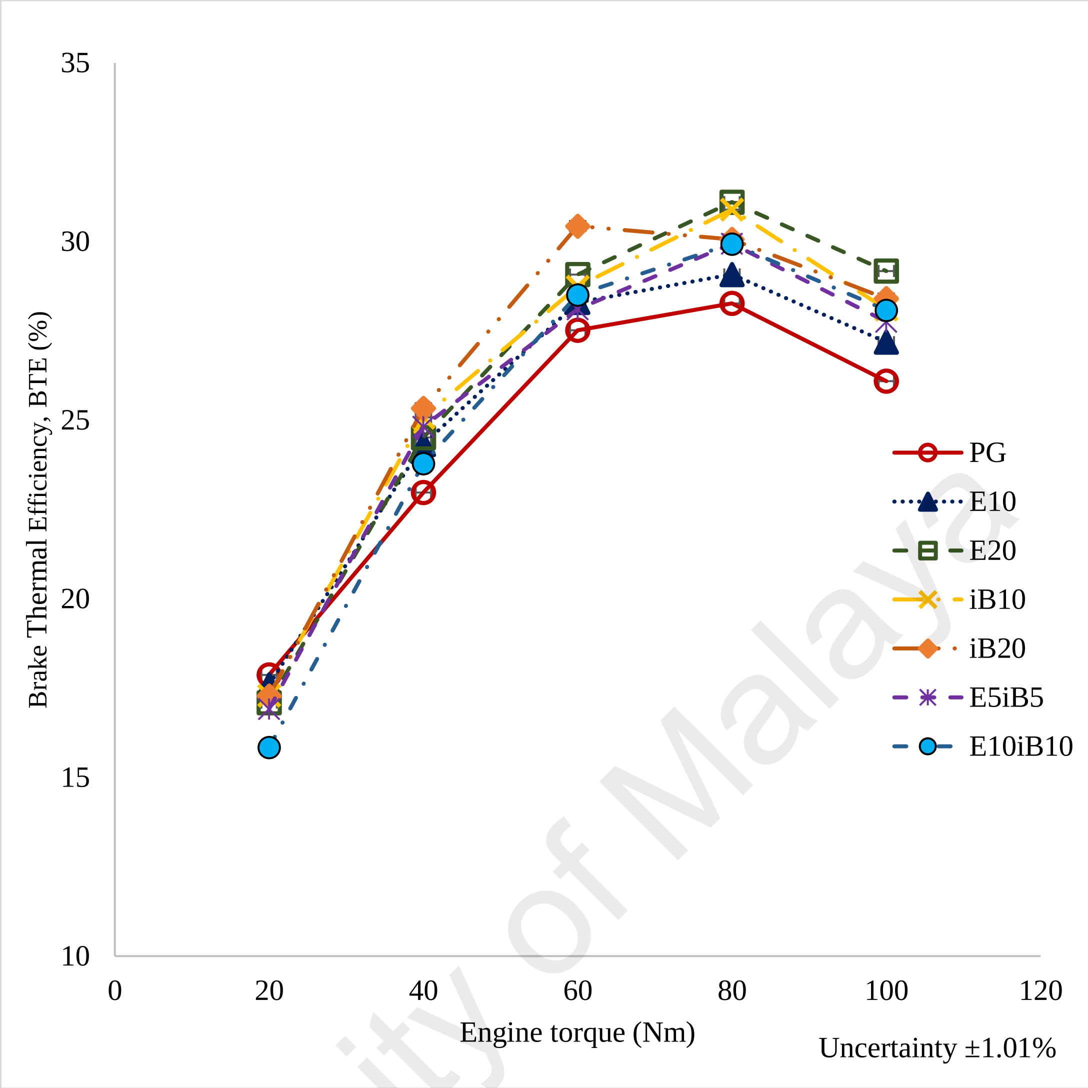
4.3.3 Brake thermal efficiency

Brake thermal efficiency (BTE) is a measure of the efficiency or completeness of the engine to produce brake power from the thermal input over the fuel amount supplied. **Figure 4.3** shows the variation of BTE for all tested fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed condition. At the constant full throttle condition as shown in **Figure 4.3(a)**, it can also be observed that the BTE is lower at low engine speed and BP and subsequently increase with higher engine speed and BP. There is a slight increase in the BTE for the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend relative to that of PG, with an average enhancement of 8.01, 13.61, 5.54, 6.45, 7.97 and 8.35%, respectively. It can be seen that the BTE value for the lower carbon alcohol, i.e. ethanol is greater than higher carbon alcohol, isobutanol. In fact, ethanol has greater oxygen content than isobutanol, thereby enhances combustion efficiency and eventually produces higher BTE than butanol (Campos-Fernandez et al., 2013). The maximum BTE was 22.9% at 5000 rpm when E20 was used in the fuel blend. Similar trends has been proven by Masum, Kalam, Masjuki, Palash, et al. (2014), who determine the BTE of the ethanol-gasoline blend is greater than butanol-gasoline blend due to better combustion efficiency.

At a constant engine speed condition in **Figure 4.3(b)**, the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend have higher BTE, with an average enhancement of 3.06, 6.71, 6.02, 7.16, 3.92 and 2.80%, respectively, relative to PG. It can be observed that the BTE is lower for all the alcohol-gasoline blends compared to the PG at lower engine torque of 20 Nm. This is due to the higher auto-ignition temperature and HOV of the ethanol and isobutanol which inhibit mixing between these alcohols and air and consequently reduces combustion efficiency and thermal efficiency. However, there is improvement in the BTE at middle and higher engine torque from 40 to 100 Nm for all the alcohol-gasoline blends. In fact, the throttle position increase proportionally with the engine torque at a constant speed. The larger throttle opening at higher engine torque has shifted air fuel mixture to become slightly leaner, enabling complete combustion of the fuel and eventually increase the BTE. As the evidence, the alcohol-gasoline blend produces more CO_2 emissions than PG due to improve complete combustion.



(a)



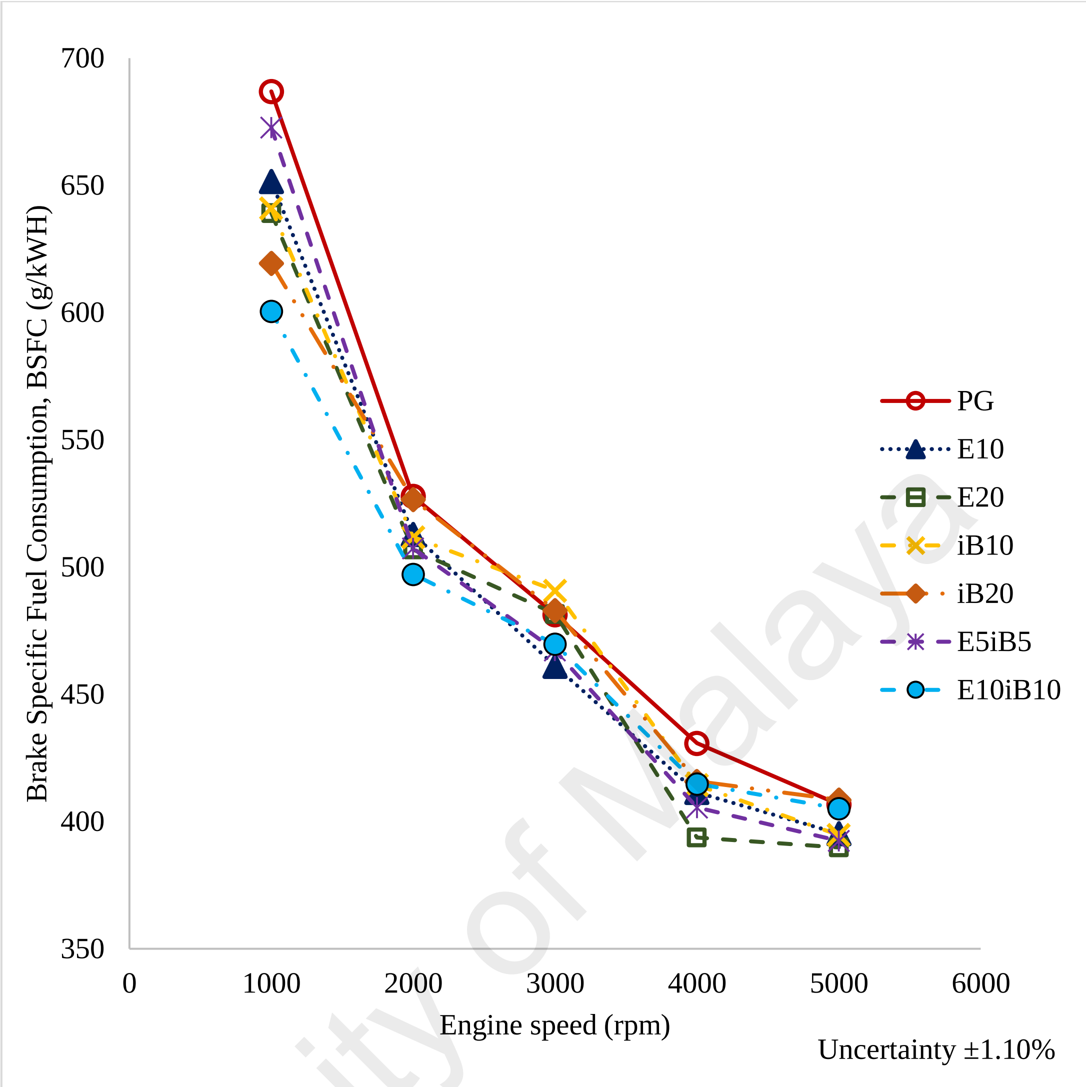
(b)

Figure 4.3: Variation of brake thermal efficiency as a function of (a) engine speed and (b) engine torque for all tested fuel blends

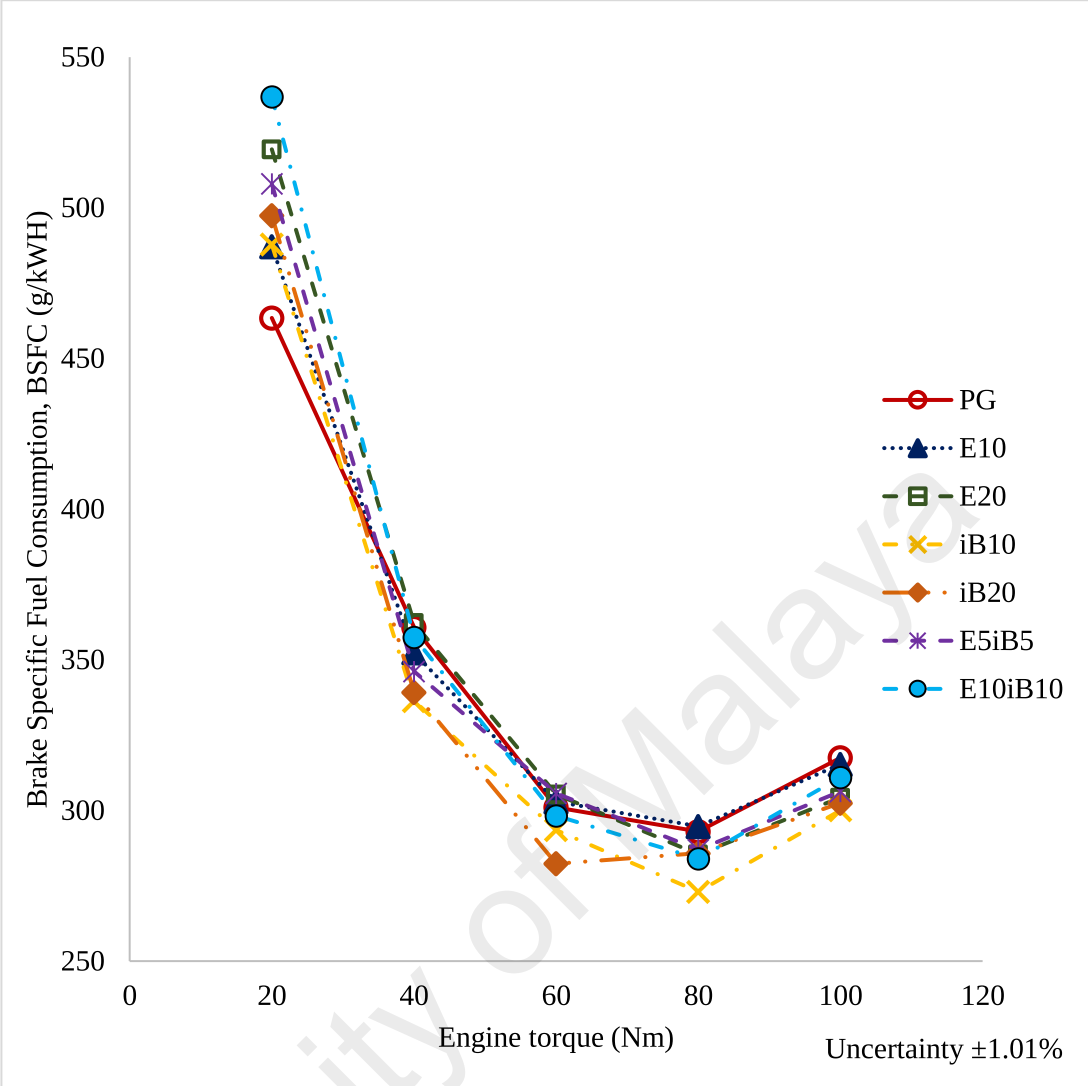
4.3.4 Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is simply a measure for the fuel efficiency of the engine which indicates the usage of fuel during operation. In other words, BSFC is the ratio of the rate of fuel consumption to the brake power (g kW^{-1} h^{-1}). Obviously, lower amount of BSFC is desirable. **Figure 4.4** presents the variation of the BSFC for all tested fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed condition. As shown in the **Figure 4.4(a)**, the BSFC of the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend is lower relative to that of pure gasoline with average values of 4.00, 4.83, 3.19, 3.17, 3.48 and 5.77% respectively. The reduction of the BSFC on the addition of ethanol and isobutanol was caused by the normal consequences of BTE behaviour as shown in **Figure 4.3(a)**, where the BTE for the blends were higher than PG. The typical findings were founded by Al-Hasan (2003) and Najafi et al. (2009) who determined the BSFC decreases with the addition of ethanol percentage in fuel blend.

At a constant engine speed in **Figure 4.4(b)**, it can be observed that the BSFC of the PG is the lowest among the tested fuel blends at lower engine torque (10 Nm). This is due to higher value of BTE of PG with 17.9% as presented in **Figure 4.3(b)**. However, the BSFC of the alcohol-gasoline blends were lower than PG at higher engine torque (80 to 100 Nm) due to improve combustion efficiency, thereby increase the thermal efficiency and concurrently reducing the value of BSFC.


700
650
600
550
500
450
400
350
0
1000
2000
3000
4000
5000
6000
Brake Specific Fuel Consumption, BSFC (g/kWH)
Engine speed (rpm)
PG
E10
E20
iB10
iB20
E5iB5
E10iB10
Uncertainty ±1.10%

(a)



(b)

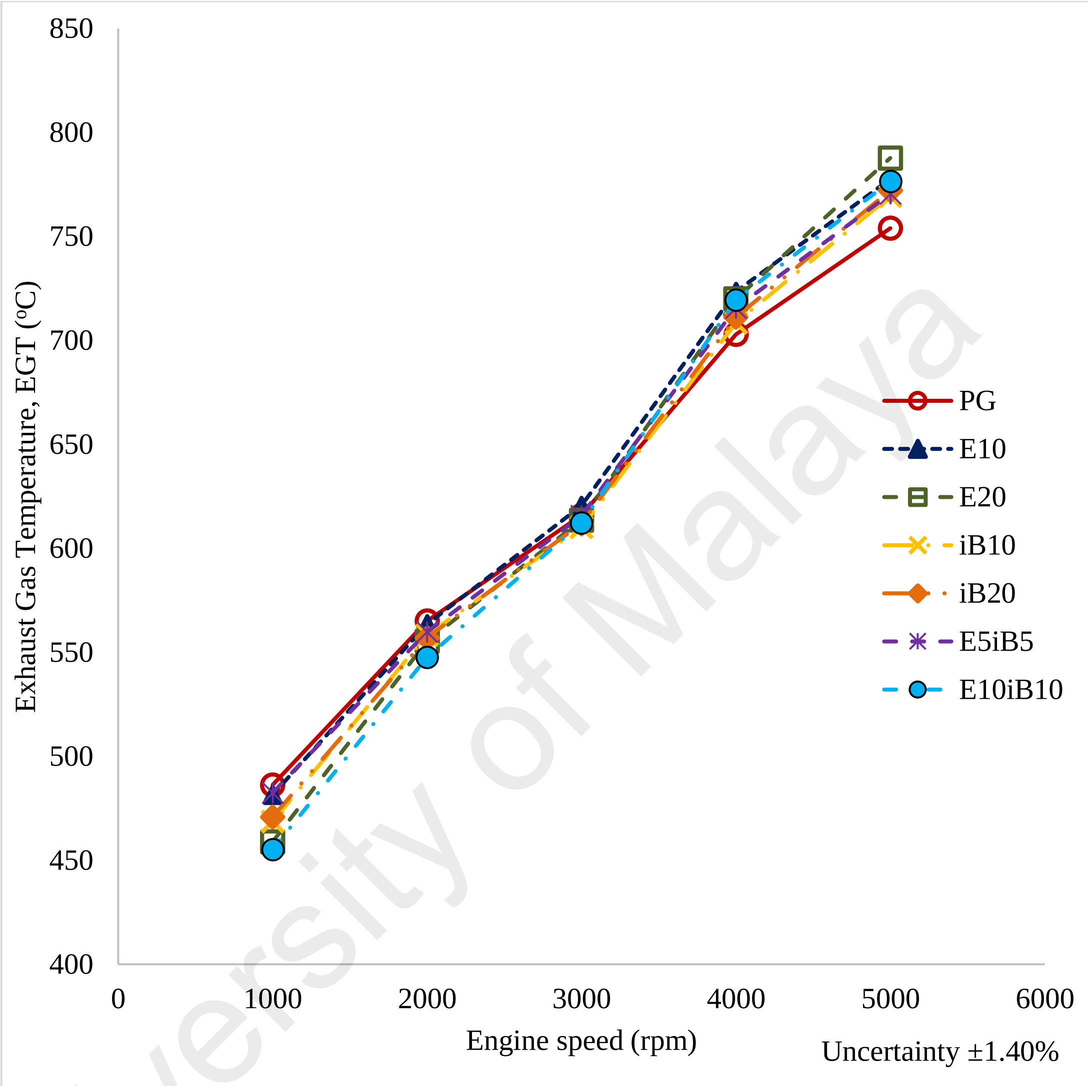
Figure 4.4: Variation of brake specific fuel consumption as a function of (a) engine speed and (b) engine torque for all tested fuel blends

4.3.5 Exhaust gas temperature

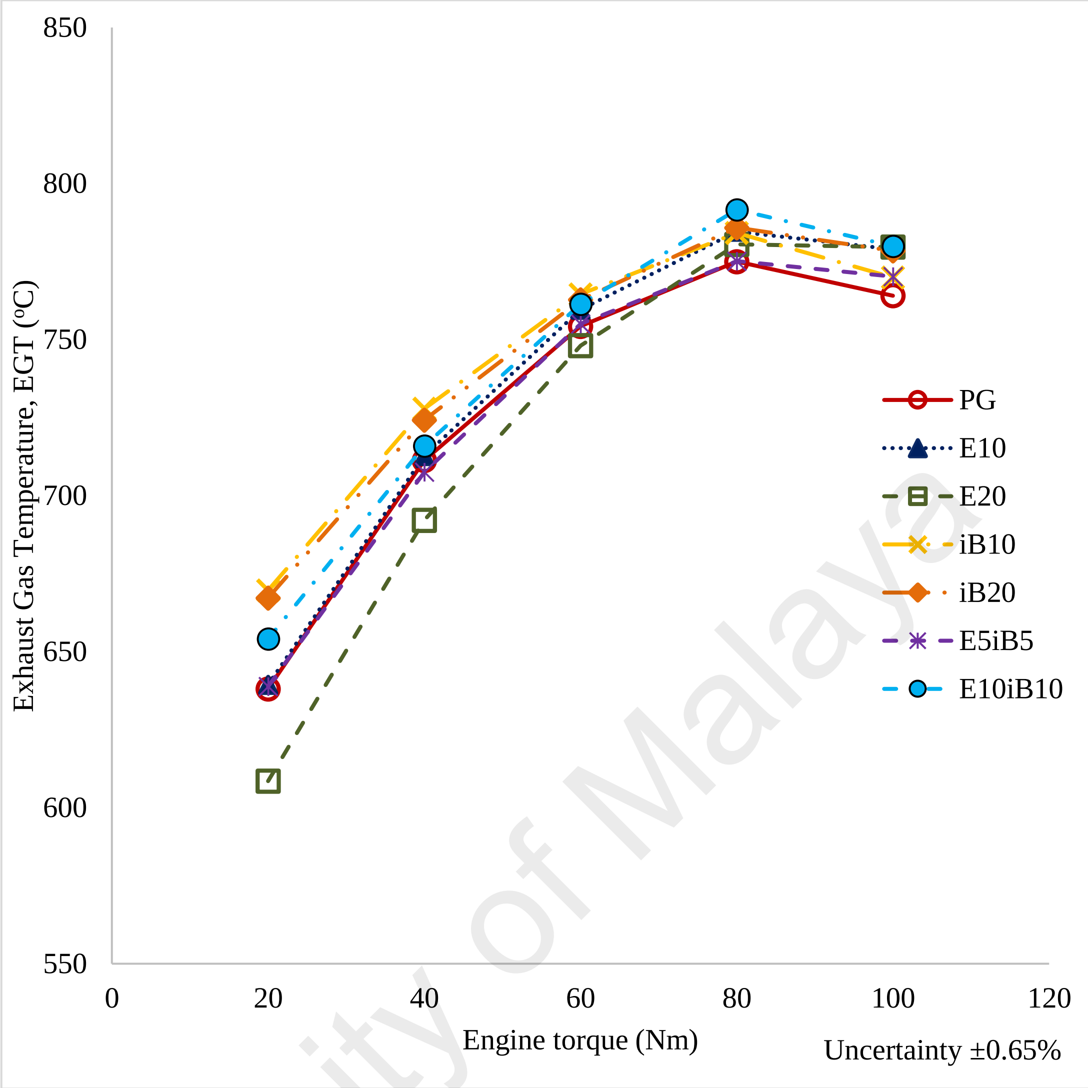
Exhaust gas temperature (EGT) is a significant indicator of the cylinder temperature as a function of combustion temperature. **Figure 4.5** presents the variation of EGT for all tested fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed. It can be observed that the EGT of the alcohol-gasoline blends were lower relative to that of PG at lower engine speed. The addition of alcohol in fuel blend may reduce the exhaust temperature due to more efficient conversion process of heat to work (Topgül et al., 2006). At lower engine speeds, the higher latent HOV of the ethanol and isobutanol in comparison to gasoline produces higher temperature drop in cylinder charge at the end of intake valve stroke, resulting in lower temperature at the end of combustion stroke and proportionally lower in EGT at the end of combustion. Besides that, the decrease in EGT is also due to lower heating value of ethanol and isobutanol as compared to gasoline (Ansari & Verma, 2012). However, interestingly, the EGT of the alcohol-gasoline fuel blend is slightly higher than that for PG at higher engine speeds (4000–5000 rpm). The E20 blend has the highest EGT at 5000 rpm (with a percentage difference of 4.5% relative to PG) due to improve fuel vaporization and combustible mixture formation during compression stroke (S. B. Singh et al., 2015).

In **Figure 4.5(b)**, the EGT of all the tested blends increases with increasing engine torque. It reaches maxima at engine torque of 80Nm, and then it starts decreasing with further increase in engine torque. In addition, the variation in EGT for all the fuel blends is observed to be statistically insignificant in comparison to PG. The EGT of E10, iB10, iB20, E5iB5 and E10iB10 blend is higher relative to that of PG with average values of 0.89, 2.01, 2.08, 0.11 and 1.65%. Meanwhile the EGT for E20 blend is lower than PG with average value of 0.93%. It can be seen that the EGT of the E20 blend is lower than

PG at lower engine torque (20-60 Nm). This is due to very high amount of latent HOV of the blend (by nearly 32%) with respect to PG, which is reflected by drop in EGT.



(a)



(b)

Figure 4.5: Variation of exhaust gas temperature as a function of (a) engine speed and (b) engine torque for all tested fuel blends

4.4 Exhaust emissions

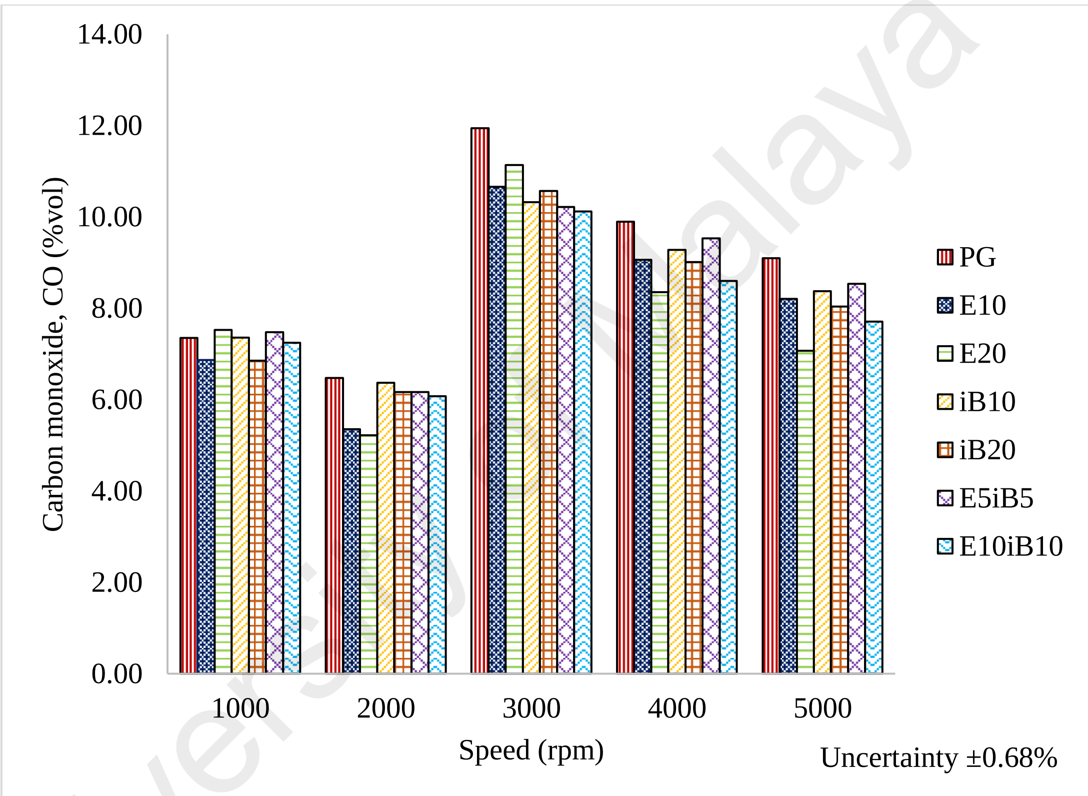
The measurements for all regulated emissions i.e. carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC) and nitrogen oxides (NO_X) was observed and discussed in details.

4.4.1 Carbon monoxide emissions

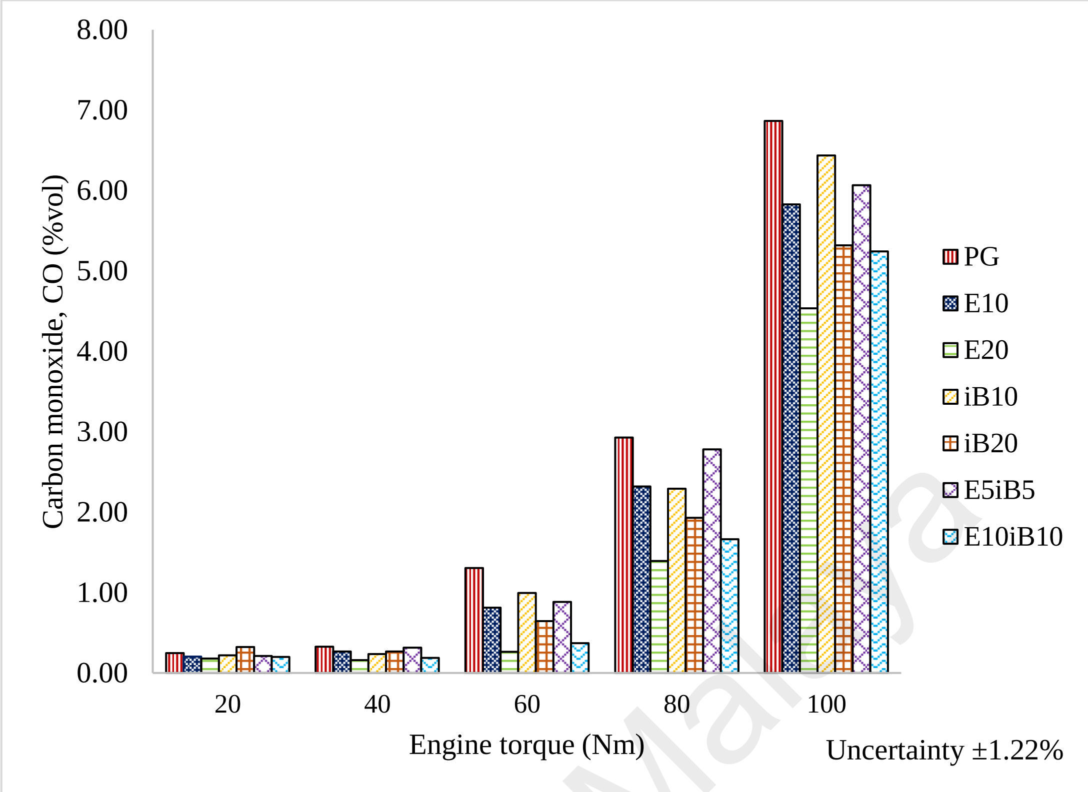
CO emission is a product of incomplete combustion of hydrocarbon fuel due to lack of air in the air-fuel mixture as well as time delay during the combustion cycle (Bayindir et al., 2010; Masum, Kalam, Masjuki, Rahman, et al., 2014). **Figure 4.6** shows the concentration of CO emissions of all the fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed. In overall engine speed range, it is evident that the CO concentration of E10, E20, iB10, iB20, E5iB5 and E10iB10 were lower, with an average reduction of 10.29, 12.20, 6.82, 9.21, 6.35 and 11.21%, respectively, relative to PG. The E20 blend gives the lowest CO emission among all the tested fuel blends, especially at an engine speed of 4000 and 5000 rpm. The fuel blends which contain alcohols are oxygenated fuels, therefore, they may enhance the oxygen content in gasoline blends and improve the leaning effect and combustion effectively, which in turns, reduce the CO emissions (Canakci et al., 2013; Mittal et al., 2013). In addition, the higher flame speed of ethanol and isobutanol also facilitates in completing the combustion process earlier, which reduces CO emissions (Feng et al., 2013; Masum et al., 2015).

At a constant engine speed of 4000 rpm in **Figure 4.6(b)**, the concentration of CO emissions increases with increasing engine torque. At lower engine torque, less fuel quantity is needed while higher engine torque needs more fuel quantity injection, leading to higher amount of CO emissions. On average, the CO emissions of the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend decreased by 19.17, 44.02, 12.77, 27.29, 12.10 and

34.36%, respectively, relative to PG. The CO emissions of the alcohols-gasoline blends is comparable to PG at lower engine torque, however marginally higher than PG at higher engine torque. The significant reduction of CO emissions is due to presence of fuel oxygen in the alcohols, which enhances the combustion efficiency, which in turns reducing CO emissions.



(a)



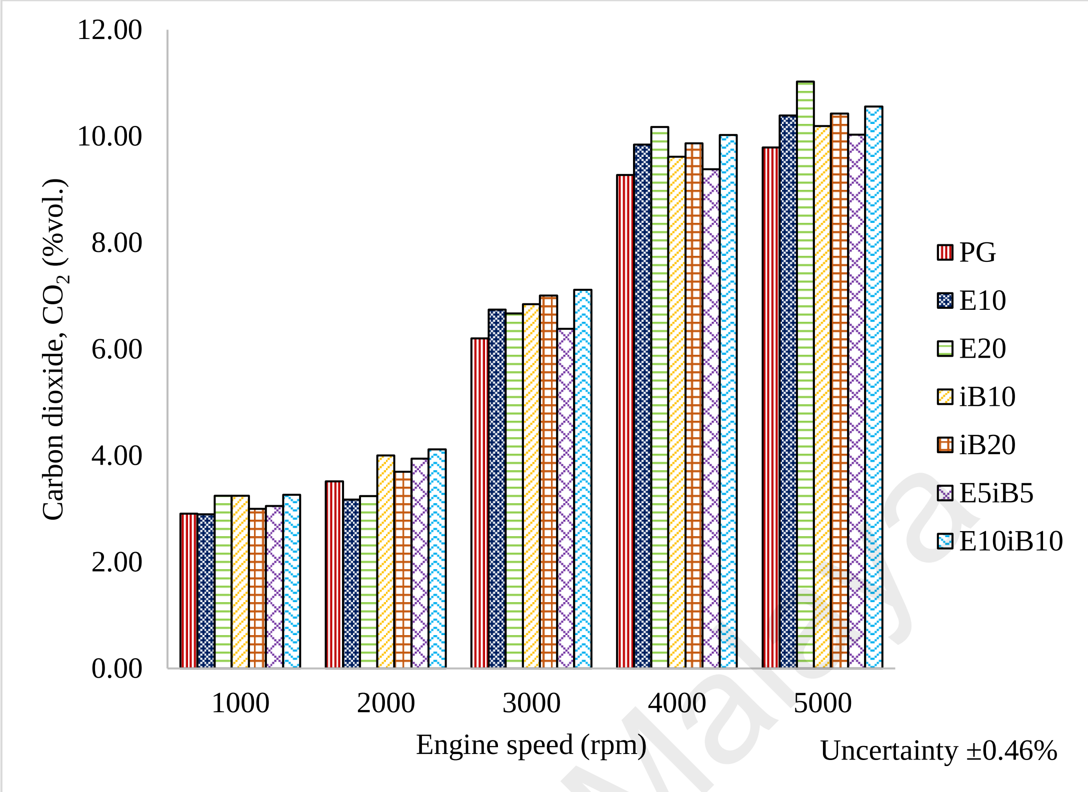
(b)

Figure 4.6: Variation of CO emissions as a function of (a) engine speed and (b) engine torque for all tested fuel blends

4.4.2 Carbon dioxide emissions

CO_2 emission is a primary greenhouse gas (GHG) that is formed from the complete combustion of the air-fuel mixture in an internal combustion engine. **Figure 4.7** shows the concentration of CO_2 emissions of all the fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed. In overall engine speed range, it is apparent that the amount of CO_2 concentrations is higher for all the fuel blends compared to that PG. The E10iB10 blend produces the highest concentration of CO_2 emissions with an average increase of 10.67% with respect to PG. This is followed by the E20, iB20, iB10, E10 and E5iB5 blend, with an average increase of 8.41, 7.27, 6.96, 4.25 and 3.44%, respectively with respect to PG. The variation of CO_2 emissions is a stark contrast to CO emissions in **Figure 4.6**. The results indicate that the higher amount of CO_2 concentrations is released upon fuel combustion. This is perhaps because of the present of oxygen content in the alcohols, which leads to lean burning and promotes complete combustion. This in turn, decreases the amount non-complete combustion products i.e. CO emissions.

In **Figure 4.7(b)**, the concentration of CO_2 emissions increases with increasing engine torque. It reaches maxima at engine torque of 60Nm, and it starts dropping with further increase of engine torque. At higher engine torque, excess fuel quantity is injected to maintain the engine speed, resulting in insufficient amount of oxygen and lower thermal efficiency, therefore lower CO_2 emissions is produced. In addition, the CO_2 emissions of all the fuel blends is similar or slightly higher than pure gasoline, except for E5iB5 blend which produces 0.66% lower CO_2 emission with respect to PG. Meanwhile, the E10, E20, iB10, iB20 and E10iB10 blend releases higher concentration of CO_2 emissions compared with PG, with an average increase of 1.23, 0.97, 0.42, 2.82 and 1.00%, respectively.



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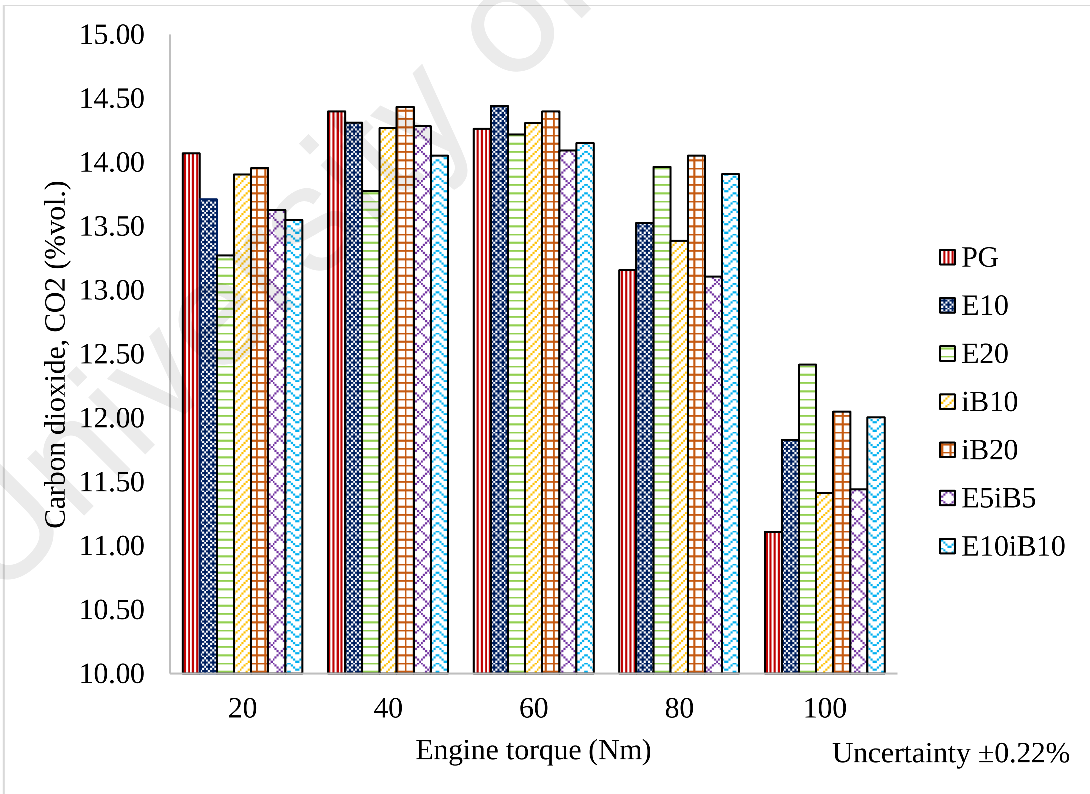


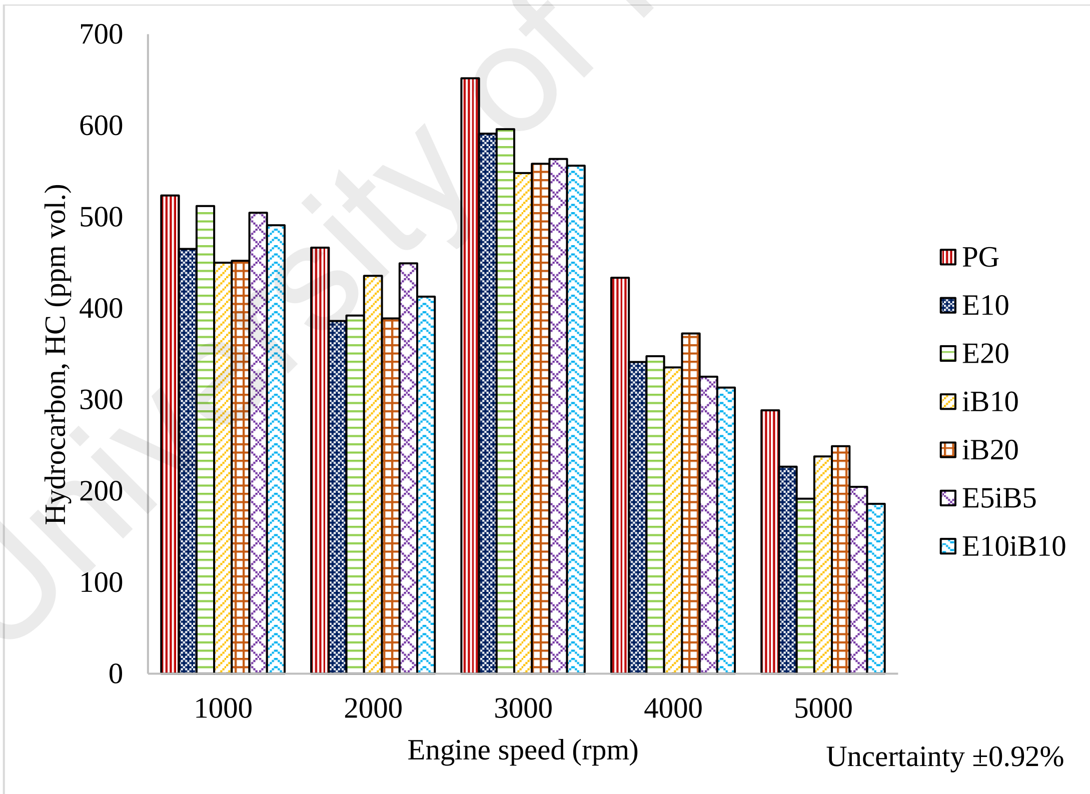
(b)

Figure 4.7: Variation of CO_2 emissions as a function of (a) engine speed and (b) engine torque for all tested fuel blend

4.4.3 Hydrocarbon emissions

HC emissions are found in unburned mixtures of fuel molecules as a consequence of improper mixing and incomplete fuel combustion in an internal combustion engine. The mechanisms of HC emissions formation of gasoline engine were explained in the previous studies (Alasfour, 1999; Blint & Bechtel, 1982; G. Lavoie et al., 1980; G. A. Lavoie & Blumberg, 1980). **Figure 4.8** shows the concentration of HC emissions of all the fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed. As shown in **Figure 4.8(a)**, it can be observed that the concentration of HC emissions decreases with increasing engine speeds except for the abrupt increase at engine speed of 3000 rpm. The incomplete combustion is due to the inhomogeneous charge of air and fuel which then leads to higher HC emissions. Besides that, the E10, E20, iB10, iB20, E5iB5 and E10iB10 blend releases lower concentration of HC emissions compared with PG, with an average reduction of 13.57, 13.71, 15.11, 14.50, 13.40 and 17.13%, respectively. It is also can be seen that the addition of alcohols in gasoline slightly reduces HC emissions level especially at high engine speed of 5000 rpm compared to the lower engine speed of 1000 and 2000 rpm. This is due to that the air-fuel mixture that homogenises at high engine speed tends to raise the in-cylinder temperature and enhances combustion efficiency. In addition, the reduction of HC emissions is caused by the leaning effect which is associated with the higher oxygen content in the alcohols, which enhances fuel combustion efficiency (Feng et al., 2015; Koç et al., 2009). The reduced HC emissions also attributed to the faster laminar flame speed of the alcohols, thus producing the lowest amount of HC emissions (Khuong et al., 2016).

It can be observed in **Figure 4.8(b)** that the concentration of HC emissions increases with increasing engine torque for all the tested fuel blends. The higher engine torque needs more fuel quantity injection per engine cycle to maintain the engine speed, therefore more HC emissions is produced. Besides that, the E10iB10 blend releases the lowest concentration of HC emissions with an average reduction of 46.32% with respect to PG. This is followed by the E20, iB20, E5iB5, iB10 and E10 blend, with an average reduction of 44.39, 35.06, 31.49, 25.24 and 21.31%, respectively with respect to PG. This is due to the presence of oxygen in the alcohols, which assist complete combustion, resulting lower HC formation. The faster laminar flame speed of the alcohols compare to gasoline may enhance combustion efficiency, therefore reducing amount of HC emissions (Sayin, 2010).



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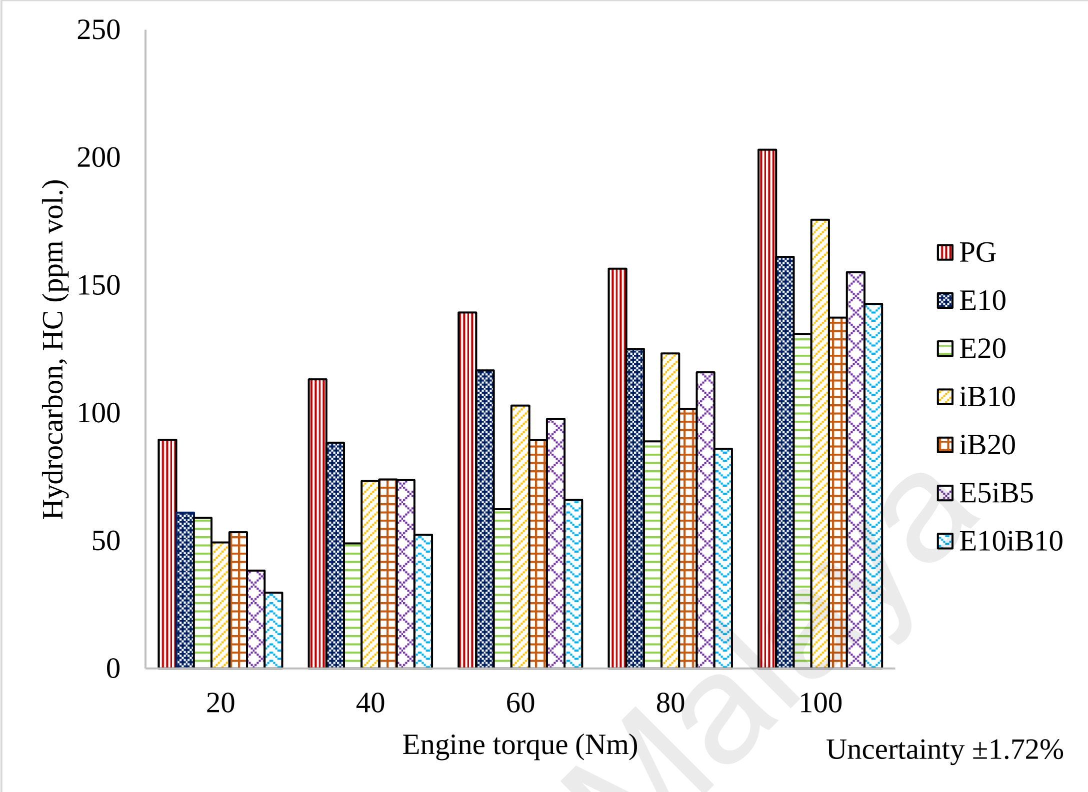


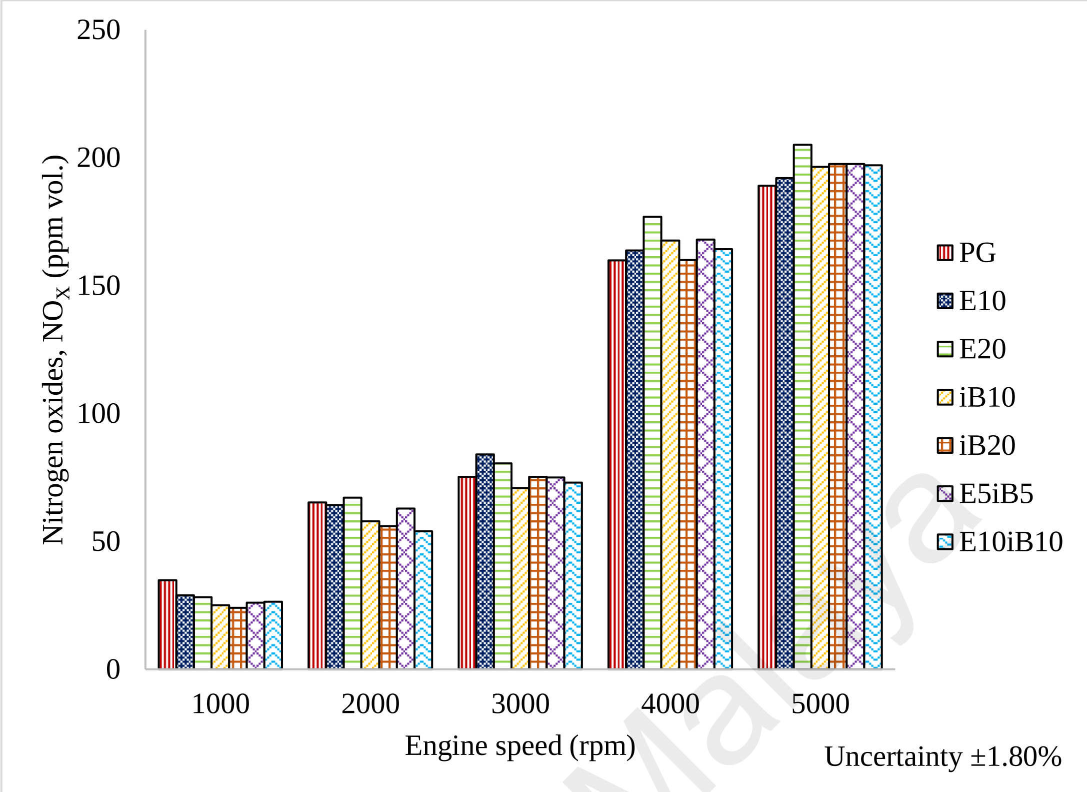
(b)

Figure 4.8: Variation of HC emissions as a function of (a) engine speed and (b) engine torque for all tested fuel blends

4.4.4 Nitrogen oxides emissions

NO_X emission is a group of gases formed when nitrogen combines with oxygen. The endothermic reaction of nitrogen and oxygen takes place inside the engine cylinder during the combustion cycle at high temperature, producing NO_X. The two most common NO_X are nitric oxide (NO) and nitrogen dioxide (NO_2). The mechanism of NO_X formation in gasoline engine were briefly explained by Masum et al. (2013). **Figure 4.9** depicts the concentration of NO_X emissions of all the fuel blends as a function of (a) the engine speed at constant full throttle condition and (b) the engine torque at constant engine speed. It can be seen that in **Figure 4.9(a)**, the variation of NO_X emissions increases with increasing engine speeds. In overall engine speed range, the concentration of NO_X emissions of E10, E20, iB10, iB20, E5iB5 and E10iB10 were higher, with an average increase of 19.56, 34.56, 19.04, 20.30, 22.07 and 16.37%, respectively, relative to PG. The significant increase of NO_X emissions is indicates to higher combustion temperature and EGT, which is associated with the higher oxygen concentration of the fuel containing ethanol and isobutanol (Feng et al., 2015; Gravalos et al., 2013).

It can be observed in **Figure 4.9(b)** that the concentration of NO_X emissions increases with increasing engine torque. The NO_X emissions reaches maxima at engine torque of 60Nm, and it starts deescalating with further increase of engine torque. At lower engine torque of 20Nm, the lower combustion temperature results in lower formation of NO_X emissions. The high combustion temperature with additional oxygen availability during higher engine torque results to more reaction between nitrogen and oxygen to form NO_X. However, when an excessive amount of fuel is injected to the combustion chamber to maintain engine speed, it leads to lower charge temperature which causes lower NO_x emissions. The NO_X emissions of all the fuel blends is similar or slightly higher than pure gasoline, except for E5iB5 blend which produces 2.80% lower NO_X emissions with respect to PG. The E10, E20, iB10, iB20 and E10iB10 blend releases higher concentration of NO_X emissions compared with PG, with an average increment of 1.58, 0.64, 1.27, 0.49 and 2.26%, respectively, with respect to PG.



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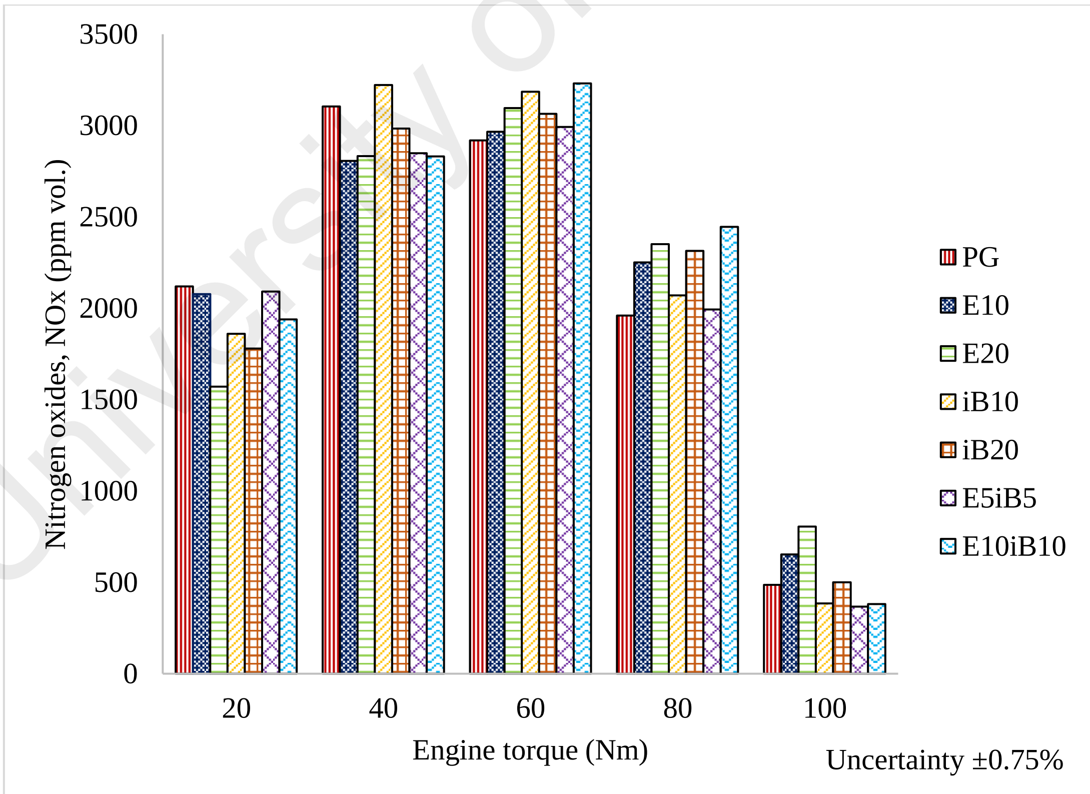

(b)

Figure 4.9: Variation of NO_X emissions as a function of (a) engine speed and (b) engine torque for all tested fuel blends

4.5 Summary

This chapter discussed the physicochemical properties, engine performances and exhaust emissions of various fuel blends i.e. E10, E20, iB10, iB20, E5iB5, E10iB10 and PG. The results can be summarized as follows:

1. The alcohol-gasoline fuel blends have a significant increase in the density, viscosity, HOV and RON, but they are lower in heating value and Reid vapor pressure as compared with pure gasoline.
2. The alcohol-gasoline blends result in significant enhancement of the engine torque, BP and BTE compared to pure gasoline. The E20 blend gives the most significant enhancement for these parameters, with an average enhancement of 3.88, 2.60 and 13.61%, respectively, with respect to PG.
3. The fuel blends also result in lower BSFC than PG caused by normal consequence behaviour to BTE. The E10iB10 blend gives the largest improvement of BSFC with an average enhancement of 5.77% than that of pure gasoline.
4. However, there are no significant changes of EGT between the fuel blends and pure gasoline for both operating conditions. Interestingly, the EGT of the alcohol-gasoline fuel blends is higher than PG at higher engine speeds and engine torque.
5. The E10iB10 blend results in the lowest CO and HC emissions at various engine speeds with an average reduction of 11.21 and 17.13%, respectively, relative to pure gasoline.
6. At various engine torque, E20 and E10iB10 blends result in the lowest CO and HC emissions with an average reduction of 44.02 and 46.32%, respectively, with respect to pure gasoline.

7. However, all the tested fuel blends show higher CO_2 emissions as compared to pure gasoline for both operating conditions.
8. In terms of NO_X emission, there is no significant differences for all fuel blends with pure gasoline for both conditions. However, the alcohol-gasoline fuel blends show a higher NO_X emissions than pure gasoline at higher engine speed and engine torque.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, six types of fuel blends consist of ethanol and isobutanol were mixed with unleaded gasoline at different volume rates (E10, E20, iB10, iB20, E5iB5 and E10iB10) and the physicochemical properties of these blends are measured and compared with the pure gasoline. The fuel blends were tested on a four cylinder SI engine at various engine speeds (1000–5000 rpm) and engine torque (20–100 Nm) and the results are compared with those obtained for pure gasoline. The following conclusions are drawn based on the results of this study:

1. A significant increase in the density, viscosity, HOV and RON of all the alcohol-gasoline blends, but they are lower in heating value and RVP as compared with pure gasoline.
2. The E20 blend gives the most significant enhancement for engine torque and brake power, meanwhile the E10iB10 blend gives the largest improvement of BSFC among the tested blends. However, there are no significant changes of EGT between the fuel blends and pure gasoline for both operating conditions. The EGT of the alcohol-gasoline fuel blends is higher than PG at higher engine speeds and engine torque.
3. In terms of exhaust emissions, the E10iB10 blend results in the lowest CO and HC emissions, respectively at various engine speeds. The E20 and E10iB10 blends result in the lowest CO and HC emissions, respectively at various engine torque. However, all the tested fuel blends show higher CO_2 emissions as compared to pure gasoline for both operating conditions. There is no significant differences of NO_X emissions for all fuel blends and pure gasoline for both conditions. However, the alcohol-gasoline fuel blends show a higher NO_X emissions at higher engine speed and engine torque.

In general, it can be concluded that all of the alcohol-gasoline fuel blends in this study gives better engine performance and reduces exhaust emissions. In particular, the E20 blend improves the engine performances meanwhile E10iB10 improves the exhaust emissions of a four cylinder SI engine without engine modifications. This may be attributed to the structure of the alcohols and physicochemical properties of the fuel blend, which improves reactivity of the fuel blend.

5.2 Recommendations

Based on the conclusions have been made, the following recommendations can be drawn for the future study:

1. This study only focusses on the effect of engine performance and emissions characteristics of ethanol-isobutanol-gasoline fuel blends. Other engine tests are also important, i.e. effect on combustion performance, engine durability, lubricating oil, etc.
2. Further research is required to study these potential alcohols in gasoline fuel blend with optimum operating parameters, i.e. varying compression ratio, ignition timing, etc., therefore giving the best engine performances and exhaust emissions.

REFERENCES

Aakko-Saksa, P., Koponen, P., Kihlman, J., Reinikainen, M., Skyttä, E., Rantanen-Kolehmainen, L., & Engman, A. (2011). *Biogasoline options for conventional spark-ignition cars*. Finland: VTT Technical Research Centre of Finland.

Agudelo, J., Delgado, Á., & Benjumea, P. (2011). The lubricity of ethanol-gasoline fuel blends. *Revista Facultad de Ingeniería Universidad de Antioquia*(58), 9-16.

Al-Hasan, M. (2003). Effect of ethanol-unleaded gasoline blends on engine performance and exhaust emission. *Energy Conversion and Management, 44*, 1547-1561.

Alasfour, F. (1999). The effect of using 30% iso-butanol-gasoline blend on hydrocarbon emissions from a spark-ignition engine. *Energy Sources, 21*(5), 379-394.

Anderson, J., Kramer, U., Mueller, S., & Wallington, T. (2010). Octane numbers of ethanol− and methanol− gasoline blends estimated from molar concentrations. *Energy & Fuels, 24*(12), 6576-6585.

Ansari, F. T., & Verma, A. P. (2012). Experimental determination of suitable ethanol–gasoline blend for Spark ignition engine. *International Journal of Engineering, 1*(5).

Ashnani, M. H. M., Johari, A., Hashim, H., & Hasani, E. (2014). A source of renewable energy in Malaysia, why biodiesel? *Renewable and Sustainable Energy Reviews, 35*(0), 244-257.

Bajpai, P. (2013). *Advances in Bioethanol*. Patial, India: Springer.

Balat, M., & Balat, H. (2009). Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy, 86*(11), 2273-2282.

Bayindir, H., Yücesu, H., & Aydin, H. (2010). The Effects of λ and $\in$ on Engine Performance and Exhaust Emissions Using Ethanol–unleaded Gasoline Blends in an SI Engine. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33*(1), 49-56.

Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy, 25*(1), 1-28.

Blint, R., & Bechtel, J. (1982). Hydrocarbon combustion near a cooled wall: SAE Technical Paper.

Caiazzo, F., Ashok, A., Waitz, I. A., Yim, S. H. L., & Barrett, S. R. H. (2013). Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment, 79*(0), 198-208.

Campos-Fernandez, J., Arnal, J. M., Gomez, J., Lacalle, N., & Dorado, M. P. (2013). Performance tests of a diesel engine fueled with pentanol/diesel fuel blends. *Fuel, 107*(0), 866-872.

Canakci, M., Ozsezen, A. N., Alptekin, E., & Eyidogan, M. (2013). Impact of alcohol–gasoline fuel blends on the exhaust emission of an SI engine. *Renewable Energy, 52*(0), 111-117.

Celik, M. B. (2008). Experimental determination of suitable ethanol–gasoline blend rate at high compression ratio for gasoline engine. *Applied Thermal Engineering, 28*(5–6), 396-404.

Chiba, F., Ichinose, H., Morita, K., Yoshioka, M., Noguchi, Y., & Tsukagoshi, T. (2010). High Concentration Ethanol Effect on SI Engine Emission. *SAE International Journal of Engines, 3*(1), 1033-1041.

Costa, R. C., & Sodré, J. R. (2010). Hydrous ethanol vs. gasoline-ethanol blend: Engine performance and emissions. *Fuel, 89*(2), 287-293.

Demirbas, M. F., & Balat, M. (2006). Recent advances on the production and utilization trends of bio-fuels: A global perspective. *Energy Conversion and Management, 47*(15–16), 2371-2381.

Deng, B., Fu, J., Zhang, D., Yang, J., Feng, R., Liu, J., . . . Liu, X. (2013). The heat release analysis of bio-butanol/gasoline blends on a high speed SI (spark ignition) engine. *Energy, 60*(0), 230-241.

Dernotte, J., Mounaim-Rousselle, C., Halter, F., & Seers, P. (2009). Evaluation of Butanol–Gasoline Blends in a Port Fuel-injection, Spark-Ignition Engine. *Oil & Gas Science and Technology – Revue de l'Institut Français du Pétrole, 65*(2), 345-351.

Dhaundiyal, A. (2014). Influence of blending on the engine parameters and the Reynolds number. *International Journal of Applied Science and Engineering Research, 3*(1), 129-152.

EIA. (2016). *International Energy Outlook 2016*: U.S. Energy Information Administration.

Elfasakhany. (2014). The effect of ethanol -gasoline blends on performance and exhaust emission characteristics of spark ignition engines. *International Journal of Automotive Engineering, 4*(1), 609-620.

Elfasakhany. (2015). Experimental investigation on SI engine using gasoline and a hybrid iso-butanol/gasoline fuel. *Energy Conversion and Management, 95*, 398-405.

Elfasakhany. (2016a). Engine performance evaluation and pollutant emissions analysis using ternary bio-ethanol–iso-butanol–gasoline blends in gasoline engines. *Journal of Cleaner Production, 139*, 1057-1067.

Elfasakhany. (2016b). Experimental study of dual n-butanol and iso-butanol additives on spark-ignition engine performance and emissions. *Fuel, 163*, 166-174.

Elfasakhany. (2016c). Performance and emissions of spark-ignition engine using ethanol–methanol–gasoline, n-butanol–iso-butanol–gasoline and iso-butanol–

ethanol–gasoline blends: A comparative study. *Engineering Science and Technology, an International Journal, 19*(4), 2053-2059.

Ezeji, T., & Blaschek, H. P. (2008). Fermentation of dried distillers' grains and solubles (DDGS) hydrolysates to solvents and value-added products by solventogenic clostridia. *Bioresource Technology, 99*(12), 5232-5242.

Farkade, H. S., & Panthre, A. P. (2012). Experimental investigation of methanol, ethanol and butanol blends with gasoline on SI engine. *International Journal of Emerging Technology and Advanced Engineering, 2*(4), 205-215.

Feng, R., Fu, J., Yang, J., Wang, Y., Li, Y., Deng, B., . . . Zhang, D. (2015). Combustion and emissions study on motorcycle engine fueled with butanol-gasoline blend. *Renewable Energy, 81*(0), 113-122.

Feng, R., Yang, J., Zhang, D., Deng, B., Fu, J., Liu, J., & Liu, X. (2013). Experimental study on SI engine fuelled with butanol–gasoline blend and H2O addition. *Energy Conversion and Management, 74*(0), 192-200.

Ganguly, A., Chatterjee, P. K., & Dey, A. (2012). Studies on ethanol production from water hyacinth—A review. *Renewable and Sustainable Energy Reviews, 16*(1), 966-972.

Gravalos, I., Moshou, D., Gialamas, T., Xyradakis, P., Kateris, D., & Tsiropoulos, Z. (2013). Emissions characteristics of spark ignition engine operating on lower–higher molecular mass alcohol blended gasoline fuels. *Renewable Energy, 50*, 27-32.

Hahn-Hägerdal, B., Galbe, M., Gorwa-Grauslund, M. F., Lidén, G., & Zacchi, G. (2006). Bio-ethanol – the fuel of tomorrow from the residues of today. *Trends in Biotechnology, 24*(12), 549-556.

Hamelinck, C. N., Van Hooijdonk, G., & Faaij, A. P. (2005). Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle-and long-term. *Biomass and Bioenergy, 28*(4), 384-410.

Hosseini, S. E., & Wahid, M. A. (2013). Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia. *Renewable and Sustainable Energy Reviews, 19*(0), 454-462.

How, H. G., Masjuki, H. H., Kalam, M. A., & Teoh, Y. H. (2014). An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine. *Energy, 69*, 749-759.

Hsieh, W.-D., Chen, R.-H., Wu, T.-L., & Lin, T.-H. (2002). Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels. *Atmospheric Environment, 36*(3), 403-410.

Jin, C., Yao, M., Liu, H., Lee, C.-f. F., & Ji, J. (2011). Progress in the production and application of n-butanol as a biofuel. *Renewable and Sustainable Energy Reviews, 15*(8), 4080-4106.

Khuong, L. S., Zulkifli, N. W. M., Masjuki, H. H., Mohamad, E. N., Arslan, A., Mosarof, M. H., & Azham, A. (2016). A review on the effect of bioethanol dilution on the properties and performance of automotive lubricants in gasoline engines. *RSC Advances, 6*(71), 66847-66869.

Kito-Borsa, T., Pacas, D. A., Selim, S., & Cowley, S. W. (1998). Properties of an Ethanol− Diethyl Ether− Water Fuel Mixture for Cold-Start Assistance of an Ethanol-Fueled Vehicle. *Industrial & engineering chemistry research, 37*(8), 3366-3374.

Koç, M., Sekmen, Y., Topgül, T., & Yücesu, H. S. (2009). The effects of ethanol–unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine. *Renewable Energy, 34*(10), 2101-2106.

Kumar, M., & Gayen, K. (2011). Developments in biobutanol production: new insights. *Applied Energy, 88*(6), 1999-2012.

Larsen, U., Johansen, T., & Schramm, J. (2009). Ethanol as a Future Fuel for Road Transportation: Main report: DTU Mekanik.

Lavoie, G., LoRusso, J., & Adamczyk, A. (1980). Hydrocarbon emissions modeling for spark ignition engines *Combustion Modeling in Reciprocating Engines* (pp. 409): Plenum Press.

Lavoie, G. A., & Blumberg, P. N. (1980). A Fundamental Model for Predicting Fuel Consumption, NOx and HC Emissions of the Conventional Spark-Ignited Engine. *Combustion Science and Technology, 21*(5-6), 225-258.

Lin, W. Y., Chang, Y. Y., & Hsieh, Y. R. (2010). Effect of ethanol-gasoline blends on small engine generator energy efficiency and exhaust emission. *J Air Waste Manag Assoc, 60*(2), 142-148.

Liu, F., Liu, P., Zhu, Z., Wei, Y., & Liu, S. (2012). Regulated and unregulated emissions from a spark-ignition engine fuelled with low-blend ethanol–gasoline mixtures. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 226*(4), 517-528.

Liu, H., Wang, G., & Zhang, J. (2013). The Promising Fuel-Biobutanol. In Z. Fang (Ed.), *Liquid, Gaseous and Solid Biofuels - Conversion Techniques* (pp. 175-198): Intech.

Masum, B. M., Kalam, M. A., Masjuki, H. H., Palash, S. M., & Fattah, I. M. R. (2014). Performance and emission analysis of a multi cylinder gasoline engine operating at different alcohol-gasoline blends. *RSC Advances, 4*(53), 27898-27904.

Masum, B. M., Kalam, M. A., Masjuki, H. H., Rahman, S. M. A., & Daggig, E. E. (2014). Impact of denatured anhydrous ethanol-gasoline fuel blends on a spark-ignition engine. *RSC Advances, 4*(93), 51220-51227.

Masum, B. M., Masjuki, H. H., Kalam, M. A., Palash, S. M., & Habibullah, M. (2015). Effect of alcohol-gasoline blends optimization on fuel properties, performance and emissions of a SI engine. *Journal of Cleaner Production, 86*, 230-237.

Masum, B. M., Masjuki, H. H., Kalam, M. A., Rizwanul Fattah, I. M., Palash, S. M., & Abedin, M. J. (2013). Effect of ethanol–gasoline blend on NOx emission in SI engine. *Renewable and Sustainable Energy Reviews, 24*(0), 209-222.

Mittal, N., Athony, R. L., Bansal, R., & Ramesh Kumar, C. (2013). Study of performance and emission characteristics of a partially coated LHR SI engine blended with n-butanol and gasoline. *Alexandria Engineering Journal, 52*(3), 285-293.

Mohamed, A. R., & Lee, K. T. (2006). Energy for sustainable development in Malaysia: Energy policy and alternative energy. *Energy Policy, 34*(15), 2388-2397.

Mohiuddin, A., Rahman, A., Arfah, A., & Farraen, M. (2008). Investigation And Probable Solution Of Low End Torque Dip Problem Of Campro 1.6 L Engine. *International Journal on Mechanical and Materials Engineering*, 176.

Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. (2010). Production of first and second generation biofuels: A comprehensive review. *Renewable and Sustainable Energy Reviews, 14*(2), 578-597.

Najafi, G., Ghobadian, B., Tavakoli, T., Buttsworth, D. R., Yusaf, T. F., & Faizollahnejad, M. (2009). Performance and exhaust emissions of a gasoline engine with ethanol blended gasoline fuels using artificial neural network. *Applied Energy, 86*(5), 630-639.

Niemistö, J., Saavalainen, P., Isomäki, R., Kolli, T., Huuhtanen, M., & Keiski, R. L. (2013). Biobutanol Production from Biomass. In V. K. Gupta & M. G. Tuohy (Eds.), Biofuel Technologies (pp. 443-470). Oulu Finland: Springer.

Ozsezen, A. N., & Canakci, M. (2011). Performance and combustion characteristics of alcohol-gasoline blends at wide-open throttle. *Energy, 36*(5), 2747-2752.

Patakova, P., Maxa, D., Rychtera, M., Linhova, M., Fribert, P., Muzikova, Z., . . . Melzoch, K. (2011). *Perspectives of Biobutanol Production and Use*.

Pease, R. (2012). Traffic pollution kills 5,000 a year in UK, says study, *BBC News Science & Environment*.

Pukalskas, S., Bogdanovicius, Z., Sendzikiene, E., Makareviciene, V., & Janulis, P. (2009). The mixture of biobutanol and petrol for Otto engines. *Transport, 24*(4), 301-307.

Ramey, D. E., Eaglesham, A., & Hardy, R. (2007). Butanol: the other alternative fuel. *NABC Report*(19), 137-147.

Ranjan, A., & Moholkar, V. (2009). *Biobutanol: a Viable Gasoline Substitute through ABE Fermentation.* Paper presented at the Proceeding of international conference on energy and environment.

Rasskazchikova, T. V., Kapustin, V. M., & Karpov, S. A. (2004). Ethanol as High–Octane Additive to Automotive Gasolines. Production and Use in Russia and Abroad. *Chemistry and Technology of Fuels and Oils, 40*(4), 203-210.

RFA. (2016). Global ethanol production by country/region and year Retrieved 9 July, 2017, from http://www.ethanolrfa.org/resources/industry/statistics/#1454098996479-8715d404-e546

Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S., & Mekhilef, S. (2011). A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews, 15*(5), 2262-2289.

Saridemir, S. (2012). The effects of ethanol-unleaded gasoline blends in a single cylinder SI engine performance and exhaust emission. *Energy Education Science and Technology Part A: Energy Science and Research, 30*(1), 727-736.

Sawin, J. L. (2008). Renewables 2007 Global Status Report. Washington: Worldwatch Institute.

Sawin, J. L., Barnes, D., Martinot, E., McCrone, A., Roussell, J., Sims, R., & O'Brien, V. S. (2011). Renewables 2011 Global Status Report *A Dynamic Policy Landscape* (pp. 13-14). France: REN21

Sayin, C. (2010). Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. *Fuel, 89*(11), 3410-3415.

Shapovalov, O., & Ashkinazi, L. (2008). Biobutanol: Biofuel of second generation. *Russian Journal of Applied Chemistry, 81*(12), 2232-2236.

Sims, R., Taylor, M., Saddler, J., & Mabee, W. (2008). From 1st-to 2nd-generation biofuel technologies: an overview of current industry and RD&D activities. *International Energy Agency*, 16-20.

Singh, E., Shukla, M. K., Pathak, S., Sood, V., & Singh, N. (2014). Performance Emission & Noise Characteristics Evaluation of n-Butanol/Gasoline Blend in Constant Speed SI Engine. *International Journal of Engineering Research & Technology (IJERT), 3*(1), 993-999.

Singh, S. B., Dhar, A., & Agarwal, A. K. (2015). Technical feasibility study of butanol–gasoline blends for powering medium-duty transportation spark ignition engine. *Renewable Energy, 76*(0), 706-716.

Smith, M. B. (2013). *March's advanced organic chemistry: reactions, mechanisms, and structure* (7th ed.): John Wiley & Sons.

Soruşbay, C. (2015). *Emissions From SI Engines*. Istanbul Technical University. Instanbul. Retrieved from http://web.itu.edu.tr/~sorusbay/SI/LN09.pdf

Sulaiman, F., Abdullah, N., Gerhauser, H., & Shariff, A. (2011). An outlook of Malaysian energy, oil palm industry and its utilization of wastes as useful resources. *Biomass and Bioenergy, 35*(9), 3775-3786.

Szulczyk, K. R. (2010). Which is a better transportation fuel-butanol or ethanol? *International Journal of Energy and Environment, 1*(1).

Szulczyk, K. R., McCarl, B. A., & Cornforth, G. (2010). Market penetration of ethanol. *Renewable and Sustainable Energy Reviews, 14*(1), 394-403.

Tavares, J. R., Sthel, M. S., Campos, L. S., Rocha, M. V., Lima, G. R., da Silva, M. G., & Vargas, H. (2011). Evaluation of Pollutant Gases Emitted by Ethanol and Gasoline Powered Vehicles. *Procedia Environmental Sciences, 4*(0), 51-60.

Topgül, T., Yücesu, H. S., Çinar, C., & Koca, A. (2006). The effects of ethanol–unleaded gasoline blends and ignition timing on engine performance and exhaust emissions. *Renewable Energy, 31*(15), 2534-2542.

Transport and Air Quality, O. (2010). E85 and flex fuel vehicles (pp. 1-3). United States: United States Environmental Protection Agency.

Wallner, T., & Frazee, R. (2010). Study of regulated and non-regulated emissions from combustion of gasoline, alcohol fuels and their blends in a DI-SI engine.

Wallner, T., Shidore, N., & Ickes, A. (2010). *Impact of ethanol and butanol as oxygenates on SIDI engine efficiency and emissions using steady-state and transient test procedures*. Paper presented at the 16th Directions in Engine Efficiency and Emissions Research (DEER) Conference.

Weizmann, C. (1919). United States Patent No. US1315585.

Xialong, Y., Jing, Y., & Tieping, L. (2009). *The Effect of an SI Engine using Butanol–Gasoline Blended Fuel on Performance and Enviroment*. Paper presented at the International Conference on Energy and Environment Technology.

Yanowitz, J., Christensen, E., & McCormick, R. L. (2011). Utilization of renewable oxygenates as gasoline blending components. *Contract, 303*, 275-3000.

Yücesu, H. S., Topgül, T., Çinar, C., & Okur, M. (2006). Effect of ethanol–gasoline blends on engine performance and exhaust emissions in different compression ratios. *Applied Thermal Engineering, 26*(17–18), 2272-2278.

Yusoff, M. N. A. M., Zulkifli, N. W. M., Masum, B. M., & Masjuki, H. H. (2015). Feasibility of Bioethanol and Biobutanol as transportation fuel in Spark-Ignition Engine: A Review. *RSC Advances*.

LIST OF PUBLICATIONS AND PAPERS PRESENTED

Journal papers

1. **Yusoff, M.N.A.M.,** Zulkifli, N.W.M., Masjuki, H.H., Harith, M.H., Syahir, A.Z., Kalam, M.A., Mansor, M.F., Azham, A., Khuong, L.S., 2017. Performance and emission characteristics of a spark ignition engine fuelled with butanol isomer-gasoline blends. Transportation Research Part D: Transport and Environment 57, 23-38. **(ISI Indexed, Tier 2)**
2. **Yusoff, M.N.A.M.,** Zulkifli, N.W.M., Masum, B.M., Masjuki, H.H., 2015. Feasibility of bioethanol and biobutanol as transportation fuel in spark-ignition engine: a review. RSC Advances 5(121), 100184-100211. **(ISI indexed, Tier 1)**
3. **Yusoff, M.N.A.M.,** Zulkifli, N.W.M., Masjuki, H.H., Harith, M.H., Syahir, L.S. Khuong, M.S.M. Zaharin, Abdullah Alabdulkarem. Comparative assessment of ethanol and isobutanol addition in gasoline on engine performance and exhaust emissions **(Under Revision – Journal of Cleaner Production, Tier 1)**

Conference proceedings

1. Yusoff, M. N. A. M., Khuong, L. S., Syahir, A. Z., Harith, M. H., Masjuki, H. H., Zulkifli, N.W.M. Comparative Study of Ethanol and Isobutanol as Gasoline Blend for Internal Combustion Engine. International Technical Postgraduate Conference, 2017, Kuala Lumpur, Malaysia.